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Editorial

POLISH MARITIME RESEARCH is a scientific journal of worldwide circulation. The journal appears as a quarterly four times a year. The first issue of it was published in September 1994. Its main aim is to present original, innovative scientific ideas and Research & Development achievements in the field of :

Engineering, **Computing & Technology**, **Mechanical Engineering**,

which could find applications in the broad domain of maritime economy. Hence there are published papers which concern methods of the designing, manufacturing and operating processes of such technical objects and devices as : ships, port equipment, ocean engineering units, underwater vehicles and equipment as well as harbour facilities, with accounting for marine environment protection.
The Editors of POLISH MARITIME RESEARCH make also efforts to present problems dealing with education of engineers and scientific and teaching personnel. As a rule, the basic papers are supplemented by information on conferences , important scientific events as well as cooperation in carrying out international scientific research projects.

Scientific Board

Model tests of fast units on the open waters of Jeziorak Lake

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Abstract

Paper presents model tests of fast units carried out in the years 1956-2000 in the Experimental Centre of the Gdansk University of Technology Shipbuilding Institute on Jeziorak Lake. The experimental tests included single- and twin-hull hydrofoils, amphibian hovercraft, side-wall hovercraft and also speedboats and SWATH type catamarans. The aim of those tests was to acquire data for developing the design and safety criteria as well as computer programs for predicting the hydrodynamic properties of fast units. The gathered experimental material was used in the theoretical studies, publications and conference papers.

Keywords: *fast units, single hull, twin hull, model tests, speedboats*

INTRODUCTION

The dynamic development of fast nondisplacement craft caused demand for model tests not only in the resistance field but also in the manoeuvrability, stability and hull load problems, on calm water and on waves. Experimental determination of the above mentioned characteristics in towing tanks is possible only to a limited extent. Main limitation is the very high financial expenditure necessary for the construction of large towing tanks. Therefore, a conception was put forward to carry out model tests in open waters - lakes, rivers, canals etc. in spite of a significant drawback, i.e. dependence on the atmospheric conditions limiting the test season, in this climatic zone, to 6-7 months. An important advantage of the conception is a possibility of carrying out the tests on big manned self-propelled models. The Experimental Station of the Chair of the Theory of Ships developed into a unique Experimental Centre of the Gdansk University of Technology Shipbuilding Institute, located at Ilawa on Jeziorak Lake, where test programmes were performed of the models of displacement ships, hydrofoils, skimming boats, hovercraft and also the SWATH and Wave-Piercing catamarans. At present the centre is used also for teaching purposes, as a base for international student scientific exercises.

Model tests of hydrofoils

The K-1 hydrofoil

In 1955 pioneering model tests of hydrofoils were initiiated in the Chair of the Theory of Ships. The first of a series of tested units was an L = 4.53 m long model equipped with two V type foils. Preliminary tests were performed on the Motlawa river in Gdansk, with a negative result. The foil system required considerable design modifications. The difficulties connected with a small water area and lack of an appropriate equipment decided of moving the tests of that hydrofoil to the Experimental Centre in Ilawa. Tests on the K-1 model on Jeziorak Lake were resumed in summer 1956. The model was tested on the calm water and on waves. An optimum solution was sought to the foil system allowing to keep steady straight course and circulation as well as a shorter way of starting, i.e. raising the hull above water surface. Profiles of foils and braces were changed, deep and shallow foils tested. The experience gained had a significant influence on other hydrofoil designs developed by the Chair of the Theory of Ships. The K-1 hydrofoil was used until 1967. One of its versions is presented in Fig. 1.

Fig. 1. *Model of the K-1 hydrofoil during tests on Jeziorak Lake.*

The K-2 hydrofoil

Model of the K-2 hydrofoil, length L = 6.0 m, built in 1957, in the first version equipped with wooden foils of laminar profiles and capability of changing their lead angle and span, was used for testing the start characteristics in different loading states, as well as the transverse and longitudinal stability in calm water and on waves. In 1960 the foil system was changed in the model. Renamed to K2-M, the model had very good starting, stability and manoeuvrability characteristics in calm water, on waves and in a canal. In 1961 a divided automatically controlled Hook system bow foil was installed on the K2-M model. In this way the K2-H model was created for tests in calm water and on waves. After dismantling the foils, hull of that model was used for building the SP-03 BADACZ I measurement-towing station for testing small hydrofoil and hovercraft models.

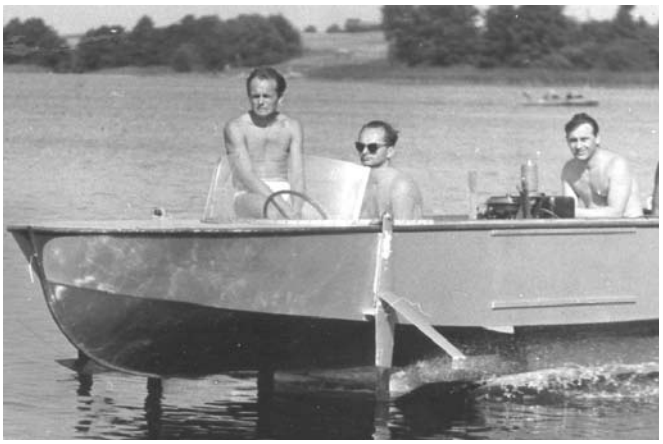

Fig. 2. *Model of the K-2 hydrofoil during tests on Jeziorak Lake.*

The K-3 hydrofoil

Built in the WISLA shipyard in 1958, the K-3 hydrofoil was an 1.5-ton unit with the hull made from aluminium and foils made from stainless steel. Modelled on the PT-20 hydrofoil, it was tested on Jeziorak Lake and on Ilawa Canal in calm water and on waves, in 1959 and 1960. It had good stability characteristics. After dismantling the foils, it was used as a transport unit and the measurement catamaran pusher tug, e.g. in the W-2 hydrofoil model tests.

Fig. 3. *Launching of the K-3 hydrofoil in the WISLA shipyard*

Fig. 4. *The K-3 hydrofoil during tests on Jeziorak Lake.*

The K-6 hydrofoil

The K-6 hydrofoil, length L = 4.24 m, was an 1:3 scale model of the K-4 hydrofoil designed for the Navy. Its tests carried out in 1958-1959 allowed to modify the shape of hull and foils in order to improve the start characteristics. Performance tests of the real K-4 WIESIA hydrofoil were carried out in the Gulf of Gdansk, in 1960-1961.

Fig. 5. *The K-6 hydrofoil during tests on Jeziorak Lake.*

Experimental investigations of small towed hydrofoil models

In the years 1962-1963 systematic investigations were performed in the Experimental Centre of small hydrofoil models towed by the floating measurement station - catamaran. The investigations were aimed at obtaining additional information on the impact of some hull and foil parameters on the hydrofoil start properties.

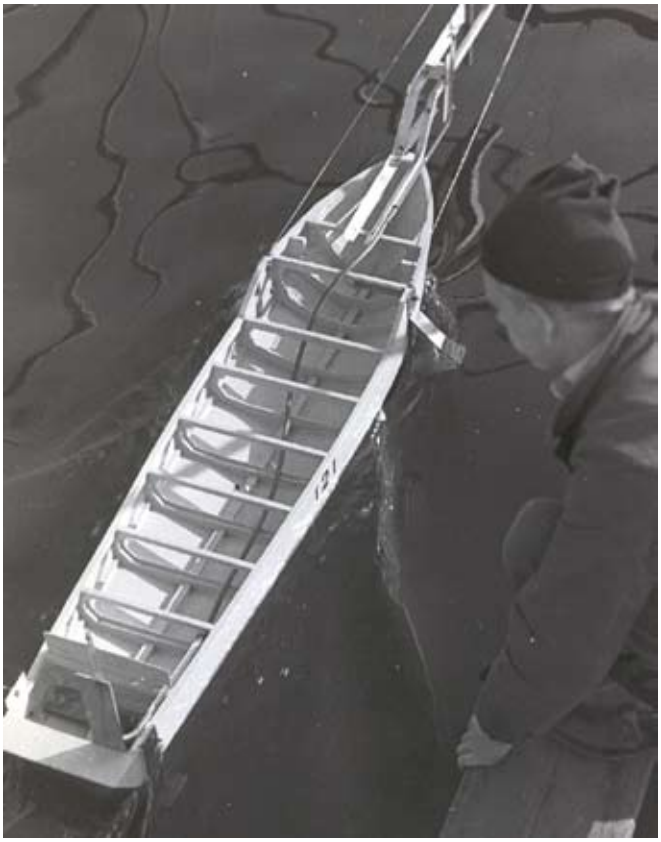

Fig. 6. *View of the towed W-2 hydrofoil model.*

The W-2 REKIN hydrofoil.

The W-2 REKIN hydrofoil, length L = 9.50 m, was an 1:3 scale manned model of a passenger hydrofoil intended for operation in the Gulf of Gdansk. The shape of hull and foils was designed from the test data of small models towed on Jeziorak Lake. During the tests performed in 1962 the W-2B hydrofoil achieved excellent results. An interesting solution was the use of the bow foil reserve surface trailing edge flaps improving the start characteristics. Further tests carried out in 1963 showed excellent operating parameters of the hydrofoil. After completion of investigations, the hydrofoil was used in the Experimental Centre in Ilawa for a long time as a recreation and transport unit.

Fig. 7. *The W-2 REKIN hydrofoil during tests on Jeziorak Lake.*

The W-3 hydrofoil.

The W-3 hydrofoil, length L = 9.20 m, was an 1:3 scale manned model of a passenger hydrofoil intended for operation in the Szczecin Bay. The first tests of that unit in September 1961 consisted in choosing of one of two foil versions from the point of view of good start and stability characteristics, in calm water and on waves. The W-3 tests performed in 1962

were aimed at improving the resistance and propulsion and also start characteristics with large longitudinal shifts of the centre of gravity. In 1965, based on those data, a passenger hydrofoil ZRYW-1 was constructed in the WISLA Shipyard in Gdansk. It was operating first on the Szczecin-Swinoujscie and then on the Gdynia-Hel route, in all weather conditions, altogether for over fifteen years. W-3 was used again in 1966 for testing a modified foil system, implemented then on the real unit.

Fig. 8. *The W-3 hydrofoil during tests on Jeziorak Lake.*

The WS-6 hydrofoil.

The WS-6 hydrofoil, length L = 7.15 m, was to be a prototype of a six-person inspection, transport or tourist unit and a model of a 30-person inland navigation passenger hydrofoil. The hull shape similar to that of W-2, the foil system was a combination of systems applied on K2-M and W-3. In front of the bow foil an additional foil was mounted, facilitating start and emerging from water at full speed. For the first time the Z type gear was used for power transmission to the propeller. Comprehensive tests of the WS-6 carried out on Jeziorak Lake in the years 1968-1969 confirmed its good stability characteristics in the whole speed range, from displacement sailing to a 50 km/h flight.

Fig. 9. *The WS-6 hydrofoil during tests on Jeziorak Lake.*

The WS-4 AMOR hydrofoil.

The WS-4 AMOR hydrofoil was a prototype of a four-person inspection or tourist unit intended for inland navigation, with an original patented hull shape and foil system. Propulsion was provided by a 35 HP outboard engine. Built in 1967, it was used as a safeguard unit during the fast craft model tests. In the years 1991-1993, within the research project KBN No. 310439101, a comprehensive set of tests were carried out of the start, manoeuvrability and stability characterisitcs on calm water and on waves, which confirmed excellent performance of the unit. The hydrofoil is still in operation.

The SP-04 BADACZ II hydrofoil.

The hydrofoil catamaran built in December 1971 by the

Fig. 10. *The WS-4 hydrofoil on the Jeziorak Lake waters.*

was obtained for the original structure of the foils. The first tests were performed in small waves on the Dead Vistula river in Gdansk Stogi. The hydrofoil with a load of five persons achieved a 16 m/s speed. Since 1972 the hydrofoil has been used in the Ilawa Centre. In 1974 it was used for comprehensive tests of real size sports kayaks and canoes. After dismantling its foils, it was used for testing of skimming boats, SWATH catamarans, Wave-Piercing catamarans as well as hydrofoils with a system of two or three foils. At present it is being used for model tests performed in the international student workshops.

Fig. 11. *The SP-04 hydrofoil model towed by SP-03 during tests on Jeziorak Lake.*

Fig. 12. *SP-04 BADACZ II during acceptance tests on the Dead Vistula river.*

Model of a hydrofoil catamaran

A model of catamaran, tested in 1996, supported by a set of three foils, was based on the design study of a 260-person passenger hydrofoil with the cruising speed of 40 knots. A 1:13 scale model was towed by the SP-04 measurement station. The tests included longitudinal and transverse static and dynamic stability as well as pitching angles and accelerations above the foils during the unit flight on waves. The results were used as verification of the programs developed within the research

Fig. 13. Model of catamaran, supported by a set of three foils, under tests

Model of a single-hull hydrofoil

A model of a 120-person passenger hydrofoil in a 1:10 scale, towed by the SP-04 measurement station, was equipped with a set of two or three foils. The tests performed in 1999 within the research project KBN No. 9T12C09914 included the start and transverse stability characteristics, particularly in the transient state of a hydrofoil moving in calm water and on waves.

Fig. 14. *Model of a single-hull hydrofoil with a set of two foils under tests on Jeziorak Lake*

Fig. 15. *Model of a single-hull hydrofoil with a set of three foils under tests on Jeziorak Lake*

Fig. 16. *Model of the M2 skimming boat under tests on Jeziorak Lake*

Model tests of a sports motor boat

In the years 1966-1968 a preliminary study was performed of a series of types of four sports motor boats, designated M1 to M4. In order to acquire reliable design data, a large self-propelled model of the M2 unit was built for tests in the Experimental Centre in Ilawa on the open waters of Jeziorak Lake. The tests were carried out in November 1967.

Model tests of a fast skimming boat

In the years 1981-1987 the Gdansk University of Technlogy Shipbuilding Institute performed a research project, financed by the Ministry of Science and Higher Education, on fast dynamic lift units in order to develop a hull shape for a patrol boat of 160-180 m^3 displacement volume and 40-50 knots operating speed. Comprehensive tests were carried out on four models: no.338 in 1:37 scale, no.238 in 1:10 scale, no.370 in 1:16 scale and the self-propelled model no.378 in 1:5 scale. Experimental tests included the influence of displacement and initial trim angle on the resistance characteristics, of longitudinal steps on the resistance and wave phenomena, of rolling stabilizers on the resistance and transverse dynamic stability and finally of model scale on the resistance and wave phenomena. In cooperation with the Rheinisch-Westfälische Technische Hochschule, Lehrstuhl für Schiffbau, Aachen, Germany, measurements were carried out of the pressure distribution and hydrodynamic loads on the bottom of the no. 378 self-propelled model in calm water and on waves, on Jeziorak Lake and in the Kiel Bay.

Fig. 17. *Self-propelled model during the pressure distribution and hull bottom load tests*

Fig. 18. *No. 370 model in 1:16 scale during tests on Jeziorak Lake*

Fig. 19. *No. 238 model in 1:10 scale during tests*

Fig. 20. *Self-propelled model in 1:5 scale on Jeziorak Lake*

Tests of a SWATH catamaran

In the years 1987-1988 within the Central Research and Development Programme 9.5 tests were carried out of a model in 1:18 scale of a SWATH (Small Waterplane Area Twin Hull) type catamaran in order to develop a hull shape of good resistance and stability characterisitics. A patent application was filed for an original hull shape. Based on the test results, a self-propelled model of a SWATH catamaran of 2.18 m^3 volume displacement was built in 1990. It was used for comprehensive tests of the resistance, manoeuvrability, static and dynamic stability and rolling characteristics in calm water and on waves. The tests confirmed a possibility of operating such units without the use of stabilizing fins.

Fig. 21. *Model of a SWATH catamaran during tests*

Fig. 22. *Self-propelled model of a SWATH catamaran during tests on Jeziorak Lake*

Concluding remarks

Experimental investigation of fast craft is a technically and methodologically difficult part of the ship model tests. It requires good and reliable equipment, broad experience and efficient organization. On the other hand, it provides data for development of design methods, safety rules and prediction of hydrodynamic characteristics. The accumulated experimental material has been widely used in theoretical dissertations, publications and conference papers at home and abroad.

Model tests of the resistance, propulsion and manoeuvrability of ships in the Experimental Centre in Ilawa

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Abstract

Paper presents the development of resistance, propulsion and steering quality model tests carried out on lake. Such pioneering investigations began in 1956 and were gradually improved and extended. Original equipment and measurement methods were developed. The paper presents those research methods and techniques,and also accuracy of the results, in a historical perspective. Described are also several most important research programmes accomplished in the Centre.

Keywords: *resistance, propulsion, manoeuvrability, ships*

INTRODUCTION

Rapid development of shipbuilding in Poland in the 1950s caused as rapid increase of demand for model testing of hydrodynamic characteristics of the designed ships. The first model basin (30 m) was established in the Maritime Institute (1954) and not much later (1955) a similar basin at the Chair of the Theory of Ships, Faculty of Shipbuilding, Gdansk University of Technology. Small size of those basins allowed to test the resistance and later also propulsion qualities, but results were not accurate due to the scale of the models. Manoeuvrability could not be tested. Then, on the initiative of prof. Lech Kobylinski, a decision was taken to substitute open water for a large test tank and in 1956 organization and construction began of the Experimental Centre on Jeziorak Lake in Ilawa. Specific testing conditions on a lake required special, often original, measurement techniques and investigation methods to be developed. The work was started in 1956 and in 1959 first tests were carried out. In the following years, as experience was gained, the methodology was improved, measurement equipment diversified and the scope of investigations widened.

Method and technique of the resistance and propulsion tests

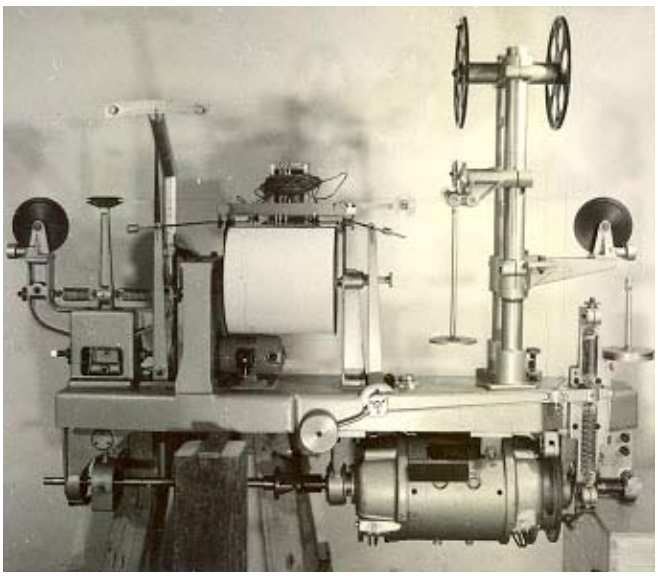


Figure 1. *First propeller dynamometr used in Ilawa (K&R type A-II)*

Preparations for such tests began in 1957. A screw dynamometer (large and heavy, combined with a DC electric motor), Ward-Leonard generating set, screw log for model speed measurements and hydrometric current meters for the wake speed measurements were bought in a well known Kempf & Remmers company. However, before that valuable apparatus was acquired, first resistance tests had been performed in Ilawa of two models of the L-250 and L-500 type ice-breakers for lower Vistula. The models were simply towed on a long line by a motor-boat and resistance was measured with an ordinary spring dynamometer. Bollard pull measurements were also carried out on the L-250 model. Both icebreakers were then built and, oddly enough, no reservations were ever made to their predicted characteristics!

More or less full propulsion tests, ordered by the inland navigation craft design office in Wroclaw, with the above mentioned measurement apparatus, were carried out in 1959 on a „Zubr" type push train model and in 1960 on a H-660 type tug model. The tests were performed on free models with helmsman, which means that the measurements were taken at the point of model own propulsion. The model speed was measured with a screw log fastened on a boom in front of the

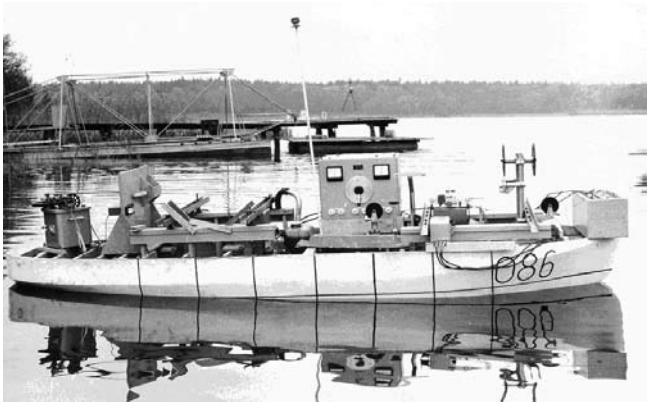


Figure 2. *Model of tug boat M-660 ready for tests*

model bow, propeller revolutions, moment and thrust with the Remmers dynamometer. The wake coefficient was determined from the measurements of nominal wake with hydrometric current meters, corrected by empirical data, thrust deduction factor from the difference between thrust and resistance and the relative rotative efficiency was assumed equal to zero.

The results were converted to the natural scale in accordance with the Froude law with correction of thrust by a 0.9 multiplier to take the scale effect into account. When the units were built, the trial trip tests showed quite a decent agreement with the prediction - the discrepancies did not exceed 5% of the predicted values. Perhaps we were just lucky.

We were aware, however, that the investigation technique was inadequate and we invented a device that was meant to simulate a test tank towing carriage. It was a floating measurement platform in the form of a catamaran with widely spaced fine floats. The tested model was placed in the fore part in the area not disturbed by waves generated by the floats, under a jutting frame, and was connected with the catamaran through a resistance dynamometer. In the first version the catamaran was pushed and steered by a motor-boat, which soon appeared to be a poor solution as it was difficult to keep straight course and constant speed of such a set. A new measurement catamaran was quickly designed and built, where each float had its own car engine, propeller and rudder. The helmsman had respective indicators and was responsible for keeping the engine revolutions equal during the test. Keeping straight course was not difficult. The generating set and most of the measurement equipment, as well as the personnel stands, were installed on the catamaran.

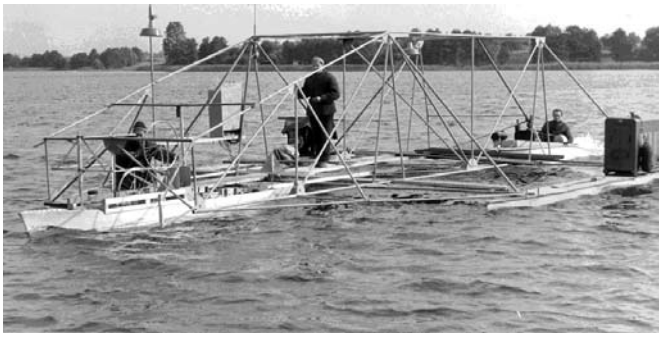


Figure 3. *First version of floating measurement platform*

Figure 4. *Modified floating measurement platform*

The resistance and propulsion tests could then be carried out in a full scope, by means of the same method as in a large towing tank. The floating measurement platform allowed to generate the pulling up force, i.e. transition to the point of model own propulsion. As changing and stabilizing the catamaran speed required long distances, a variable propeller load method, similar to the British method, was applied. Large lake stretches allowed to keep constant course in long runs. The great value of the ratio of catamaran mass to model mass practically eliminated the impact of model towing on the catamaran movement.

Hydrodynamic characteristics of an open-water propeller were determined experimentally in a similar way as in a test tank - special float was suspended under the measurement platform carrying a screw dynamometer and an electric motor moving the propeller mounted on a long shaft before the float.

In the following years, that floating „towing carriage" was systematically modernized - floats were replaced, equipment was improved (a modern screw dynamometer was purchased), the hydrometric current meters were replaced by a set of Prandtl tubes etc.. Basically the test method remained unchanged and it gave good results.

The main disadvantage of open water tests was dependence on the weather - sometimes one had to wait a week for a calm weather. Therefore the tests were often performed during the night or at daybreak (sunrise on the lake would many a time be beautiful). The tests could not, of course, be carried out during the winter.

The idea of using a floating towing carriage for open water model tests was then adopted for some time by the Gdansk Ship Design and Research Centre in their Experimental Station in Joniny, by the High Agricultural School in Szczecin (for the fishing net tests), and even in the Experimental Station of the University of California in San Francisco.

Method and technique of the manoeuvrability tests

Already in the 1930s attention was drawn to the ship manoeuvrability and the experience of the second world war stressed the importance of good steering qualities for the ship safety. Therefore, from the moment the idea of a lake experimental centre was formed, we were convinced of the need of testing the manoeuvrability qualities of newly designed ships and that open water testing facilities were particularly suitable for the purpose. There were no ready examples of such solutions

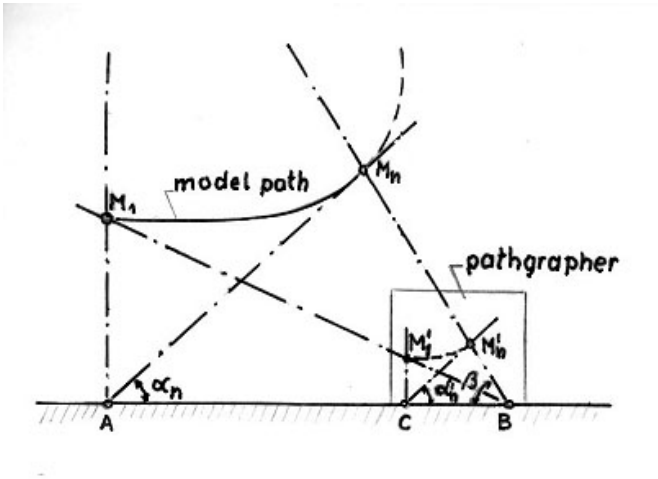


Figure 5. *Scheme of pathgrapher operation*

and the specialist apparatus was practically also not available, so we had to develop our own test methods and techniques.

The first steering tests were carried out on the above mentioned ice-breaker models in 1958, with a very limited scope due to lack of any measurement equipment. The models were self-propelled and were steered manually by helmsman. Tests were reduced to performing a series of circulation manoeuvres and various turns, with rough estimates of their effects.

A problem for those ships was steerability in the astern motion, which was easy to estimate visually and which we managed to improve considerably after those tests by introducing test-verified design changes.

In the period up to 1960 a test method was developed and a set of original measurement devices for model manoeuvrability tests in open waters were designed and built. The basic device was the so called path recorder - a device for the model path tracking and recording.

The path recorder consisted of two direction-finders A and B on the shore. The direction-finders were operated by observers who tracked the mast of the model manoeuvring in the water area before the AB base line. Movement of the direction-finder A, was transmitted by a selsyn to repeater C on the table where direction-finder B was installed. On the axes of repeater C and direction-finder B running arms were mounted moving horizontally over the table. Crossing point of the running arms marked the momentary model position. Between the running arms, at the crossing point, a timing clock generated in constant time intervals a spark piercing the sheet of paper stretched horizontally between the arms.

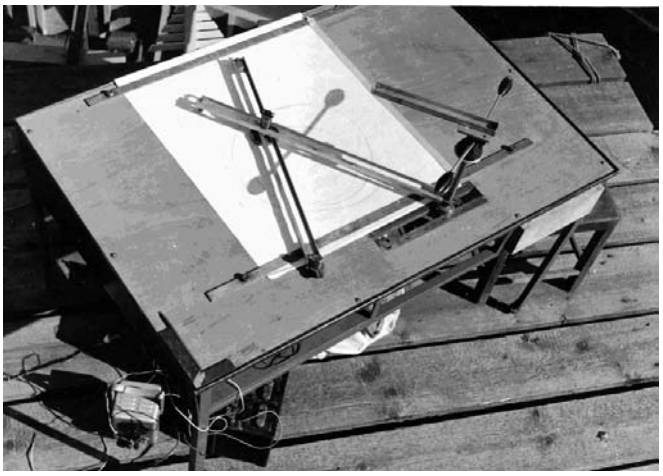


Figure 6. Operation table of pathgrapher – first version

In this way a current model path diagram was obtained in the scale determined by the AB/BC ratio. From distances of the points marked on the track in known time intervals the model speed during turn manoeuvre could be determined. In this way not only the turn manoeuvre elements but also other steerability characteristics, e.g. the stopping distance, were found. Accuracy of the diagram depended on the efficiency of the direction-finder operators (observers) and it was not as good as that of the present day automatic tracking devices, but then it was sufficient for practical purposes (the path recorder was developed by W.Welnicki and E.Adelman and patented under the patent number 55320).

For the zig-zag test an aeroplane gyroscope (a Mig plane „artificial horizon"), whose indications, photographed together with a stop-watch by means of a camera with automatic shutter spring drive, allowed to draw a diagram of heading angle as a function of time. The helmsman, observing the gyro-compass indications, laid the rudder at proper moments. Later an electric steering gear coupled with the gyro-compass was constructed and also an angular velocity measurement system. The drift angle was measured continuosly by means of a driftmeter. The driftmeter consisted of an unbalanced fin rotating freely around the vertical axis, moved out under the model bottom outside the boundary layer. The fin positioned itself always in parallel to the direction of speed and a potentiometer on its axis measured the angle between the model axis of symmetry and the direction of speed.

Figure 7. Model of fast general cargo vessel ready for tests

Also designed and constructed was a rudder stock moment measurement dynamometer, but the device was of little use due to little experience at that time with tensometric systems. Photographic technique was also used for the model tracking. From the top of a 36-meter tower positioned on the shore a stationary camera photographed, in fixed time intervals, light installed on the model, thus obtaining the model path diagram. That technique might be used only by night. Anyhow, the night tests were quite frequent as during the night it was easier to chance upon calm weather.

Tests were performed on free self-propelled models steered by man. The steering-control system allowed to use twin-screw propulsion with a possibility of independent manoeuvring of each propeller. It was planned to introduce radio-controlled models, but eventually it was not accomplished.

Beginning from 1961, the manoeuvring tests were performed in full scope, as it is today required by the IMO resolution.

Accuracy of tests

Special correlation investigations were carried out of the suitability of test methods and techniques used in the Ilawa Experimental Centre.

For the resistance and propulsion characteristics a model of the „Victory" type ship was used, for which comparative data were available from the ITTC tests carried out in Wageningen. The resistance and propulsion tests on the lake in Ilawa (1964) with the use of the measurement platform were performed on a 1:23 (5.89 m) model. The model tested in Wageningen was the same. The methodology was as described above, but the wake coefficient was determined by two methods: the effective wake coefficient - from comparison of the open water propeller and behind-hull propeller characteristics, the nominal wake coefficient was measured with the hydrometric current meters.

Comparison of the results was satisfactory:

- resistance differences for small speeds reached 7%, for greater speeds were negligible,
- the open water propeller characteristics were practically identical, as were the moment and thrust measured behind the hull,
- the w(ef) and t coefficients oscillated around the same values with a maximum deviation of ± 4%,
- the differences in propulsion efficiency did not exceed 3%.

In the tests of manoeuvring characteristics the comparative data were used from the ITTC programme of model tests performed in several test tanks and tests on real ships for the „Mariner" type ship (L=165 m). Tests in Ilawa were performed in 1965 on a 1:25 model with the above presented technique.

Comparison of the test results with the real ship characteristics was the following:

- circulation diameter: deviations from +4.5 to +8% (in Lyngby 4.7 to 9%, PMM tests),
- speed drops in circulation: mean value +3%,

- drift angle: approx. -5%,
- dimensionless yawing period from the zig-zag test: -0.5 to -8.2%,
- departure angle: -13 to -19%.

The relatively large departure angle error may be justified by model manual steering during the test, which probably caused delays in rudder laying in relation to the gyro-compass indications. The results were evaluated as good, comparable with those of well known model basins. It may be worth adding that discrepancy in the real ship circulation measurements performed by two different methods reached 6% on average.

Interesting research projects carried out in the Centre

In the years 1959–1980 some 40 models were tested in the lake centre for their resistance-propulsion and manoeuvrability properties, to the order of the shipbuilding industry, inland navigation, the navy and the engineering force design offices as well as in the government-financed research and development programmes. Many of them were tested in a few versions. At the end of 1970s the number of orders began to decrease rapidly due to opening of the large Ship Design and Research Centre (CTO) model basin in Oliwa.

The most interesting of those tasks are described here below.

One of the first and largest research programmes was the programme of propulsion and manoeuvrability tests of push trains ordered by the inland navigation craft design office in Wroclaw. The tests aimed not only at prediction of the hydrodynamic characteristics of the designed units but first of all at optimization of such elements as the shape of propeller tunnels, simplified propeller sleeve, multi-rudder systems, the impact of shallow water on the propulsion and manoeuvrability properties etc..

The tests lasted from 1959 to 1968 and covered 6 basic types of push trains, with the horsepower from 180 to 600 KM (4 twin-screw and 2 single screw units, including one with the pump-jet propulsion). The models were made in a small scale, 1:5 - 1:10, due to limited draught (small propeller diameter). One of the push trains was tested in shallow water (h/T=2.8; 4.0; 8.) to check the impact of water depth both on the propulsion and manoeuvrability characteristics. As it was impossible to find a water stretch in the lake with flat bottom and the required depth, a fish pond with adjustable water depth was rented near Ilawa, the pond bottom was levelled

Figure 8. *Train of pushed barges at tests*

and the tests were performed there. The tests resulted in many significant changes introduced to the original designs. Four types of those push trains went to series production and they have been sailing on the Odra river until now, held in good repute by the owners.

Interesting and fruitful resistance-propulsion and manoeuvrability tests were performed at the beginning of 1960s on a series of models of the landing assault ships designed by the Ship Design Office No.2. The main purpose of the tests was optimization of the stern shape and choice of propellers and an important requirement was achieving a maximum pull in the astern motion.

Another interesting task was the programme of systematic tests of fast single- and twin-propeller general cargo vessels, carried out in the years 1969-1975 within the 08.12 research programme in cooperation with the Ship Design Office No.1. Preliminary resistance tests were performed on 11 small models in the GUT Department of Ship Hydromechanics test tank and the resistance-propulsion and manoeuvrability tests were carried out in Ilawa on 8, large 6-meter models. The programme included also measurements and analysis of the velocity distribution in the propeller disk for the stern shape optimization from the propeller design point of view.

In the 1984/85 winter interesting tests were performed of an ice-breaker in natural ice. For that purpose the non-freezing mouth of the river Ilawka to the lake was used - the model could gather momentum in the ice-free water and then enter the ice field with impetus. The problem to be solved there was the scale effect in the ice thickness and strength calculations.

In the years 1986-1991, within the 9.5 research programme, the task no. 9: „Hydrodynamic design of an energy-saving medium-size bulk carrier" was carried out. The project was performed in cooperation with the Polish Steamship Company in Szczecin. Part of the large model tests were performed in the CTO towing tank and part in Ilawa. The aim of the research work was optimization of the hull shape with particular attention given to the stern shape in order to increase the propulsive efficiency. Within that programme a patented design of fore-propeller nozzle was developed, which gave almost 5% improvement of the propulsive efficiency. It was then confirmed by measurements taken in a trip of the real ship.

An interesting task was testing of the resistance-propulsion and manoeuvring properties of a fast (40 knots) „wave-piercing" passenger catamaran, carried out in 1994. It was financed by a Scientific Research Committee grant „Twin-hull ships - an energy-saving type of ship for the near future". The model was 8 m long, speed was 9 m/s and it was driven by two outboard motors. Because of the great speed, the resistance and propulsion tests were carried out with the fast measurement platform normally used for the hovercraft and hydrofoil tests; the manoeuvrability tests were performed on the same free manned model.

Figure 9. *Fast catamaran model at turning test*

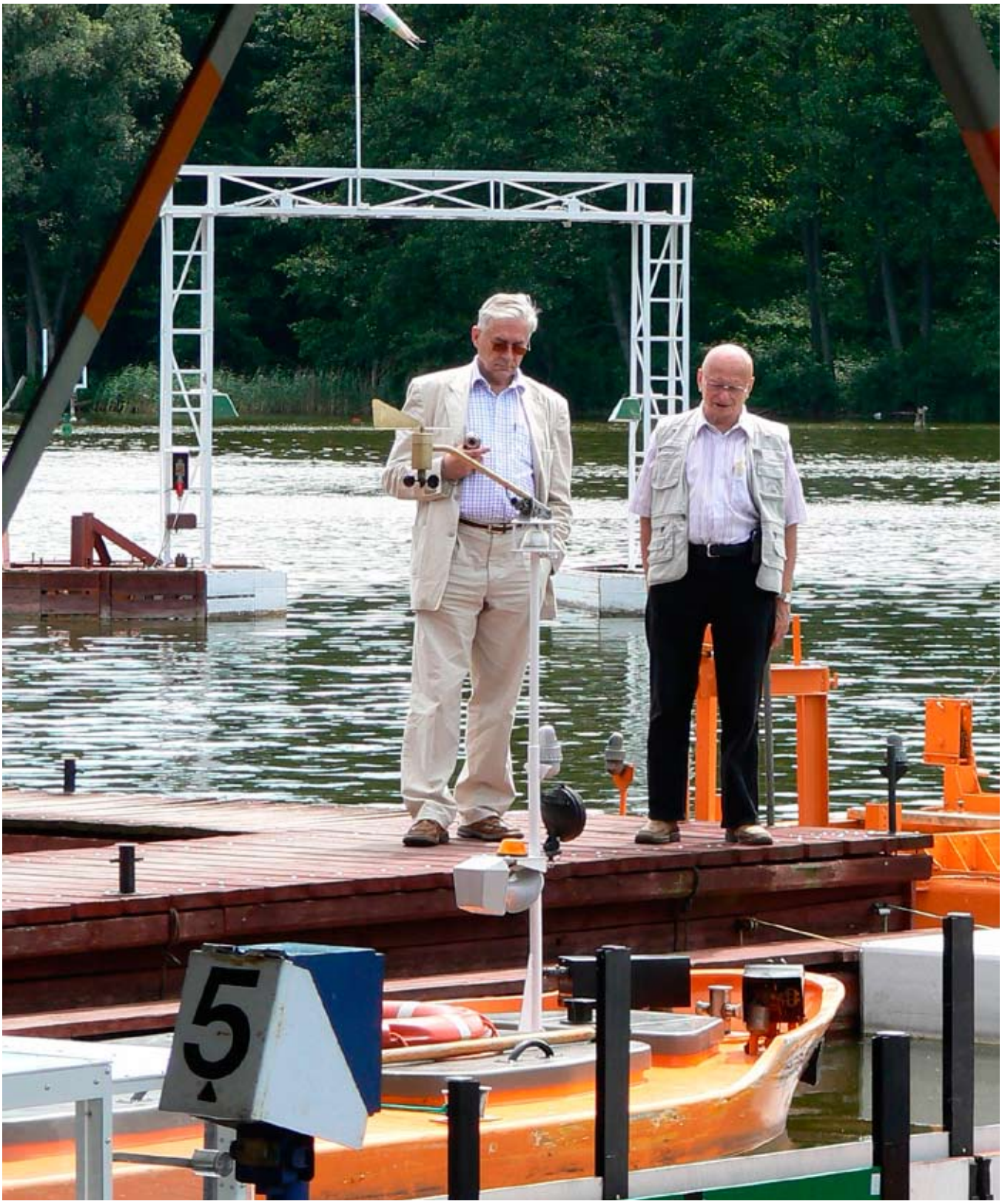
Other non-standard investigations included testing the thrusters for the 773 and 775 navy units (1969-1970), bulk-carrier optimization tests (1984-1986), investigations of the scale effect in the propulsion characteristics performed on the „Zawrat" type large tanker model (1981-1982).

Typical tests performed only with the aim of obtaining predictions for newly designed ships of various types are not a subject of this paper. More than 20 models were tested for that purpose in Ilawa.

Other interesting non-typical tasks are discussed in this Symposium by other authors.

Conclusion

Results of many above mentioned investigations were published in the technical journals and in many conferences in Poland and abroad. It may now be estimated that the GUT Experimental Centre in Ilawa has played an important role in the development of the Polish shipbuilding industry, being used as a substitute for the then non-existent large towing tank and contributing in its way to the progress in ship hydromechanics. This is to the credit of the great energy and initiative of professor Lech Kobylinski as well as of the intense work, creative ideas and involvement of all the workers of the GUT Chair of the Theory of Ships and later the Department of Hydromechanics, who simply cannot be all mentioned here by name.



Open water seakeeping model tests in the research work of the Gdansk University of Technology Shipbuilding Institute in the 1960s

Jan Dudziak, retired worker
Ship Design and Research Centre

Abstract

The paper discusses technical facilities and methodological foundations for the seakeeping model tests of ships carried out on Jeziorak Lake in the 1960s by the Ship Hydromechanics Department, Shipbuilding Institute, Technology University of Gdansk. Major achievements in the research programmes performed then are also mentioned.

Keywords: *seakeeping, dynamic stability, Ilawa lake*

INTRODUCTION

The shipbuilding industry, as other sectoral industry branches, needs own research and development facilities for its existence and development. The Polish shipbuilding industry, developing rapidly at the turn of 1950s, lacked such facilities. Their development would require many years. Therefore, efforts were made by the industry and by the Shipbuilding Faculty of the Technical University of Gdansk (TUG) to fill the gap. The steps taken were transforming the Shipbuilding Faculty into the TUG Shipbuilding Institute and also initiative of the Chair of Theory of Ships, transformed then into the Department of Ship Hydromechanics, to substitute a lake for the non-existent ship model towing tanks. Thus a conception was born to carry out ship model tests on a lake, which led to establishing the Shipbuilding Institute Experimental Model Testing Centre in Ilawa, on Jeziorak Lake.

At the beginning, the ship model resistance-propulsion and manoeuvring tests were carried out in the Centre, but relatively early, at the beginning of 1960s, a conception was developed of performing the ship seakeeping model tests, including dynamic stability. This type of research work was connected with the activities of the Polish government delegation first to IMCO and then to IMO, where intensive work was conducted on the new stability criteria to improve the safety of life at sea. That work included development of new stability criteria separately for merchant ships and fishing vessels. Incidentally, the Polish delegation to the meetings of IMO subcommittees working on those criteria was chaired by Professor Lech Kobylinski, at that time head of the Department of Ship Hydromechanics and director of the TUG Shipbuilding Institute.

Performing the seakeeping and dynamic stability model tests on the natural lake wind wave required a range of methodological and technical problems, not met in the towing tank conditions, to be first solved.

Conception of the investigations

It was decided to carry out the seakeeping model tests in large broads of Jeziorak Lake, close to the Gierczaki, Lipowy Ostrow and Bukowiec islands, near the Siemiany village, some 20 km from Ilawa (Fig. 1), with a camp set up on the Lipowy Ostrow island serving as a base. Natural waves are generated in those broads by wind.

An evident advantage of such conception is that no complicated and expensive special test tanks are needed. Its disadvantage is dependence on the atmospheric conditions and hence seasonal work, difficult planning and non-repeatability of the measurements. Lack of proper laboratories in Poland at that time and increasing interest of the shibuilding and shipping industry in the ship seakeeping qualities caused acceptance of the conception. Its implementation involved setting up original measurement stations with proper equipment and the measurement and recording apparatus and also development of measurement methods and the result processing and interpretation procedures.

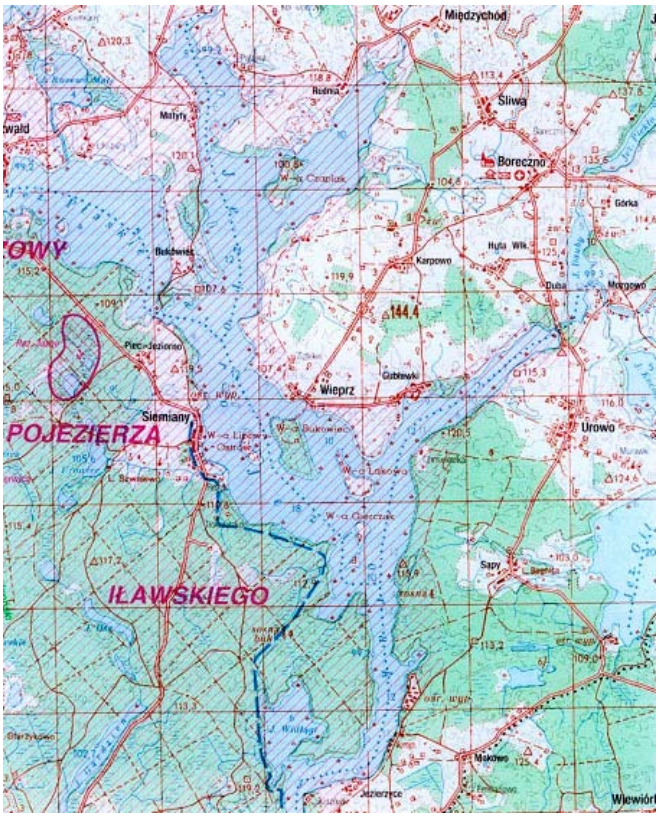


Fig. 1: *Map of broads in the northern part of Jeziorak Lake*

The seakeeping model tests are carried out, as a rule, on the irregular stationary wave. For the stationary waves to develop in an open water stretch at a given wind speed, a minimum time and a minimum water area in the direction of wave propagation are required. In the lake conditions, the stationary waves seldom appear in a given area and time. Most

often developing or vanishing waves occur, with characteristics depending on time and place and also on additional factors, e.g. shore configuration. A relatively short time is needed to determine behaviour characteristics of a ship model in irregular waves, usually not exceeding 10 minutes. Within such a short time the waves may be considered as approximately stationary. Water areas with approximately constant wave characteristics should be chosen for ship model tests.

Wave measurements carried out for the first time in 1964 allowed to determine wave characteristics, such as effective wave height, mean wave period, frequency range of the energy spectral concentration function etc., which in turn allowed to determine the maximum model scale that may used for tests on the lake. The scale was from 1:20 to 1:15.

In the seakeeping model tests the natural lake waves may be considered a sea waving model or stochastic excitation whose characteristics may be determined from measurements. The former approach may be applied in exceptional cases: probability of encountering waves that may be considered, in the ship model scale, a model of sea waves is extremely small. Therefore, the lake waves are usually interpreted as a stochastic exciting force. Such approach, with an assumption that the ship-wave system is a linear system, allows either to determine experimentally the frequency characteristics (within a limited range of ship model heading angles in relation to the wave direction) or to verify the stochastic characteristic calculation methods by comparing the results of experiments and calculations. Such an approach provides also some premises to the development of new calculational methods describing the behaviour of a ship in waves, with an assumption that accuracy of the theoretical description of some phenomena in the model scale guarantees also accuracy of the description of similar phenomena in nature.

The lake conditions cause that apart from action of the generalized forces of waved water, also generalized forces of wind act on the model. This makes the conditions closer to the real ones but causes additional difficulties in the interpretation of results as the wind impact on the model has a different scale than the wave impact. This can be observed when wind influences significantly the behaviour of the model, e.g. with beam waves and wind.

Measurement stations

In the seakeeping model tests on lake most often the self-propelled models are used, sometimes also the towed models. Self-propulsion ensures full freedom of motions, without limitations on the degrees of freedom or additional impact of the towing devices. Two solutions are possible: entirely free radio-controlled model or a model connected by an elastic cable. Towed model requires also a special floating measurement station. On a free model, apart from the propulsion and steering gear, also the measurement apparatus, transmission-receiving devices and sufficiently strong power sources have to be installed. Measurement results may be recorded on the model or transmitted by radio to a shore or floating station. The former solution may appear technically difficult due to shortage of space in the model and its limited weight. Therefore the latter solution was chosen, where only the driving motor, steering gear and measurement apparatus were in the model. The floating measurement station was a catamaran carrying the power source to feed the model, model steering panel and some measurement devices together with the data recorders. Also additional environment (wind, waves) measurement equipment was placed on the catamaran, which played a similar role to that of the test tank towing carriage. General arrangement of the catamaran is shown in Fig. 2.

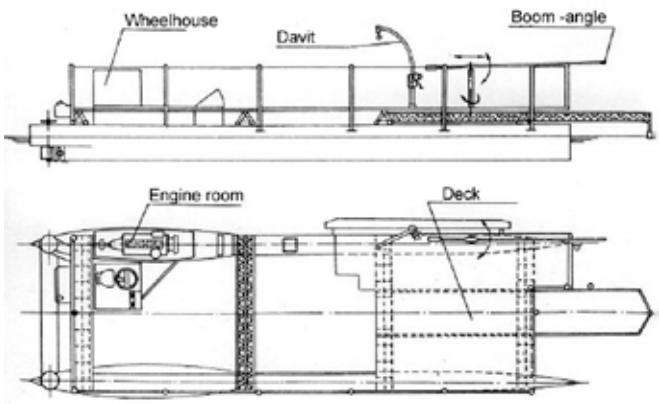


Fig. 2. Measurement platform - catamaran for seakeeping model tests on lake

In order to eliminate the catamaran impact on the model movements, the model was towed on the left hand side of the platform, slightly ahead of its bow, at a 2.5 - 3.0 m distance from the side. The cables were led to the model from the tip of a ca. 4 m long light boom (thin-walled steel pipe) fixed with an articulated joint (three degrees of freedom) to a special column in the fore part of deck on the left side. During measurements the end of boom was easily kept over the model in such a way that the connecting cable was all the time hanging loosely above the model. This is shown in Fig. 3.

When the model was towed by means of a special transverse equalizing bar and rope then the rope was fastened to a vertical boom placed on an additionally mounted 2.5 m long transverse platform. The platform was placed in the catamaran fore part on the left side. It could be raised (e.g. when closing the shore). The platform with towed model is also shown in Fig. 3. The catamaran was additionally equipped with a davit, winch and a cross-bar for easy and quick launching or lifting the model. During measurements, in the fore part of the deck were: the model steering stand with a special control panel on the left side, measurement and recording equipment in the middle, power sources (batteries) on the right side.

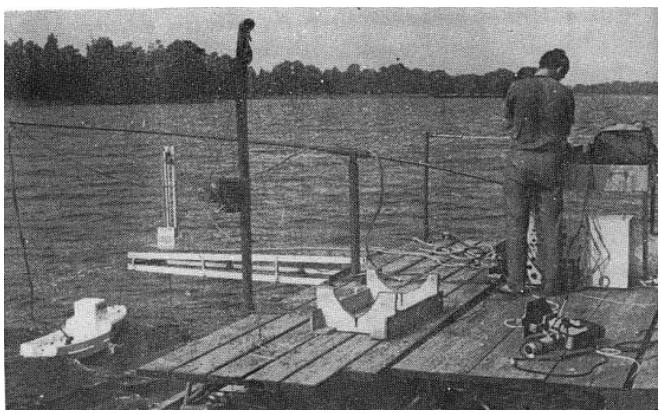


Fig. 3. Towed model of a stern fishing cutter during measurements

In the fore part of the catamaran were measurement instruments for the speed and direction of wind and wave and speed of the measurement platform, which was assumed to be a mean speed of the model. The power sources were: 220 V, 50 Hz, 0.5 kW alternating current generating set and large capacity 12 V and 24 V batteries. Total power consumption for propulsion, steering and feeding the measurement equipment was 0.6-0.7 kW.

During measurement the course and speed of the catamaran were kept constant (there was a speed indicator at the driver's stand). The measurement results were recorded only when the model moved freely and at a proper distance from the catamaran.

Measurement of the external conditions (wind and wave) was not very precise due to the motion and rolling of the platform. Therefore an additional measurement stand was constructed: a steel pontoon - island with a triangular deck (triangle height and base 5 m and 4 m respectively) and 7 m long steel pipe legs in the corners. In the floating condition the legs were elevated and could be lowered to the lake bottom at a depth not greater than 5 m. The pontoon could then be raised above water by means of manual winches, steel ropes and blocks, to form a fixed reference point for measurement of external conditions. Pontoon had a sheltered compartment for the measurement apparatus and power sources. It didn't have propulsion and was towed to the measurement region. The pontoon is shown in Fig. 4.

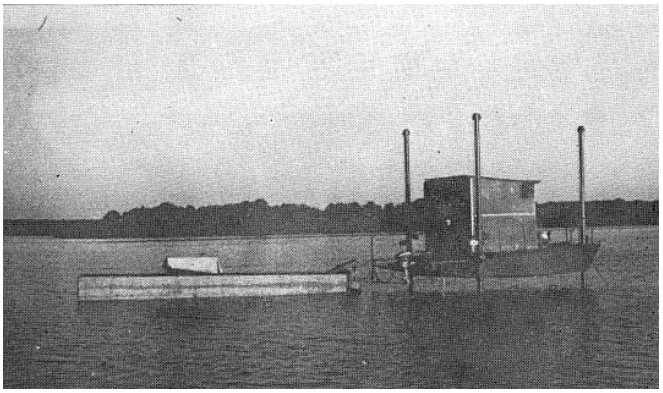


Fig. 4. *Pontoon - island positioned on the lake bottom*

Model propulsion and steering

Models were driven by the electric alternating current motors fed from the generating set through an autotransformer mounted in the control panel. The motor drove the propeller through a mechanical transmission. The autotransformer ensured infinitely variable motor rotational speed adjustment and therefore the required speed of the model.

Model was steered by means of one of the following solutions:

- step-by-step system
- continuous follow-up system
- „pulse" system.

The best results were achieved with the continuous follow-up system which gave smaller angular errors and smaller delay of the rudder movement to the „steering wheel" movement comparing with the first solution.

The measurement and recording apparatus

The measured values may be subdivided into two groups:

- parameters of the external conditions
- parameters of the model behaviour.

The external conditions were characterized by the speed and direction of wind. The model behaviour was described by: model speed and heading angle in relation to the wave direction, angular oscillations (rolling, pitching, yawing), accelerations of linear oscillations (surging, swaying, heaving), relative changes of the water level in specific points of the hull, resistance due to waves etc.. As steering had an impact on the model behaviour, the rudder angles were recorded.

Parameters of external conditions could be measured in a stationary system (pontoon) or in a moving system (catamaran). For that purpose the pontoon was equipped with: wind speed measurement - vane or hot-wire anemometer, wind direction - weathercock with potentiometric transducer, waves - resistance wave probe. The measured values were absolute values.

The same values were measured on the catamaran in a moving system. The measurement gave a relative wind speed and relative wind direction. As the catamaran rolled on waves, the wave probe situated on the left side of catamaran bow measured relative vertical movements of the water level at that point. The wave probe movements due to catamaran rolling may well be considered vertical. In order to determine the wave characteristics in a stationary system, measurement of those movements was necessary. A vertical accelerometer placed exactly above the probe was used for that purpose. The catamaran vertical accelerations at the probe installation point and catamaran speed were the moving system defining parameters.

Measurement of the external parameters from catamaran had the following advantages:

- simple and time-saving procedure,
- simultaneous measurement of external conditions and model behaviour,
- close distance of the measurement points of external conditions and model behaviour.

The model behaviour parameters were measured in the following way:

- mean model speed, assumed equal to the catamaran speed - with an impeller pulse log placed in the fore part of catamaran,
- model heading angle in relation to wave direction - visual estimation,
- rolling and pitching - with a gyroscopic vertical of a vertical rotation axis, with two measurement axes and potentiometric transducers,
- yawing - with a gyroscopic vertical of a horizontal rotation axis and a potentiometric transducer,
- linear oscillations - accelerometers with potentiometric transducers: vertical (heaving) and horizontal (surging and swaying) rigidly connected with the model;
  the accelerometers measured also the gravitational acceleration component acting on the measurement axes due to angular movements of the model,
- relative movements of water level on the catamaran side - resistance wave probes placed at different points on the model (bow, stern, sides),
- rudder angles - potentiometer on the rudder stock,
- resistance due to waves - dynamometers with potentiometric or tensometric tranducers (used only on towed models).

Elements of the individual measurement systems, power source, recording output channel and a common time marker were placed in a panel box.

Depending on the wave intensity, speed and heading angle, the measurement gauge sensitivity could be changed stepwise by means of switches installed in the panel box. The measurement systems were each time prepared in accordance with the test character and programme. Measurement results were recorded on a loop oscillograph and paralelly on a magnetic recorder. Besides, there were indicators of the instantaneous wind speed and instantaneous catamaran speed installed on the catamaran (the latter at the driver station).

Recording on the light-sensitive paper was troublesome in processing (the tape required developing and fixing) and

in further use, but it allowed visual evaluation of the results. Magnetic tape recording made the processing (determination of individual run characteristics) much easier but visual evaluation was not possible.

The measurement apparatus required careful calibration.

Filming was also widely used in the seakeeping model tests.

Models and preparing them for tests

The tested models had usually reproduced abovewater hull shapes, such as sheers, bulwarks, superstructures and deckhouses. Models were fully watertight, which made e.g. capsizing tests possible. Inside models, apart from measurement apparatus, driving and steering devices, there was ballast fastened to the model structure in a movable manner, so that proper static and dynamic balancing was possible. Ballasts were also placed on the deck and on vertical masts, easily movable vertically and horizontally, which allowed to change quickly, in a limited range, the ordinate of the centre of gravity and the moment of inertia in relation to the longitudinal axis. Additional displacement of ballast inside the model allowed to change the centre of gravity position in a wide range. Models were statically and dynamically balanced. Static balancing was performed by means of scales and inclining test, dynamic balancing - by measuring the rolling period on a special cradle (determination of the moment of inertia in relation to the transverse axis) or by suspension on prisms (determination of the moment of inertia in relation to the longitudinal axis).

Result processing technique

The functions recorded on the loop oscillograph paper tape or on magnetic recorder tape were realizations of the respective stochastic processes of ship seakeeping properties. Further processing of those results depended on the character of functions measured. Two extreme cases may be distinguished here:

- the model phenomena (movements, flooding, increased resistance) are within a linear theory,
- the phenomena are clearly non-linear.

In the case of phenomena described by the linear or linearized theory, processing of the recorded data was performed in accordance with a standard procedure. Its objective was to determine characteristics of the external forces acting on a ship (wind, wave) and characteristics of the ship responses (movements, movement speed, acceleration, green water shipment, etc.), which further allows to determine ship dynamic characteristics such as the frequency characteristic. The so determined characteristics may be used for finding parameters of ship behaviour in different environment conditions (sea states) or they may be compared with similar calculated characteristics.

Processing of the measurement results was carried out on a special analogue computer ISAC. For each measurement data set it could calculate: autocorrelation function, spectral concentration function, ordinate distribution function and also mutual correlation function of any two data sets simultaneously recorded on magnetic tape. The processed data sets might have different lengths. Usually from a 10-minute recording a 6-7-minute section was chosen for processing, which for an average case (model size, heading, wave) corresponded to 100-400 relative periods. Such data set ensured sufficient statistical accuracy of the results, but there was a possibility of extending or shortening of the measurement runs.

Difficulties occurred when the model moved with a speed V and the heading angle b in relation to the wave direction. Then instead of w we had the encounter frequency we equal to

and after the computer processing all the spectral concen-

$$\omega_e = \omega\left(1 - \frac{V\omega}{g}\cos\beta\right) \tag{1}$$

trations were obtained as functions of we. Transition to an absolute system, i.e. to functions of w, is possible in a general case only for heading angles b from the bow sectors:

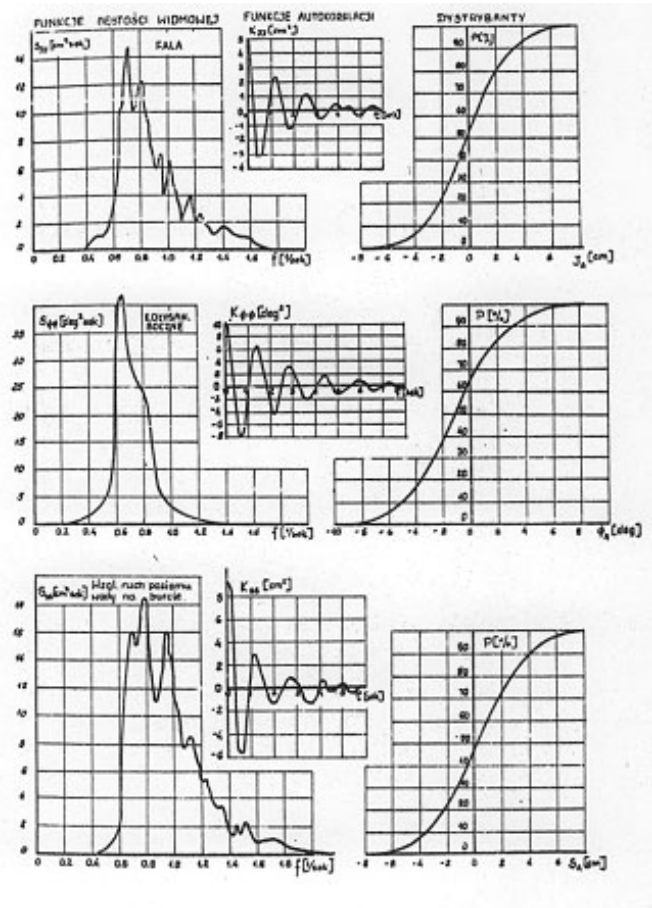


Fig. 5. Example of measurements processed on the analogue computer

$\beta \in \left[+\frac{1}{2}\pi; +\frac{3}{2}\pi\right]$ The conclusion is that the amplitude characteristics of those phenomena could in the general case of $V \neq 0$ be determined only for waves coming from the bow sectors. This limits to a degree the possibilities of seakeeping testing but this limitation applies equally to lake and to the test tank.

When clearly non-linear phenomena were tested, such as e.g. ship capsizing, the above described processing methods were of little use. In such case the phenomenon was tested in a narrow time interval as determined, occurring in stochastic external conditions. The testing methodology of such phenomena was not mastered fully.

Fig. 5 and 6 present examples of the results of such investigations. Fig. 5 presents partial results of the analogue computer processing of the recording of model rolling and deck flooding in beam waves; Fig. 6 shows recorded capsizing of a model in following waves and in beam waves.

Test programme and major achievements

Tests carried out in the second half of 1960s were connected first of all with the stability safety of small ships, fishing vessels in the first place. Statistics of losses caused by the stability failure accidents show that the smaller the ship size the greater

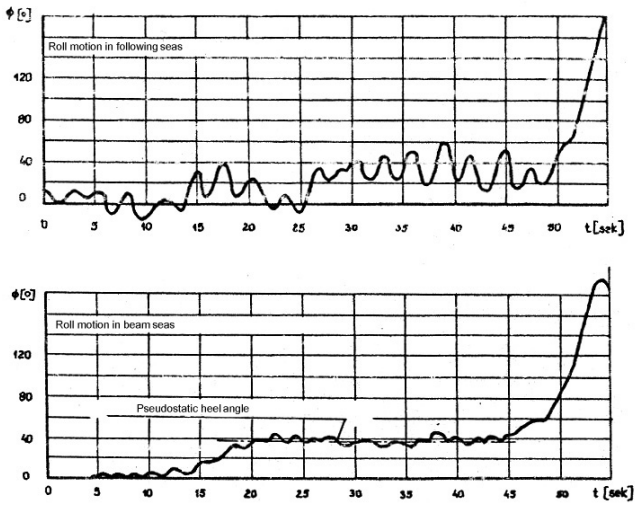


Fig. 6. Examples of recorded model capsizing

the number of ships sunk. A significant percentage of those are fishing vessels. The reason of that is not only small size of fishing vessels but also their specific functions. The increased fishing vessel safety hazard, comparing with other ship types, is connected with the fishing process when additional forces from the fishing tools act on the ship and the hold hatches are usually open which facilitates water penetration into the hull. The threat increases when fishing is continued at higher sea states and the ship overloaded with fish either because of desire to get higher profits or inadequate crew qualifications and control of the ship loading condition. That was the justification of research work aimed at increasing the safety of small ships, particularly fishing vessels. Three fishing ships were tested:

- the B-14 type side trawler,
- the B-10 type trawler-drifter,
- the TRT-18 type stern fish cutter,

operated by Polish fishermen or built by the Polish shipyards. The aim of investigation was not so much improvement of those ship types but drawing some more general conclusions regarding stability criteria, freeboard (amidships and at the bow) etc.. Particular subject of investigations was behaviour of the low-side fishing vessels in the beam waves and side wind as well as the following wave conditions. One of the interesting findings was that in the beam wave and side wind conditions the so called pseudo-statical angle of heel may occur due to asymmetric deck flooding, which quite often leads to ship turning over on the windward side (Fig. 6).

The test results were partly used in formulating the IMO recommendations regarding the freeboard height and protective freeboard as well as bow height of fishing vessels. (Those recommendations were later included in the Torremolinos Convention).

The tests allowed also to observe many phenomena connected with capsizing of non-damaged fishing ships. It is impossible to observe such events in nature. This is, for instance, capsizing caused by broaching, like that of the B-10 trawler-drifter. The mechanism of the event was the following: the ship sailed in a following wave; a group of waves appeared with relatively long crests and the wavelength approximately twice the ship length. The model speed was smaller than the wave phase velocity, i.e. the wave was overtaking the ship. When the model stern was on the wave crest and the bow in the wave trough, the model would lose its linear motion stability and sharply turn to the left. When the wave passed, the model returned to the original course but already second or third overtaking wave would cause another sharp turn to the left so that the model was almost broaching; flooded violently, the model heeled and capsized. The capsizing occurred always on the windward side, as in the case of deck flooding by beam waves, in spite of the contrary action of wind.

Concluding remarks

The fishing vessel stability safety model testing programme was not the only programme in the seakeeping domain. Commercial orders were also carried out, e.g. on the effectiveness of a special type of bilge keel (ordered by the Maritime Institute) or accelerations on the 10000 DWT general cargo ships (a Polish Ocean Lines order). Also a programme of model tests on ship damage stability was accomplished. Observations from that programme were used in other research work on the unsinkability and damage stability of ships.

In my opinion, full use of the model experiment results was somewhat limited by lack of appropriate mathematical models and respective computer programs and also by the research team personnel rotation. Nevertheless, it was an excellent school of practical execution of the seakeeping model tests and the experience gained there was later used by some members of the Jeziorak Lake test team in their work in other research institutions in Poland and abroad.

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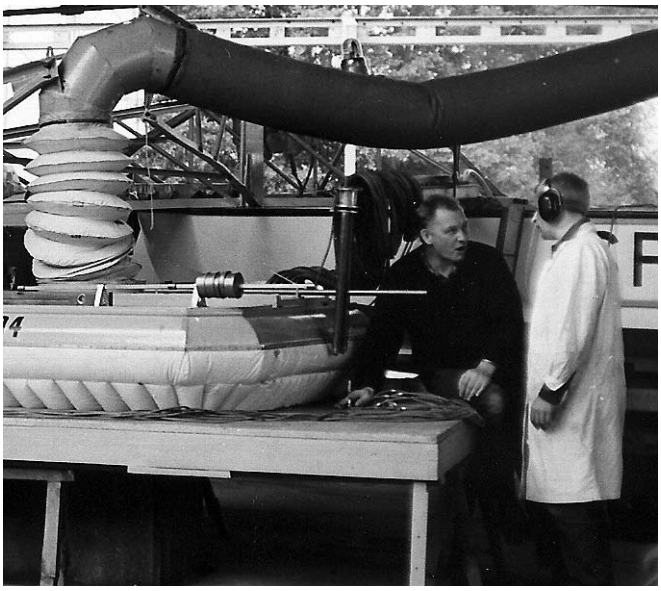

Complex investigations of a cycloidal propeller in Ilawa in the 1960s

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Keywords: *cycloidal propeller, IMP-PAN, circulation cycle*

Research work on the cycloidal propeller in the Department of Ship Propellers of the Institute of the Fluid Flow Machines, PAS (IMP - PAN), included:

- theory of cycloidal propellers (the hydrodynamic, kinematic and dynamic problems), including kinematic systems ensuring the required blade movements, with their designs and solutions avoiding the existing patent claims,
- propulsion tests of a harbour tug,
- propulsion tests of a push-train,
- manoeuvring tests of a push-train with the use of a photogrammetric method.

The last three groups of tests were carried out with an invaluable cooperation of the IMP-PAN Department of Ship Propellers and the GUT Department of Hydomechanics.

Before discussing some of the scientific aspects of that cooperation, I wish to express my greatest appreciation of the initiator of the two above mentioned Departments, prof. Lech Kobylinski. The founder of the Polish school of hydromechanics, he assembled a group of co-workers around his professional ideas of developing this scientific discipline for the needs of the Polish maritime economy, first in the GUT Chair of the Theory of Ships and then - in the years 1955-1962 - in the IMP-PAN Department of Ship Propellers. In both these centres the framework of the Polish contribution to the world ship hydromechanics was constructed. One may now conclude with some pride that lasting achievements of the Polish ship hydromechanics are known in the world. Ilawa is an impressive example how the Polish ship hydromechanics community was able to make up for the lack in the post-war years of an indoor towing tank and manoeuvrability test tank and to create substitute model testing facilities and later to develop those ideas into a centre of extensive research work. The initiator and „spiritus movens" of those activities was full of ideas and creative energy professor Lech Kobylinski.

The cooperation of both Departments in the Ilawa Experimental Centre was most often unconventional in the sense that the balance of mutual services was based on friendliness, confidence, without any trace of institutional egocentrism. As the IMP-PAN workers, we might use, and we did use in practice, all the facilities of the lake laboratory, its workshop and hotel, without unnecessary legal or financial formalities. On our part, we contributed, however modestly, to the development of that laboratory.

The workers of both Departments formed a good team overcoming all the difficulties inherent in that open-air laboratory exposed to all the changing atmospheric conditions. We remember with some satisfaction our living there in a spirit of community.

The IMP-PAN Department of Ship Propellers carried out in the GUT Shipbuilding Institute Experimental Centre a programme of investigations of a cycloidal propeller and its application as a harbour tug propeller and a river push-train propeller. The programme of lake tests included:

I. Construction of a tug model and outfitting it with two cycloidal propellers designed and made in our workshop.
II. Construction of two concrete barges, forming together with the tug a cycloidal push-train (21 m long).

Phot.1 *Bow cycloidal propellers on a tug*

Phot.2 *Cycloidal propeller before installing on a tug model*

III. Installation of a tower on foundations near the lake in Ilawa for the use of a photogrammetric method in the manoeuvring tests of a cycloidal push-train (tower height 35 m).

Phot.3 *Cycloidal propellers after installing on a tug model*

IV. Propulsion tests of the tug with bow cycloidal propellers.

V. Propulsion and manoeuvring tests of the cycloidal push-train.

Particularly interesting are points III and V of this research programme. The aerial photogrammetry methods were used for the manoeuvrability tests of the cycloidal push-train.

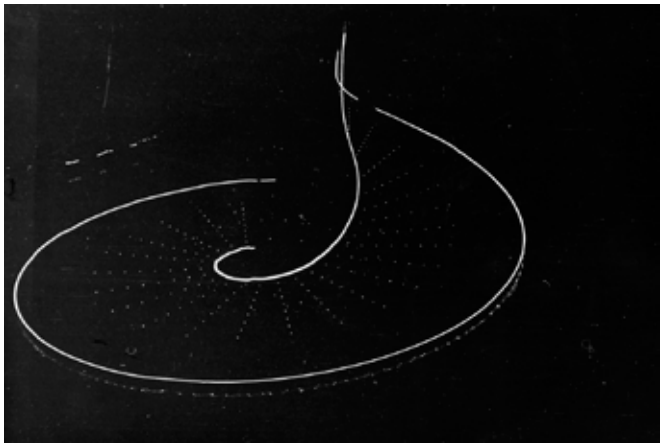
Phot.4 *Cycloidal push train*

A railway signalling-lighting tower (35 m high) removed from the Bydgoszcz railway station was obtained for the cost of its disassembly and transport to Ilawa. From the top of the tower the manoeuvring push-train was photographed by night and three its points (bow, stern and the centre of gravity) with continuous light and 8 points with flashing lights (distributed in straight line every 1 m from the centre of gravity towards stern and flashing simultaneously every 6 seconds) were recorded.

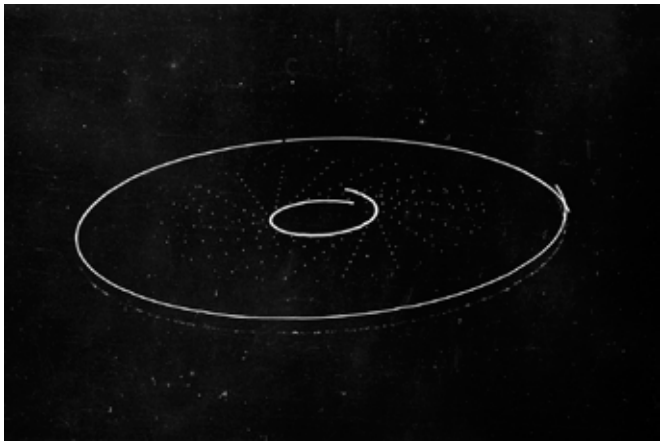
The proposed photogrammetric method provides full information on the push-train movement during the turning manoeuvre:

- path shapes of any number of selected points,
- velocities of the centre of gravity and other points,
- angular v elocity of the push-train,
- angular drift velocity.

The tests were carried out overnight and each circulation cycle (one full turn of the train) was photographed with open diaphragm during the whole cycle. Conversion of the photographs from the photographic plate plane to the push-train movement plane may be done by analytic processing. Uniqueness of the representation in the projection processing is ensured by four pairs of homologous points. Four light points are fixed in the movement plane for a unique mutual situation of the photographic plate plane and the train light plane. The proposed method allows to obtain precise picture of the kinematic relations in the push-train turning manoeuvre. It makes a valuable check on the results of the theoretical analysis of the push-train movement, by insight into the system of forces and obtaining practically verifiable theoretical solutions.



Phot.5 *Push train performing circulation, $V = V_0$*



Phot.6 *Push train performing circulation, V = 0*

Model tests in open waters – a concept that did pay off

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Foundation for Safety of Navigation and Environment Protection

Abstract

The paper presents the concept of performing model tests in open waters. This concept was realized in the Ilawa Experimental Station arranged on the shore of the Jeziorak Lake in 1956. Since then model tests of high-speed craft, manoeuvrability and propulsion characteristics of conventional seagoing ships and inland waterways push tugs-barges systems have been performed there. New concepts of how to perform the tests were developed. The advantages of performing model tests in open waters were stressed and future possible applications suggested. The activity of the experimental station that belonged to the Technical University of Gdańsk greatly contributed to.

Keywords: *high-speed craft, ship model tests, ship hydrodynamics, the development of ship hydrodynamics science in Poland*

INTRODUCTION

Model test are the most important tool in ship design. When William Froude in 1872 constructed the first towing tank for testing ship models, in order to predict resistance and propulsion characteristics of ships to be built, the model testing technique started to develop rapidly. In several countries interested in shipbuilding a number of towing tanks were constructed, and in the course of years, apart from testing ship resistance and propulsion characteristics of ships, other facilities were constructed for testing cavitation characteristics of ship propellers, seakeeping and manoeuvring characteristics of ships and for testing hydrodynamic characteristics specific to some types of ships. Large universal ship hydrodynamic laboratories came to life. The cost of building and operating such laboratories was, however, enormous.

In Poland, after the WW II shipbuilding industry started to develop rapidly and there was an

initiative to build a hydrodynamic laboratory. This, however, would require several years to achieve. There was a compelling need to arrange model tests as soon as possible in order to perform research programs, to train students and research workers for the future towing tank as well as to solve current problems of the industry that would require model testing.

In this situation in the year 1956 in the Chair of Naval Architecture, Technical University of Gdansk the concept was proposed to conduct model tests in open waters, such as lakes and large ponds. Suitable place was found in Ilawa and preliminary tests were performed there. The concept appeared to be very successful and in the following years many research projects were executed there as well as hundreds of ship models were tested for the shipbuilding industry.

Strictly speaking the concept of conducting model tests in open waters was not new. There were some historical references about model tests performed in open waters in 18th century, e.g. tests performed by D'Alembert in 1775. Later, construction of towing tanks caused that performing model tests in open waters was not expedient.

In the early 1930s the need emerged to predict manoeuvring characteristics of ships during the design stage and then free running self propelled models started to be used for this purpose. Such tests could not be performed in the conventional Froude-type towing tanks and this resulted in increased interest in performing model test in open waters. In the early 1970s some nine experimental stations were involved in this activity [4]. Ilawa experimental station was, however, unique because it was able to perform wide range of model tests, including resistance and propulsion, seakeeping and manoeuvring test, tests of high speed and non-conventional craft and many others. The ideas and facilities were developed over the years and the whole enterprise started in 1956 with tests of a hydrofoil craft manned model.

Construction of a hydrodynamic laboratory by the shipbuilding industry caused that some model tests were not performed in the Ilawa experimental station any more. There were attempts made in order to find suitable field of activity for the facility. One of the new fields was to use large manned model for training of ship masters and pilots in ship handling. This idea appeared to be very fruitful and in the late 1980's – early 1990's a separate ship handling research and training centre was organized on a nearby Silm lake. The old experimental station is still active used mainly for performing tests of high-speed craft and to perform some non-conventional tests impossible to execute in a towing tank.

The development of the Ilawa experimental station is illustrated by two sketches: Fig.1 showing the lay-out of the station in 1957 and Fig. 2 – in 1971. At present the plan of the station is almost the same.

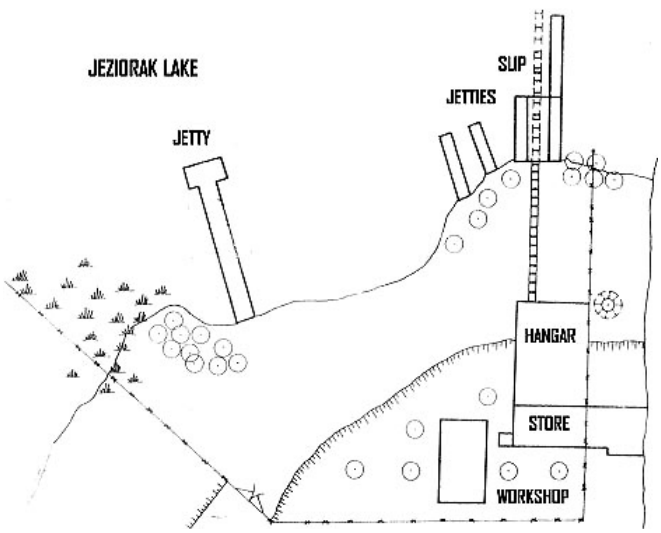
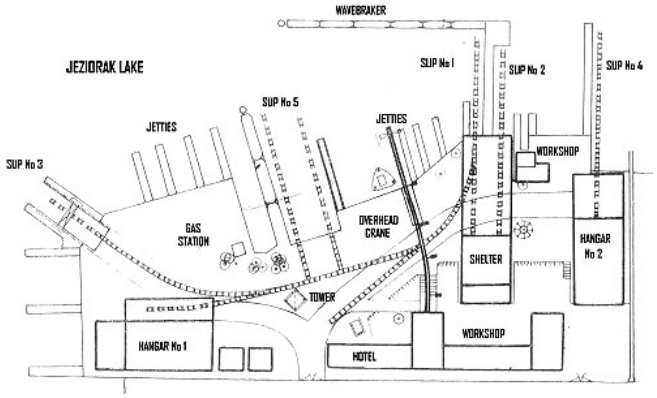


Fig.1. *Ilawa experimental station in 1957*
Fig.2. *Ilawa experimental station in 1971*



Tests of propulsive characteristics of ship models

From the point of view of ship design the most important issue is prediction of speed and power required. This is usually achieved on the basis of results of propulsive characteristics of ships.

From the early beginning of the activity of the Ilawa experimental station attempts were made to test propulsive characteristics of models as accurately as possible. The main difficulty consisted in measurements of resistance and propeller characteristics of models. In towing tanks there is a routine technique where model is towed by the towing carriage. In order to test propulsion characteristics the model is self-propelled , but in order to achieve self propulsion point of ship it is necessary to apply to it additional towing force to allow for the difference between frictional resistance of the model and full scale ship

During the first trials the models used were self propelled and manned, however it was impossible to measure model resistance without propulsion and also to apply additional towing force in the self-propulsion tests. Prediction of speed and power was therefore not accurate enough. But as the proverb says: "the need is mother of invention", so later a kind of towing carriage was built in the form of a catamaran (Fig.3) where model was towed (or rather pushed) enabling measurements of resistance without propeller and measurements of propulsion characteristics with additional towing force applied. Measuring team was located on the catamaran where also all measurements were taken. This method made open water tests very similar to measurements taken in a towing tank. The advantage of this method was that the measurement stretch was not limited and could be even a few kilometers, which was very useful for example, for taking measurements of pressure distribution in the propeller disc [2].

The above described method of performing propulsion tests was very successful, and in the industrial ship hydrodynamic centre similar catamaran had been built and used until the time

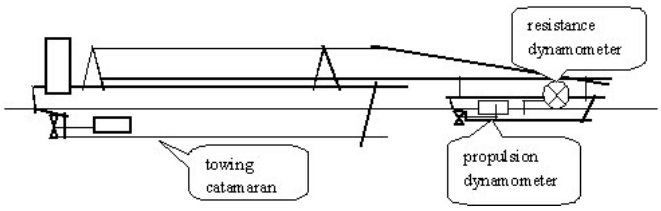


Fig.3. Scheme of the towing catamaran and model

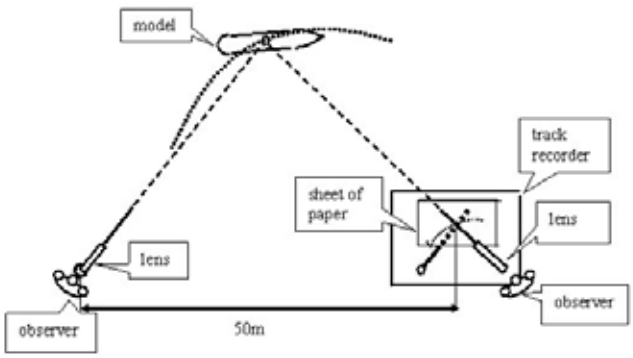
when the towing tank under construction was in operation. Some models were tested using this catamaran on Wdzydze Lake. Altogether in Ilawa in the years 1960-1975 almost 50 large self-propelled models were tested. Later, when the towing tank in Oliwa was put into operation the resistance and propulsion tests for shipyards were not performed any more, but still the catamaran was used for research purposes.

Tests of manoeuvring characteristics

Model tests are essential for the prediction of manoeuvring characteristics of ships during the design stage. When the Ilawa experimental station was organized, there already existed a few experimental stations in the world using free-running models tested in open waters. In Ilawa from the very beginning free-running self propelled and manned models were used for testing manoeuvring characteristics, and in particular turning tests, zig-zag tests, stopping tests and course-keeping tests were performed. The main problem to be solved was to arrange reliable monitoring system of the track of the model. The original method developed was "track recorder" based on the simple idea of observing model from two points located at certain distance. This idea is illustrated in Fig. 4.

Fig.4. *Scheme of the track recorder*

The instrument consisted of a table on which sheet of



paper was spread. There were two arms, one was attached to the lens and the other was under the sheet of paper and remotely controlled by another lens located at the point at a distance of 50 m. Two people observing the mast of manoeuvring model operated these two lenses. At every second, or half second, the spark was induced at the cross-section between two arms making small hole in the paper. The series of holes reproduced turning circle of the model in a reduced scale. The method was very accurate provided the two observers carefully followed motion of the model.

In the Ilawa experimental station also a different method of model tracking was used. In this method the camera located on a high tower on the shore of the lake recorded motions of the model on which there were two small lights blinking in one or half-second period. This method was used at night time only, and the main difficultly was to draw model track from the series of dots appearing on the plate.

In the 1960's and early 1970's there was little demand by shipyards for prediction of manoeuvring characteristics of conventional seagoing ships, therefore the majority of manoeuvring tests were performed with inland waterways vessels. In particular several pushing tug-barge systems designed for the Odra river were tested where different configurations of rudders were installed. Sometimes the models of pushing tug-barge systems tested were as long as 20m.

Tests of high-speed craft

The programme of development of high-speed craft was established in the Technical University of Gdansk quite early, in 1955. The main goal was to investigate possibilities of bui-

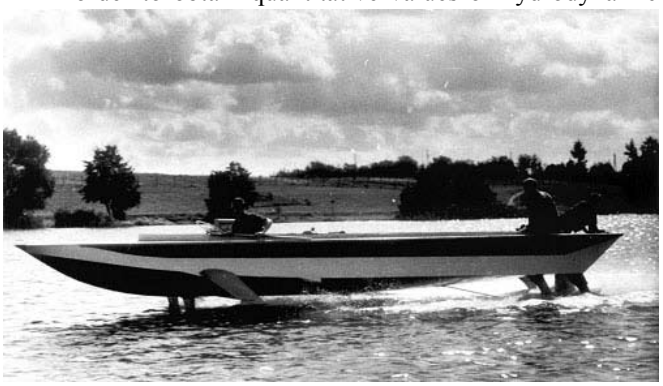
lding hydrofoil craft for military and commercial applications. In the 1970s also design studies of hovercraft were included. Also high-speed planning boats were investigated.

The important part of this programme consisted of model tests; all of them were performed in the Ilawa experimental station. Actually the development of the station started with test of hydrofoil craft, because the first experimental model craft must have been tested in large open water areas and the suitable place at that time was found in Ilawa.

From the very beginning of executing the research programme on the development of hydrofoil craft, the craft designed was tested in the model scale. The models were constructed in a large scale say 1:3, they were propelled either with an overboard motor or with the built-in motor as in the full scale craft and controlled by the crew. This method allowed testing not only propulsive characteristics of the model, but also manoeuvring and seakeeping characteristics and overall behaviour of the model in different operational situations – different loading, trim, effect of initial list etc. Completion of such tests provided very comprehensive view on the operational characteristics of the designed craft. Fig.5 shows photo of a model under tests [3].

Fig.5. *Hydrofoil model W-2 undergoing tests in Ilawa experimental station*

In order to obtain quantitative values of hydrodynamic

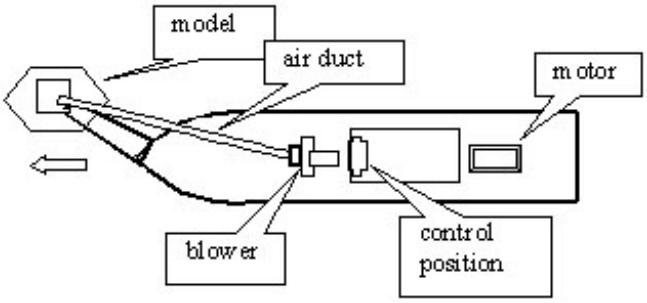


characteristics of the model ingenious measuring apparatus had to be designed and constructed, because at that time it was impossible to acquire suitable apparatus in the market. With the development of electronic computerised measuring devices the situation at present is completely different, but forty years ago there was nothing of that kind in the market.

In early 1970's research programme concerning design aspects of hovercraft was established and a series of tests of different configurations of skirts were performed. The skirts must be tested in a rather large scale and for this purpose a special towing platform was constructed. It consisted of one of the large boats available in the station. The motor driven blower was installed on the boat and the hovercraft model was attached to the outrigger and connected by the air duct with the blower. Many different skirts were tested using this facility (see fig 6) [5].

For testing resistance characteristics of hydrofoil models and other high-speed craft the high-speed towing platform was constructed. The principle was similar to that of the towing platform for testing conventional vessels, in the form of a catamaran where the model was located in front of the platform, but the speed of the catamaran was considerably higher, up to 7 m/s allowing to test high speed models. This catamaran exists up to present days and is still used.

Fig.6. *Sketch of the arrangement for testing hovercraft skirts*

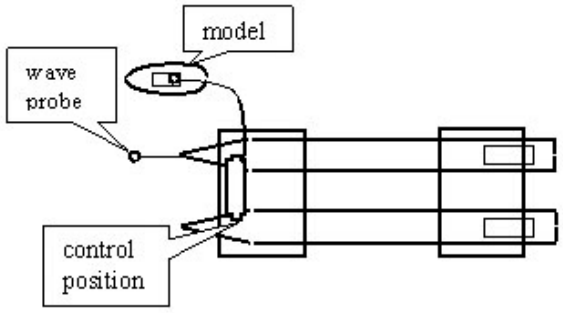


Seakeeping and stability tests

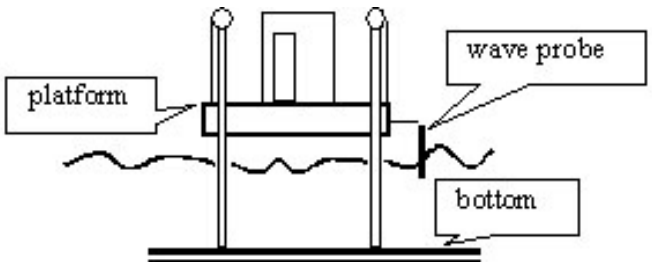
In the late 1960's – early 1970's research programme on stability criteria was established and as a part of this programme tests of behaviour of models in natural seaway leading to capsizing were planned. The University of Hamburg team previously performed capsizing experiments where remotely controlled models were tested on Ploener Lake.

In Ilawa different technique of performing these tests was used. Special floating platform in the form of a catamaran was constructed. The model was self-propelled running in proximity of the platform and connected with the platform with flexible cables. This solved the problem of power supply to the model and transmission of data, which were recorded on the platform. This allowed also to locate the research team close to the model, making photographs and visual observations that were very important. The sketch of the arrangement is shown in Fig.7 [1].

Fig. 7. *Sketch of the arrangement for capsizing tests*
Fig.8. *Sketch of the platform for wave measurements.*



Waves were measured in front of the catamaran using wave



probe. Other measurements of waves were taken in the area of experiments. For this purpose a movable platform on three legs resting on the bottom of the lake was constructed (Fig.8).

The arrangement used in Ilawa was a model for a similar arrangement used later by the University of Berkeley in San Francisco Bay.

Non- conventional tests

Apart from the above mentioned tests quite often Ilawa experimental station was used for non-conventional tests. In each such case original testing technique and measuring system must have been invented taking into account financial and technical limitations. Such non-conventional model tests comprised *inter allia*:

- tests of the tractor tug with various types of cycloidal propellers
- tests of model with jet-gas propulsion
- tests of side launching
- tests of side-wall air cushion craft
- test of fishing nets
- tests of sporting canoes
- tests of segmented barge
- tests of large SWATH model

and some others.

Training of ship masters and pilots

In the mid-1970's it was proposed to use the Ilawa experimental station for training ship masters and pilots in ship handling using large manned models. This method had been already used for some time in Port Revel in France and a few Polish masters were sent there for training, but as the cost of the training was very high the possibility was investigated to use Ilawa for this purpose.

There was already accumulated experience in Ilawa with building and operating large manned models, also some experiments intended to test port arrangement from the point of view of a possibility of easy handling of ships were already performed. In these tests the mock-up of Northern Port in Gdansk (under construction) was installed in the scale 1:25 in the northern part of the lake in shallow water and large tanker model was handled there using four model tugs. Students who pulled thin wires representing towropes in appropriate scale handled tugs. The experience gathered made it possible to prepare the experimental station for training purposes.

The first model for training purposes was put into operation in 1980 and in the following years two other models were included into the fleet of models used for training. It appeared, however, that Jeziorak lake, on the shore of which the Ilawa experimental station is located, was not particularly suitable for training purposes. There was too much traffic of sailing yachts and other craft. The shores are not sheltered enough from prevailing winds and there was very limited possibility to install mock-ups of different ports and other facilities required for training. Therefore plans for a separate training centre located on lake SILM nearby were drawn and were presented to the Secretary General of IMO, Mr. H.Srivastava during his visit to Poland (see Fig.9) receiving his full support. Ultimately in 1990 new training centre was put into operation and the Foundation for Safety of Navigation and Environment Protection was created as a joint enterprise of the Technical University of Gdańsk, Marine Academy of Gdynia and the City of Ilawa. Now the Foundation is running the training centre [6]. In the years 1980-1990 almost 500 Polish ship masters and pilots were trained in Ilawa experimental station in week-long courses.

Contribution of the Ilawa experimental station to the development of ship research.

Organization of Ilawa experimental station and opening of the possibilities to perform model tests contributed greatly to the progress of knowledge in ship hydrodynamics in Poland. A number of research workers and students from the university, but also from other institutions, who performed model tests in Ilawa in open waters studied hydrodynamic phenomena connected with ship motions, many of them based their doctor thesis on experiments realized there. Many research programmes were accomplished, if only to mention *inter allia* the following:

- Investigation of basic hydrodynamic and design problems of hydrofoils and other high-speed craft
- Investigation of stability and capsizing phenomena in waves
- Optimisation of hull form of cargo vessels from the point of view of resistance and propulsion
- Optimisation of nozzle-propellers
- Investigation of scale effect in propulsion model tests
- Optimisation of rudder arrangement and manoeuvring characteristics of push-barge systems

Fig. 9. *Visit of the Secretary General of IMO, Mr. Srivastava in Ilawa experimental station (1975)*

The results of the research programmes and model tests in Ilawa were described in numerous articles in scientific magazines, papers presented at the conferences and in internal reports. In the list prepared in 1974 there were 240 items mentioned.

In 1971 the Symposium on Model Tests in Open Waters was organized in Ilawa. This was the first conference in Poland on ship hydrodynamics. It was followed in 1973 by the first HYDRONAV conference held also in Ilawa, which was the first in the series of conferences on ship hydrodynamics organized every second year by different interested institutions (the last one was 16th in the series, held in Ostroda). Since 1995 these conferences have had international character with papers presented in English. They create important forum for presenting results of research programmes and exchanging experience and views in the field of ship hydrodynamics.

General view on perspectives and possibilities of open water model tests

From the perspective of 50 years of existence of the Ilawa experimental station it may be stated that open waters, like lakes or large ponds, form an excellent area for performing model tests of various kind. They do not supersede towing tanks – routine model tests of propulsion, seakeeping tests, some manoeuvring test certainly could be better executed there. However, having suitable open water area considerably extends research capability.

First of all experience gathered in Ilawa shows that designing high-speed craft, in particular hydrofoils, hovercraft or wing-in-ground craft requires building large manned models forming intermediate stage between small model tested in a towing tank and full-scale craft. Only such large model al-

lows to investigate all motion characteristics of the craft and the effect of handling it.

Another field, where large models in open water are of use, is manoeuvrability. All manoeuvring characteristics including turning tests, stopping tests, spiral tests etc. could be performed only in open waters. Manoeuvring tanks are as a rule too small. Small models used there are burdened by considerable scale effect. Training in ship handling using large manned models requires also large open water area.

Open water areas are also very useful to perform non-conventional model tests. This was obvious from the experience gained in Ilawa. Finally, testing models by the towing catamaran over a very long distance reaching sometimes a few kilometres is very instructive allowing to make observations and measurements that could hardly be made on the short measuring section of a towing tank.

Open water model tests have also many disadvantages, first of all dependence on the weather conditions. From this point of view routine model tests with strict schedule and fixed deadline for providing results are difficult to perform. Model tests performed by universities within the scope of research programmes, student model experiments etc. are typical jobs of open water experimental stations. The advantage of such stations is rather low investment cost

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Searching for objects under the sea bed by the nonlinear acoustics methods

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Abstract

Paper presents rules of producing sources of the parametric acoustic waves as an effect of the propagation of two parallel acoustic beams. Wave is generated in the mutual impact area, with a frequency equal to the difference of the frequencies of waves radiated from the original sources. This principle is a base of the construction of parametric sonars with very narrow directional characteristics and relatively low wave frequency. Moreover, the directional characteristics do not have side lobes - a drawback of the classic sonars. Parametric sonars are a good tool of detecting objects on the sea bed and particularly those buried in the sea bed. The use of parametric sonars in searches for objects such as mines or pieces of archeological value is a modern way of carrying out directed exploration of the sea bed.

Keywords: *Sea exploration by acoustic methods – nonlinear acoustics, parametric sources*

INTRODUCTION

Exploration of the sea bottom is most often performed by means of the acoustic devices based on the generally known phenomena of the acoustic wave propagation, mainly the wave reflection and backward scattering. Classification and identification of objects on or under the sea bottom surface is extremely difficult, particularly in the latter case. The difficulties are caused by a relatively weak echo due to similar acoustic impedance properties of the wave reflecting object and its environment. Besides, damping of the elastic waves in the ground is significantly greater than in water and the wave intensity decreases rapidly. It is commonly known that wave damping, i.e. general wave energy dissipation, strongly depends on the wave frequancy. Therefore, application of the low frequency wave sources is well recommended, but it should be remembered that in general the space resolution is then reduced due to increased length of the sounding wave. This inconvenience may be considerably limited by the use of parametric sources. Parametric sonars are a kind of underwater observation and search devices of a significantly different method of operation than the classical sonars.
Fig. 1 shows the principle of sea bottom sounding with the use of parametric sonars.

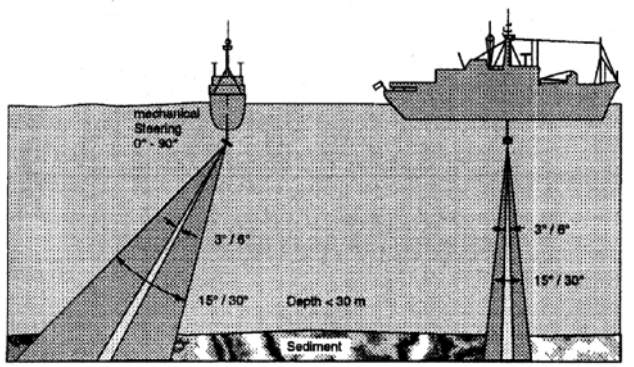

Fig. 1 *Diagram of sea bottom sounding with the use of acoustic devices*

Principle of the parametric wave generation

If two sources emit two waves of different frequencies and if those waves propagate in the same area then a nonlinear interaction takes place between the acoustic beams, which generates a wave of a frequency equal to the difference of the original wave frequencies.
The differential wave may be generated only when the original waves are of a nonlinear character.

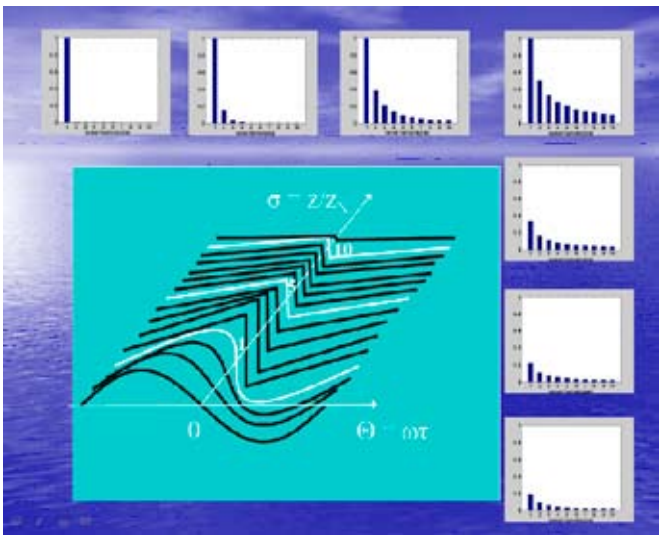

Fig. 2 *Nonlinear wave propagation principle*

An example of the use of a differential wave beam as a parametric echo sounder is shown in Fig. 3.

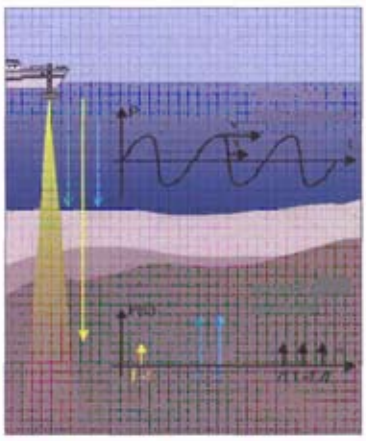

Fig. 3 *Parametric echo sounder operation principle*

An example of the use of a parametric echo sounder for the search for objects under the sea surface is shown in Fig. 4.

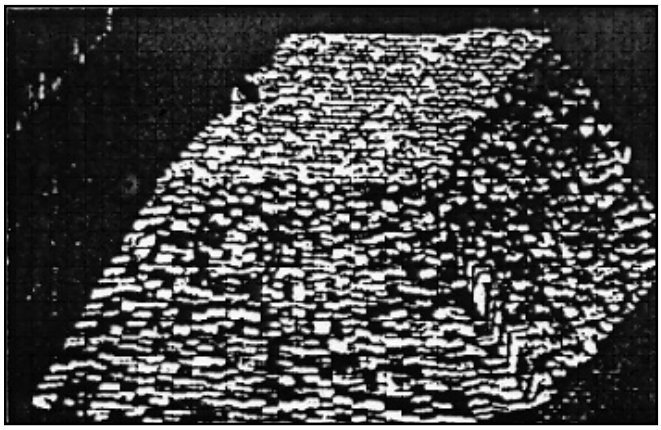

Fig. 4 *Acoustic image of an object at a 25 m depth under the sea bed surface obtained by means of a parametric echo sounder*

Fig. 5 shows a sea bed section obtained by means of a parametric sonar.

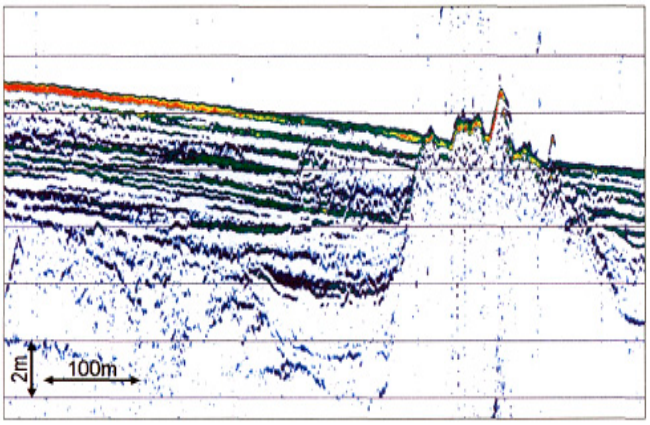

Fig. 5 *Geological section of sea bed obtained by means of a parametric sonar*

Conclusions

Parametric sonars are a modern underwater search tool. They are particularly useful in the search for small objects, e.g. sea mines on the sea bed or covered with mud. Parametric sonars are also capable of searching for objects under the sea bed, which is very important in the marine archeological investigations.

Therefore, parametric sonars extend the limits of applicability of the classical sonars. They have very good angular resolution due to very narrow directional characteristics without the side lobes.

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Present day activities of the Ilawa experimental centre

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Gdansk University of Technology

Abstract

Paper presents activities of the GUT Experimental Centre in Ilawa in the recent years. Its main tasks have been organizing international student scientific camps and sailing courses for GUT students. For that purpose the laboratory and hotel facilities of the Centre have been modernized and new measurement techniques implemented. The conclusions outline possibilities of future use of the Centre.

Keywords: *Gansk University of Technology, Faculty of Ocean Engineering and ShipTechnology, experimental centre, Fundation for Safety of Navigation and Enviroment*

At the beginning of the 1990s, administration of the Ilawa Centre was taken over by the Foundation for Navigation Safety and Environment Protection, established on 10 May 1990 by the Gdansk University of Technology, Maritime Academy in Gdynia and Town of Ilawa. That was caused by moving the ship master training courses to lake Silm (September 1990) and by shortage of research orders from the industry due to generally bad financial situation of the shipbuilding industry. In the following years some limited business activity was carried out in the Centre. Formal takeover of the Centre by the Foundation took place on 30 April 1993 and was based on an agreement with the Gdansk University of Technology, where 25% of the Centre capacity was put free of charge at the University's disposal. That was quite sufficient for the Ship Hydromechanics Division. At that time model tests were performed of fast craft, financed from the Scientific Research Committee grants won by prof. M. Krezelewski and assist. prof. W. Welnicki. At the same time the Centre business activity consisted mainly in constructing platforms on Jeziorak lake, carrying out technical work for the lake Silm Ship Handling Centre as well as hauling ashore, winter harbouring and summer mooring of private yachts.

In 1997, on the initiative of the then Dean of the Faculty of Ocean Engineering and Ship Technology prof. K. Rosochowicz, an International Ship Research Student Centre (ISRSC) was created in Ilawa, whose task was to run international scientific training camps for the shipbuilding faculty students from all over the world. It should be mentioned here that scientific training camps for the GUT Shipbuilding Faculty students were organized in Ilawa as early as the second half of the 1960s. In order to popularize the international student centre, an intensive information campaign was organized among the technical universities with ship technology faculties, coordinated by dr. M. Gerigk. The efforts of the Faculty were crowned by two international meetings in Ilawa in July and September 1998 - Ilawa-ISRSC-Workshop'98, presenting the Centre to the foreign partners. The participants were representatives of WEGEMT, ABS, VBD Duisburg, TU Berlin, TU Denmark. Also a leaflet was prepared and issued describing the Centre's facilities and a programme of possible practical training. It included also manoeuvring exercises in the lake Silm Ship Handling Centre run by the Foundation for Navigation Safety and Environment Protection.

Thanks to the very positive opinions about setting up the International Ship Research Student Centre received from foreign universities, liquidation of the Centre, looming at the end of 1990s, could be avoided. Its area was to be taken over by the town of Ilawa for recreation purposes. But a measurable effect of those meetings was obtaining financial means from the American Bureau of Shipping for procurement of the measurement equipment.

In the same year two scientific camps were organized for the GUT Faculty students and the second one coincided with the above mentioned July Workshop. One of their tasks was to prepare the Centre for student training, which included setting everything in order, preliminary preparation of models and presentation of the Ilawa Centre potential to the foreign observers. In practice, there were no critical opinions about the laboratory facilities - unique in the world - but there were some problems at that time with social amenities in the Centre. For that reason the maximum number of students in one course was limited to eight persons.

In July 1999 the Centre was taken over by the Gdansk University of Technology. Three scientific courses for the GUT students were organized from June to August of that year with a similar objective - preparing the Centre and working out a practical model of the international training courses.

In 2000 the international student courses started. Four courses were organized with participation, among others, 4 students from DTU in Lyngby.

Fig. 1. *Preparing a model for tests*

At the end of that year a complex restructuring of the Centre social part was begun. The Dean's representative for the Ilawa Centre development was appointed Mr. J. Światek. Workshop and motor store were liquidated and modern lavatories installed for students, employees and guests, including those for disabled persons. That part of work was finished in June 2001. A high capacity central heating boiler was installed, which allowed to liquidate the bathroom and kitchen water heaters

and a separate hotel and boatswain's lodge central heating systems. Another major change made in 2001 and 2002 was rebuilding of the former joiner's shop. It was divided into two parts. One was made a store of the fast craft small models and the other - a store of measurement apparatus and a computer room where test results may be processed. In 2002 the hotel part was modernized. Small single-bed rooms were combined into two larger dormitories. Now the Centre can lodge twelve persons in a decent standard conditions. In the spring of 2005 the old roof of the social building was replaced by a new light roof with thermal insulation. At the same time replaced were all windows as well as the central heating, gas and electrical installation, and also the kitchen equipment - cookers, fume hoods etc..

Some time at the turn of the century a student practical training programme was shaped. Students of our Faculty had the practical training after the third year of the MSc studies. It was decided that the training would be concentrated on testing non-conventional units, in accordance with the Centre's tradition, and on manoeuvrability exercises on the Silm lake Ship Handling Centre facilities. Four standard models were prepared: a skimmer unit, SWATH type catamaran and two hydrofoils: single hull and twin-hull units. The models are towed by the „Badacz-2" towing platform. The number of trainees should not exceed eight persons. This is in order to maintain the necessary safety conditions on the relatively small „Badacz-2" catamaran.

The first days are devoted to learning the measurement technique used and operating the measurement apparatus and also the gauge calibration. Besides, instruction is given on the industrial safety requirements and general behaviour during the exercises. Simultaneously lectures are presented on the fast craft problems and the manoeuvring qualities of modern ships. During a two-week stay students visit the town of Ilawa and its surroundings on a full day trip by the „Konrad" motorboat around Jeziorak lake.

Standard tests consist of the measurements of resistance, towing speed and position of the unit in relation to water. An extension of those tests is testing of the transverse and longitudinal standstill stability and stability as a function of speed. Besides, dynamical stability at the operational speed is also tested. All the test results are subject to real time computer recording, which allows to analyse and interpret them later in full scope.

Another objective of those exercises is practical learning of the manoeuvring qualities of contemporary ships. Therefore, students perform personally a cycle of manoeuvring tests, in accordance with the IMO requirements, on a selected model from the Ship Handling Centre fleet on Slim lake. During the manoeuvres the model motion trajectory and other characteristic values are currently recorded. Then students analyse the results and compare them with the IMO manoeuvring standards. One course comprises approximately 60 teaching hours (40 hours of lectures and 20 hours of laboratory work).

In the years 1998 to 2005, the student scientific camps in Ilawa received 203 students, including 45 students from foreign universities, mainly from DTU Lyngby, TU Berlin and TH Bremen. Details are given in Table 1.

Fig. 2. *Hydrofoil model during tests*

In 2002 Rector of the Gdansk University of Technology, prof. J. Rachoń, put forward an idea that each student of our University should have a yachtsman certificate, which is to underline the maritime character of the University. The sailing courses were to be organized in the Ilawa Centre. The „UniSail" programme was started to put the idea into practice. The hotel facilities needed extension and the former hovercraft hangar H1 was converted into two four-bed dormitories and a lecture and recreation room. Also a small kitchen was arranged there. The former measurement equipment store was transformed into living compartments for six persons. Today, 22 persons may be lodged in two camping huts and in the above mentioned additional compartments. After all those extensions of the Centre hotel facilities, altogether 34 beds are available.

The Centre was prepared in 2003 for the sailing courses. However, the courses started in 2004 and 60 students were trained in that year. In 2004/2005 two Micro Polo type yachts were built within the „UniSail" programme for the sailing courses. In 2005, in four courses some 70 students were trained for the lowest yachtsman rank. This year four training courses are planned, organized by the Gdansk University of Technology Yachting Section of the Academic Sports Association (AZS).

The Centre is partly financed from its own activity. The network of yacht mooring jetties has been developed in recent years and now up to 25 bigger yachts can be moored there. The users pay for stay, hauling ashore and winter harbouring and considerable sums of money support the Centre budget. Worth mentioning here is the contribution of Mr. S. Urbański, who was personally involved in the development of jetties in the Centre in Ilawa.

Finally, I would like to underline the uniqueness of our Centre. Nowhere in Europe (and, I presume, in the world) are there such student training facilities available. This has been confirmed by numerous very positive opinions from the Shipbuilding Faculties which sent their students to those training camps. This is also a place and opportunity of cooperation between Polish and foreign students, which may prove fruitful and profitable in the future.

Year	1998	1999	2000	2001	2002	2003	2004	2005
Number of camps	2	3	4	4	4	4	3	3
Number of participants	16	20	32	32	32	31	23	17
Foreign participants	-	-	5	7	6	8	7	12

Table 1 *This year (2006) four camps are planned with many foreign students participating.*

A Historical Review of Ship Model Testing in Open Waters

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Abstract

Specific features of model testing on hydrodynamic ship behaviour will be discussed, in particular with respect to extreme motions in a natural seaway of open waters. Ship model features described are model scale, water tightness, auto - pilot and remote control, data recording, testing procedures and choice of model situations. Wave gauges supported by buoys allowed measuring seaway. Logistics of open water model testing is compared with new procedures in water tanks generating seaway extremes. A short glimpse is given concerning results found with respect to ship capsizing in random seas. Some photographs allow a lively remembrance of early activities in model runs on a lake many decades ago.

Keywords: *Capsizing of ships, free-running ship model, open water testing, random seaway*

INTRODUCTION

It has been a great pleasure to have been invited for the celebration of the 50th anniversary of founding the Ilawa Research Centre. For the last years, this Research Centre has become very popular among Bremen N.A. students. They like to come here attending your wonderful summer classes with a lot of instructions and lively demonstrations on various ship and boat types and their hydrodynamic qualities. This year we can also celebrate 30 years of official co-operation of the cities of Gdansk and Bremen, inaugurated in 1976. Both our Naval Architecure Departments of TU Gdansk and of Bremen University of Applied Sciences started to co-operate in 1981. These 25 years of our co-operation has been filled with life on many research projects.

The Ilawa Centre is a very special research facility: It is situated right at the border of a wonderful lake, using the natural waters as a testing ground for ship models. This allows demonstrating the hydrodynamic qualities of various designs, and giving a good insight for students and research. Having the research facilities right at a lake required little investment in the "model basin" itself. Water basin, wind and waves are there just by nature. This idea of using the lake as a testing ground has even led to establishing the Ilawa Foundation for Safety of Navigation and Environment Protection. Pilots and ship officers can use automotive ship models for training of handling and manoeuvring in critical situations. This really has been a success story.

Plön Lake and Eckernförde tests 1961-1968

When the Ilawa Research Centre was founded in 1956, shipping safety was of particular concern due to many ship losses because of the influence of the seaway. Regulations at that time relied solely on the Rahola still water criteria established 20 years before. The general feeling was that a mathematical solution of the extreme ship motions was not within reach for years to come. So conducting model experiments with wave makers in a tank was started. In Hamburg, Grim 1951 was one of the first to study resonance phenomena of extreme roll in following seas. Arndt and Roden 1958 presented their experiments on roll motion in following seas in a Hamburg tank. In the U.S.A., Paulling 1961 published his results on extreme roll motion in following seas measured in a towing tank.

The today 50th anniversary of the Ilawa Research Centre is a nice opportunity to remember the old days when model testing in open waters was started. In the founding year 1956 I was still a student of N.A. However, two years later, after some time at ship-yard, I was very happy to join the young team of Professor Wendel in Hamburg working on new stability criteria. Kurt Wendel (1908-2003) at both the Hanover and Hamburg Universities started thinking on a revolutionary probability approach for safe subdivision of ships (at the same time Robertson independently in the U.S.), which was the basis of the SOLAS equivalent subdivision concept on damage stability (IMO Resolution A.684(17) adopted on 6 November 1991).

Wendel had always been open for new ideas. When Siegmund Roden came up with the proposal to conduct ship model tests on a lake using the natural wind generated irregular seaway, research was started with the aid of Deutsche Forschungsgemeinschaft (DFG). Tests on a lake allowed running the ship model a long distance in any heading towards the waves. Thus it should be possible to detect and study severe conditions of the ship even in irregular seas. This seems to be very simple. However, the seaway at the lake must be measured, and the ship model must be free-running. At that time even information on Ocean seaway spectra was very scarce, but was needed to prove similarity of the waves.

Our very first free running model trial at Plön Lake in the North of Germany was on 15 March 1961. In 1962 at the Symposium on Ship Hydrodynamics in the Institut für Schiffbau of Hamburg University, celebrating the 65th anniversary of Professor Georg Weinblum (1897-1974), Roden and Kastner reported on the results of these capsizing model tests. For the next years we set up some electronic Laboratory in the boat station of the Plön Biological Research Institute, and in 1968 we also used the facilities of the Navy Development Centre in Eckernförde.

It was in these early years, that our team in Hamburg was very excited to learn about a scientist in Poland who had started using a lake for conducting ship model testing. This young Polish scientist was Professor Lech Kobylinski of Gdansk Technical University.

So open water model testing was the new tool to generate a data base for the development of safety criteria of righting arms in a seaway. The Navy had asked Professor Wendel to establish new stability requirements, so we tested various models to cover different ship types and hull shapes. Arndt 1965 reported on the new Navy regulations at STG, and Arndt et al on the working experience with the new requirements at STAB 1982. In fact, those criteria developed in the sixties are still in force today, so they have been quite successful. I always could

observe with some satisfaction the improved freeboard on Navy ships that was necessary to fulfil the stability required.

San Francisco Bay tests 1969-1974

To cope with a new ship type, the container vessel, having a fine hull form at large speed, the U.S. Coast Guard supported extensive research by Professor J. R. Paulling at the U. C. Berkeley on ship motion extremes in open waters. I had the opportunity to join the team. Paulling constructed a catamaran research vessel "Froude-Kriloff" to support the measurements in S.F. Bay, with 35 feet length and 12 ½ feet beam, photo at the end of this paper. The vessel carried all equipment for each testing day to the site and back again. The wave buoy was carried at the bow, while the ship model was heaved up between the two cat hulls.

To make the model watertight while allowing quick opening of the hatches we used some special O-Ring construction. Clamps pressed the circularly shaped soft rubber profile into a rectangular shape of the hatch profile, filling the rectangle completely. Any change the vertical position of the centre of gravity of the ship model required opening of a hatch. Two ballast weights had been situated around the main section as far to the side as possible to keep a correct transverse radius of gyration. The weights were bolted to vertical beams allowing 8 different pre-defined height positions. So the vertical centre of gravity G could be changed (example American Challenger, light condition) in predefined increments of 9.2cm, covering a range of initial stability GM up to about 60cm. The roll radius of gyration versus beam was within 0.335 through 0.394.

After launching the wave buoy, it was levelled from a rubber boat, and then this boat was anchored nearby. Test runs were controlled from the large catamaran. The wave buoy was in fact a three-column tension platform that allowed measuring the directional seaway spectrum. Depending on wind velocity, fetch and duration we could find quite stable repeatable conditions. Usually in the afternoon we encountered a typical wind sea with the right model waves. Good guidance was given by observation of the waves in comparison with the length of the ship model.

The initial heading of the ship model to the waves was given by remote control, while during the run a gyro controlled the course automatically. Capsizing could rarely be foreseen by the observers, but followed some probability distribution. A photo of one 1972 extreme roll amplitude measured 1972 is shown on the last page. Kobylinski and Kastner give more details in a book published recently with Elsevier 2003.

Model scale

The Plön models had a scale λ from 25 to 40, which lead to a model length between about 2 m and 3m depending on ship type and design to be tested. In S. F. Bay, model scale of the American Challenger cargo ship was about 30, and of the Sealand-7 container vessel the scale was 55. The models were about 5m in length, which resulted in a model displacement of up to 725 kg! It was naturally hard to handle those large weights in the Bay. So we had a special gantry crane between Froude and Kriloff for launching and retrieval. To right the capsized model by hand was impossible, so we used a long pole with a weight at the end to be attached to the bottom of the model after she had capsized. The new weight balance of model plus pole turned the model to the right position again. The pole fell off and was recovered by a safety rope.

The motion behaviour of the ship model follows Froude's Law. Ship and model quantities according to Froude correspond as follows:

Length: $$\frac{L_S}{L_M} = \lambda$$

Time: $$\frac{t_S}{t_M} = \sqrt{L_S / L_M} = \sqrt{\lambda} \qquad (1)$$

Weight force: $$\frac{F_S}{F_M} = \frac{\rho_S}{\rho_M}\sqrt{\frac{L_S^3}{L_M^3}} = \frac{\rho_S}{\rho_M}\cdot\lambda^3$$

Speed: $$\frac{V_S}{V_M} = \sqrt{\lambda} \qquad (2)$$

Angular velocity: $$\frac{d\alpha / dt_S}{d\alpha / dt_M} = \lambda^{-0.5}$$

Acceleration: $$\frac{a_S}{a_M} = \lambda^{-1} \qquad (3)$$

The scale effects must be taken into account not only in evaluation of the measurements, but already in the model preparation. The choice of the geometric scale λ of the ship model depends on the length of the waves in the test area and the displacement needed to carry the measuring equipment. Scale λ determines the model weight to be handled. Of particular concern is the time scale. It affects the motion frequency of the ship model, the required angular rate of rudder motion, the course control, and the roll damping.

The frequencies of the model motions were from 5 to 7.4 times larger than at the full ship size. In order to give a closer view at the real motions of the full-scale ship, we tried to take film at larger speed and reduce the speed when showing it. With mechanical cameras at that time, this reduction was limited by a factor of not more than 2. Motion picture in Plön had been taken on 16mm film, black and white, while Paulling in Berkeley took colour super 8mm.

The models have been run with an autopilot. A gyro keeps the track, while deviation of the model will be automatically corrected. The control system has been set up as an electronic proportional differential control circuit with dead band, a so-called PD – control. The rudder angle δ is determined by the yaw deviation β, which is in fact the course error, and by the yaw rate $\dot{\beta}$, as follows:

$$\delta = a_1\beta + a_2\dot{\beta} \quad \text{for} \quad |\beta| \geq \beta_0 \qquad (4)$$

The parameters of the control were chosen as follows, example American Challenger:

β_0 = +/- 3.5 deg	dead band
$a_1 = 1.6$	rudder-yaw ratio /-/
a_{2M}=2.12 sec	rudder angle-yaw rate ratio

The ratio of both coefficients at model scale is 1.33, corresponding to the full scale ratio as:

$$(a_2 / a_1)_S = \sqrt{\lambda}\cdot(a_2 / a_1)_M = 5.5\cdot 1.3 = 7.3 \qquad (5)$$

Due to the time scale, the helm response rate of the model must also be larger than at the ship. Based on +/-30 degree rudder action within 25sec, the helm rate at the model is:

$$\dot{\delta}_M = \sqrt{\lambda} \cdot 60\,\text{deg}/25\,\text{sec} = 5.5 \cdot 2.4 = 13.2\,\text{deg}/\text{sec} \qquad (6)$$

Evaluation procedure of random capsizing

Even for long runs, in order to end up with at least some capsizing, a comparatively small GM had to be established. To give some idea, initial ship stability GM in still water could be in the range from 10cm to 50cm, naturally depending on ship type and hull form.

The duration of running time until capsizing corresponds to a probability density distribution of exponential type versus time t

$$p_C(t) = \frac{1}{T_C}\exp(-\frac{t}{T_C}) \qquad T_C = \int_0^\infty t \cdot p_c(t)dt \qquad (7)$$

Based on the distribution of measured model capsizing, a method was used to extrapolate to GZ values of the hydrostatic righting levers at heel that made the ship safe from capsizing. Kastner presented the method in the 1964 paper on "The capsizing of M.V. "Lohengrin".

The same procedure was applied to developing the Navy standards (1966). In my view, the practical application to setting up the stability criteria of German Navy ships demonstrated the effectiveness of the method, considering the knowledge on ship stability in random seas available at that time.

Current numerical simulation and tank testing

Today research on numerical solving of coupled non-linear motion equations allows an analysis with good results and is the tool for coping with safety in severe seas. I want to cite just the one paper presented in Gdansk by Cramer and Krüger in 2001. The state of the art can be followed in the Transactions of the STAB Conferences.

At the STG Meeting in Berlin 2005, J. Hennig described a very new method for the pre-calculated generation of not just random seaway, but of specific extreme irregular time sequences that can occur in Ocean seas. Therefore even in a closed water basin specific random extremes of the seaway can be generated, allowing detailed studies of severe ship motion.

I have tried to give you a short glimpse at some first stages of conducting open water model tests from my experience. Most of the known testing in open waters has been set up for specific projects and for a limited time. Of course testing is not restricted to motion extremes. Hydrodynamic behaviour of new design ideas on various ship types and boats can be measured, analysed and demonstrated. On top of that, the Ilawa Foundation has been demonstrating the effective use of larger ship models in open waters to train pilots and ship officers to cope with severe situations.

Here in Ilawa you have managed to keep the open water testing alive, so students, researchers and ship operators can be grateful to the Gdansk University of Technology and to the persons who made it work. I wish you at least another 50 years of excellent academic life in your Research Centre.

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The influence of hydro-meteorological factors on the risk of harbour operations

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Abstract

The paper presents a study on the environmental impact on the risk of harbour operations. The hydro-meteorological elements have been recognised as the most important safety factors with regard to the ship entrance into the harbour and berthing inside the docks. They are identified as real time, short and long term factors and they all should be considered in the safety assessment of harbour operations. The risk of each operation should be determined on the basis of weather forecast and the modelled prediction of the total water level, surface currents and waves. Several topics have been discussed in the paper with regard to the safe ship approach and navigation inside the harbour. The application of different tools for the prediction of ship performance is presented. The stochastic method for the determination of probability that the ship will navigate within the boundaries of the required navigational width and low speed manoeuvring standards proposed by Panel H-10 SNAME have been considered. The real scale experiments carried out in Port of Gdynia and the several trials performed using the Full Mission Simulator convinced that the open water model tests are necessary for the proper prediction of ship performance during berthing. The program of the proposed open water investigations is presented in the paper. The experimental stand constructed for the tests of ship-berth interactions, in the lake Silm at the Ilawa Ship Handling Training and Research Centre facilities is described.

Keywords: *harbour operations, hydro-meteorological elements, model tests of self-berthing, real scale experiments, safety of navigation, ship motion simulation*

INTRODUCTION

The difficulty of navigation in restricted areas is closely connected with external conditions. The biggest influence of the hydro-meteorological elements on the ship safety is mainly observed for the ships approaching the harbour entrance and ships berthing inside the harbour. The most important influencing factors are wind, waves, current and under keel clearance. The changes in the bathymetry and extension of the breakwaters affect both wave propagation and current conditions in the harbour entrance and inside the docks. According to the evidence of harbour incidents caused by weather conditions, the information of the real time hydro-meteorological data is not sufficient. The short term and long term factors should also be considered [2].

The advanced environmental monitoring systems can integrate the measurements of several hydro-meteorological parameters: wind speed and direction, air pressure and humidity, rain fall and solar radiation, visibility, water salinity, sea current speed and direction, wave data and tide level. The collected data are stored and processed. The time lag between the wind forcing and the water level, surface currents and wave responses is considered. This allows to introduce the navigational warnings and restrictions via the vessel traffic system.

The implementation of the hydro-meteorological systems in port areas depends on local requirements. However in all cases the risk of operation should be determined at least on the basis of weather forecast and modelled prediction of water level and surface currents. Prediction of water level is the basic information. The lack of prediction of the surface currents parameters could become a very serious threat during the gusty wind conditions [2].

Evaluation of the safety of ships navigating near the harbour entrance and berthing inside the harbour is very important for big ships, but especially for self-manoeuvring ferries and passenger vessels. There are many studies conducted on this subject in the fields of sea traffic engineering and port facilities design [7], [11]. The most advanced investigations concern the port areas with long period waves (with the period of 60 s to 180 s).

The main tool used for the prediction of ship performance in particular weather conditions is the numerical simulation. To determine the wave and current conditions in the particular layout of a port area the hydrodynamic models are used. The implementation of external, hydro-meteorological conditions as the models of a stochastic nature gives the complex model of ship motions, quite close to reality.

Risk of ship entrance into the harbour

Permission of ship entrance into the harbour is dependent on the decision of the Harbourmaster. The decision can be consulted with the pilot and Ship Master. The bylaws and harbour Safety Management System procedures are used as the basic rules and guidelines. The vessel/harbour operational conditions are always considered. The assessment of the influence of hydro-meteorological elements on the safety is of the greatest importance.

The self-manoeuvring vessels like the passenger cruisers, ro-ro vessels and ferries usually get an exemption from the towage or tug assistance, up to a given wind force. However if the problems with keeping the vessel on the waterway appear due to the strong, transverse wind, the tug assistance is not always used and the ships very often navigate with the higher speeds then the allowable. This decreases the safety margin and can be the cause of an accident, when the wind parameters rapidly change [2]. Therefore the proper determination of the risk is necessary.

Harbourmaster may exempt from the towage any ship in any particular case and the economic reasons are always taken into account. To avoid too large or too small safety margins the personal experience and intuitional judging must be aided. In advanced applications of vessel traffic management systems (VTMS) the advisory systems are used.

Several tools are used to assess the risk. The sea traffic engineering statistical methods [7], based on computer simulation of ship motion as well as the measurements of the real ship performance are very reliable. However they need to collect a big set of data. The recently proposed probabilistic method,

for the assessment of ship containment within the allowable navigational width [14], seems to be an alternative approach for the risk assessment. Also in some particular cases, one of the slow speed standards called MER (Minimum Effective Rudder) can be applied to assess the ship safety in the approach waterways.

Risk of ship entrance into the harbour – Application of the stochastic method to the risk assessment

In 2005 Vorobyov [13] presented the model of the probability that a ship can navigate within the boundaries of a fairway, of the navigational width equal to Bn (figure 1). The probability has been proposed as a new representative characteristic of the assessment of ship dynamics controllability. The influence of wind, regular waves and constrained waters on a vessel has been considered as a stochastic process. If it is assumed that the yawing angle, drift angle and rate of turn are small (1) the solution of the system of differential equations describing the ship motion, during her navigation along the fairway, is a multidimensional Markov process and the joint density function of probability of this process satisfies the equation of Fokker - Plank -Kolmogorov.

$$|\psi| \le 0.4 \ , \ |\beta| \le 0.2 \ , \ \text{rot} \le 0.1 \tag{1}$$

where:

$$\text{rot} = \left|\dot{\psi}\frac{L}{u}\right|$$

L – length between perpendiculars [m],
u – ship velocity [m/s].

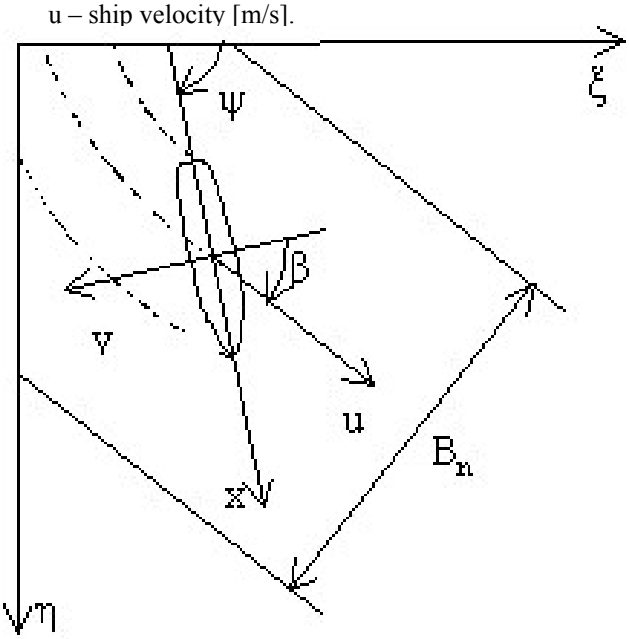

Figure 1. *Trajectory of the VLCC2 during the MER trials in the training area of Ship Handling Research and Training Centre of the Foundation for Safety of Navigation and Environment Protection in Ilawa-Kamionka and MER trial results.*

Probability P of the fact that a vessel will never cross (or even touch) the boundaries of the fairway of navigational width equal to B_n can be determined from the Chebyshev inequality proposed by Vorobyov in the form (2) [14].

$$P\left(\left|\left(\frac{1}{2}-\overline{x}_f\right)X_{13}+X_{15}\right| \ge \frac{|B_n - B|}{2L}\right) < \\ < 4L^2 \frac{\left(\frac{1}{2}-\overline{x}_f\right)^2 k_{13,13} + 2\left(\frac{1}{2}-\overline{x}_f\right)k_{13,15} + k_{15,15}}{(B_n - B)^2} \tag{2}$$

where:

P – probability that the vessel will navigate within the boundaries of the fairway of navigational width equal to B_n,
B – vessel breadth,
B_n – navigational width of the fairway,
x_f – longitudinal centre of floatation,
$\overline{x}_f$ – x_f/L,
X_{13} – random function describing ship yaw angle,
ψ - component of the vectorial Markov process ,
X_{15} – random function describing ship sway ç - component of the vectorial Markov process,
$k_{i,j}$ – correlation coefficients for the assumed value of B_n
L – length between perpendiculars [m],
u – ship velocity [m/s].

The risk of the ship entrance into the harbour can be determined, as a risk R of crossing the boundaries of a fairway (3), using the probability P (2).

$$R = (1 - P) \cdot S \tag{3}$$

where:

P – probability that the vessel will navigate within the boundaries of the approach fairway,
S – consequences.

The probability (2) that the vessel will navigate within the boundaries of the navigational width, should be determined for a particular distance of the approach fairway or for a given interval of time. This is caused by the unstable form of the matrix, of the system of stochastic equations of ship motion, for some combinations of wind disturbance and vessel velocity values.

The consequences S are dependent on the ship and harbour operational conditions – for example: distance to the breakwaters and navigational obstructions, close proximity to the dangerous and sensitive areas or dangerous cargo on board the vessel.

Practical aspects of MER trial implementation to the safety assessment of a ship approaching the harbour

The main reason to introduce the low speed manoeuvring standards [8] was the assessment of the manoeuvring performance of a particular ship in the restricted areas. The standard trial proposed by Panel H-10 SNAME (The Society of Naval Architects and Marine Engineers) called Minimum Effective Rudder (MER) has been developed to decide whether a vessel has got the sufficient controllability to navigate in the narrow channels and waterways. This standard information can be the most required for the big vessels, to decide whether the tug assistance is required.

The proposed standard is a combination of the pull out and limited spiral trials. It is performed starting from the steady speed and the 30° helm to port side, when the rate of turn gets

the constant value, the helm is put to zero and kept midship until the yawing speed becomes constant again. The helm is changed consecutively 2°, 4° and 6° to starboard until the value of constant rate of turn is zero or gets the opposite sign. This rudder angle is defined as MER. The collected constant values of the rate of turn, at the rudder angles of 30°, 0° and if necessary 2°, 4° or 6° allow to assess ship course stability. The trial should be performed to port side and to starboard. Although this characteristic does not give any advice regarding the whole range of ship controllability, it is a big help to a Ship Master and pilot in narrow waterways. The example of the MER trial results for the deep water conditions is presented in table 1 [8].

The proposed trial has been tested in the way of its application to the assessment of the ship controllability during her navigation in approach waterways.

The tests were conducted for VLCC vessels using Full Mission Simulator of Gdynia Maritime University - VLCC1 [6] and self-propelled man manned model - VLCC2, at the training area of Ship Handling Research and Training Centre of the Foundation for Safety of Navigation and Environment Protection in the Silm lake in Ilawa-Kamionka. The parameters of the tested vessels are presented in table 2.

The simulator runs of the trial, in different conditions, show the dependence of the yaw rate on the vessel speed, observed for the deep water – table 3. In shallow water conditions there was almost no dependence of the rate of turn on vessel speed, also the influence of the propeller side force was not observed during manoeuvres in shallow water. Figure 2 presents the non-dimensional rate of turn (4) for MER to starboard.

$$rot = r \cdot L / u \tag{4}$$

where:
r – rate of turn [rad/s]
L – length between perpendiculars [m].

***TABLE 1**. The example of the MER trial results for the deep water conditions [hwang].*

Approach Speed [kts]	5 (DSAHD)		10 (HAHD)		16 (FAHD)	
Initial Rud [°]	30 L	30 R	30 L	30 R	30 L	30 R
Initial Yaw Rate r*L / U	-0.594	0.592	-0.616	0.614	-0.603	0.602
Rud Sequence #1						
Rud Angle [°]	0R	0L	0R	0L	0R	0L
Initial Yaw Rate r*L / U	-0.229	0.222	-0.200	0.193	-0.161	0.152
Swing direction changed?	no	no	no	no	no	no
Ship is directionally	unstable	unstable	unstable	unstable	unstable	unstable
Rud Sequence #2						
Rud Angle [°]	2R	2L	2R	2L	2R	2L
Yaw Rate r*L / U	-0.212	0.205	-0.181	0.174	0.000	0.000
Swing direction changed?	no	no	no	no	almost	almost
Rud Sequence #3						
Rud Angle [°]	4R	4L	4R	4L	4R	4L
Yaw Rate r*L / U	0.000	0.000	0.000	0.000	0.279	-0.283
Swing direction changed?	almost	almost	almost	almost	*yes*	*yes*
Rud Sequence #4						
Rud Angle [°]	6R	6L	6R	6L		
Yaw Rate r*L / U	0.335	-0.337	0.338	-0.341		
Swing direction changed?	*yes*	*yes*	*yes*	*yes*		

***TABLE 2.** Main parameters of tested models VLCC1 and VLCC2.*

Vessel	VLCC1	VLCC2
Displacement [t]	291,154	232,660
Length [m]	315.00	324.00
Breadth [m]	56.00	57.00
Draft [m]	19.36	20.60
C_B	0.787	0.83

The performance of the proposed trial is very much dependent on the accuracy of the mathematical model used for the simulation, especially in the shallow water conditions. The open water model tests performed on the self-propelled man manned model

***TABLE 3.** Main parameters of tested models VLCC1 and VLCC2.*

Speed	ROT [°/min]			MER [°]		
	Deep water	h/T=1.2	h/T=1.1	Deep water	h/T=1.1	h/T=1.1
HALF	-8.6	-2.8	-2.1	-2	-2	-2
SLOW	-6.7	-2.4	-2.5	-2	-2	-2
DEAD SLOW	-7.4	-2.5	-1.9	-2	-2	-2

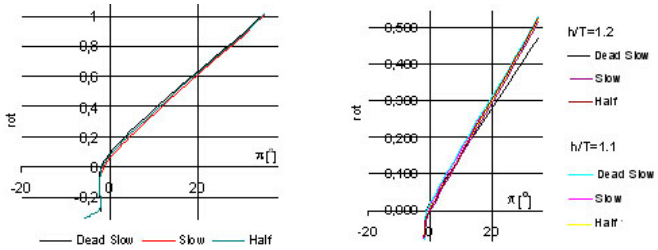

***Figure 2.** Results of VLCC2 MER trial simulation in deep and shallow water conditions.*

of VLCC confirmed that the trial is very sensitive to wind. The big manoeuvring area is necessary to conduct the trials. There are five runs presented in figure 3. Only two of them can be used for MER assessment due to the wind disturbances. The results of the MER trials to port and to starboard side, for the deep water conditions are presented in figure 3.

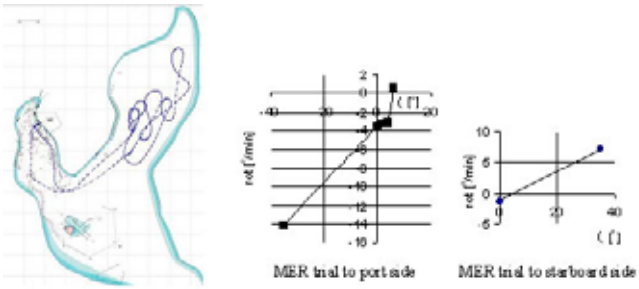

***Figure 3.** trajectory of the VLCC2 during the MER trials in the training area of Ship Handling Research and Training Centre of the Foundation for Safety of Navigation and Environment Protection in Ilawa-Kamionka and MER trial results.*

Risk of berthing operations

The safety of berthing operations in particular conditions can be assessed on the basis of model tests carried out during the ship design. The results are mainly used for the determination of the necessary power of the bow and aft thrusters for the self-berthing vessels. The prediction of the real ship performance is difficult to determine because of the scale effect. Mathematical modelling of the self-berthing operation is still not solved due to the small model scale and the complicated interactions. The mathematical models used for berthing simulation still need further, usually heuristic, tuning.

The methods used to determine the safety of berthing operations, applied in port design and planning of harbour manoeuvres, are mainly based on the stochastic models. The multiple runs of the same manoeuvre in different environmental conditions are performed. The ship motion simulations are usually applied but the observations and measurements of real ships performance are also used [7]. The methods are very reliable, but need much effort and their accuracy is also dependent on the accuracy of the mathematical models used for the simulations.

The accepted safety measures used in berthing and debert-

hing operations are the allowable impact force and sufficient power of tug boats. For self-berthing vessels, the safety measure is also the available thrust of ship propellers and thrusters in the particular external conditions [3].

The basic factor of the safety of berthing operations is the berthing energy. This is the energy to be absorbed by the fenders and is usually calculated by multiplying the vessel total kinetic energy by the berthing coefficient c:

$$E_k = \frac{1}{2} c \cdot D \cdot V_s^2 \tag{5}$$

where
E_k - impact energy [MJ],
D - vessel displacement [t],
s - vessel speed [m/s],
c - berthing coefficient.

The coefficient c is the product of several factors. The eccentricity factor accounting for ship's rotation, berth configuration factor which represents the portion of energy absorbed by the cushion effect of water between the approaching vessel and the quay wall, softness factor which represents the portion of energy absorbed by deformation of fender and ship hull, friction coefficient between the fender and ship side and mass factor which depends on the momentum transferred from the ship to surrounding water are considered. The mass factor depends on the water depth to ship draft ratio and a type of berth, fender stiffness, berthing velocity and the deceleration of ship. Usually all the above factors are defined by simple empirical formulas or constant values. For large vessels the approaching speed should not exceed 0.1 – 0.2 m/s and for the high performance fender systems, used in some of the cruise vessels terminals, the available contact speed could be 0.15 m/s. For this berthing operations conducted on DP (Dynamic Positioning) system the reliability of this system is an important safety factor. The DP systems require very reliable mathematical models of ship motions. Training of the navigators based on Full Mission Simulators is now a very efficient way to prevent the accidents.

Modelling of ship self – berthing manoeuvre

The accuracy of the mathematical models used for the simulation depends on the available experimental data because it is still very difficult to model the manoeuvres when the transient, turbulent flow is induced.

The model tests results are strongly influenced by the scale effect. The CFD (Computational Fluid Dynamics) methods still need further development with regards to the accuracy of turbulence models.

To obtain the realistic performance of simulated manoeuvres, the heuristic tuning of the mathematical models is mainly implemented in ship handling simulators, used for training and research purposes. Although the experienced masters and pilots can report an unusual performance of the modelled ships, the accuracy of modelling is much more important for the research and design applications.

To improve the accuracy of mathematical models the investigations on modelling of the different interactions have been carried out in many research centres - mainly based on the towing tank tests [9], [10],[12], [13]. Full scale trials of the assisted berthing were successfully performed and used as the validation data for a numerical model of ship parallel berthing based on CFD methods [4]. However, the conclusions following from the real scale tests, conducted at Gdynia Maritime University, for the training vessel Horyzont 2 (figure 4) [1], convinced that due to the very strict experimental conditions, model tests would be a much more efficient method to evaluate the mathematical model of ship self-berthing.

Figure 4. *Real scale tests of BATHING – research and training vessel of Gdynia Maritime University "Horyzont " at "Indyjskie" Quay in Port of Gdynia.*

Good results could be achieved using a big model and open water experimental facility. A program of experiments based on the open water model tests has been developed for the self-propelled model of a car-passenger ferry of model scale 1:16. The experiments will be conducted at the Ship Handling Training and Research Centre of the Foundation for Safety of Navigation and Environment Protection in Ilawa-Kamionka.

The experimental stand under construction and the man manned scale model of the car-passenger ferry during the tests in the research area of the Ship Handling Research and Training Center of the Foundation for Safety of Navigation and Environment Protection in Ilawa-Kamionka is presented in figure 5.

Figure 5*. Experimental stand under construction and the man manned scale model of a ferry during the tests in the research area of Ship Handling Research and Training Center in Ilawa-Kamionka.*

The experiments will involve force measurements. The changes in forces with the following parameters will be accounted:

- water depth,
- ship distance to the quay,
- ship approach angle,
- rudder angle,
- propeller power,
- bow thruster power,
- berth type.

Conclusions

The hydro-meteorological elements are the most important safety factors with regard to the ship entrance into the harbour and berthing inside the docks. Both linear and neural network models are used to improve significantly short-term and long term predictions of the environmental parameters. To determine

their influence on the risk of harbour operations they can be subsequently implemented in the real-time simulator for the purpose of pilots training or evaluating the new designs under the real environmental and structural conditions.

Application of the stochastic method proposed by Vorobyov [14] can give very promising results, but it is necessary to include current parameters in the stochastic model and find out the effective method of combining the values of risk, determined for the particular parts of the approach fairway and harbour entrance, into the total risk.

MER trial is a very useful tool to predict ship controllability in narrow channels and approach fairways. However it is very difficult to perform due to the wind sensitivity and big manoeuvring area necessary to conduct the trials. It could be assumed that the real scale MER test would be very difficult to perform in normal sea conditions and as it was proved the simulations were very much dependent on the mathematical modelling of shallow water effect.

The model tests of different kinds of interactions are necessary for practical applications in mathematical models used in ship handling simulators as well as for the validation of CFD methods. The available model scale, and possible accuracy of measurements are of the greatest importance for the accuracy of modelling.

The open water model tests of ship-berth interaction will allow to recognise the dependence of the interaction forces on several parameters. Further research will focus on the formulation of the interactions.

Acknowledgement

The presented open water model tests have been carried out in collaboration with the Shiphandling Research and Training Centre of the Foundation for Safety of Navigation and Environment Protection in Ilawa, Poland. The research regarding the influence of a ship distance from the quay on the efficiency of the ship propellers and thrusters is currently conducted according to the research project No. 4T12C01029 sponsored by Polish Ministry of Education and Science.

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Possibilities of representing the ship-tug cooperation in the free model tests

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Abstract

Model tests of ship manoeuvring in ports and in other restricted waters require the tug forces and moments to be taken into account. As the additional tug forceRhol can be relatively easily allowed for with reasonable approximation in a computer simulation system, the free model tests require more complicated methods. This paper contains a review of the methods used in the Experimental Centre in Ilawa and then in the Foundation for Safety of Navigation and Environment Protection in order to represent the ship-tug cooperation in the free model tests.

***Keywords**: ship-tug cooperation, free model tests, ship manoeuvring*

A bit of history

It is assumed that the first ship with a mechanical propulsion system intended for towing was „Charlotte Dundas" launched in 1801 in Great Britain (Fig. 1). In the next year, towing of two 70-ton barges in the Forth of Clyde waters near Glasgow showed that even the biggest ships might be safely towed inside restricted port water areas by other ships and not by rowboats with 10 oarsmen as it had been practiced before. That event was the beginning of a new type of specialist ship - tug and new method of manoeuvring by means of tugs.

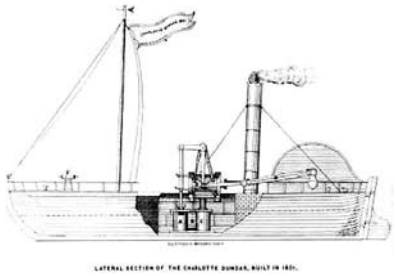

***Fig. 1** - Plan of the steamship „Charlotte Dundas" launched in 1801*

The idea of aiding the ship manoeuvres in ports by tugs spread quickly, particularly in view of quick increase of ship size, development of the mechanical propulsion systems and confined port space in those days. For instance, in 1828 an old side-wheeler was converted into a tug in New York. It probably looked similar to a dozen years younger ship presented in Fig. 2. In 1850 in New York the first tug with a screw propeller was launched. Its name was „Sampson" and it cost its owner USD 4500.

***Fig. 2** - Side-wheeler „Norwich" in the port of New York, built in 1836 and converted into a tug in 1842*

The following years are characterised by fast development of tugs, constructed then in accordance with individual designs. The ships of those times were mainly ocean-going clippers and single-screw vessels of increasing dimensions and limited manoeuvring capability, requiring the assistance

***Fig. 3** - Single-screw tug with steam engine built in 1890 in the United States. Port of New York*

of tugs during entering and leaving ports. Fig. 3 shows a tug at the end of 19th century.

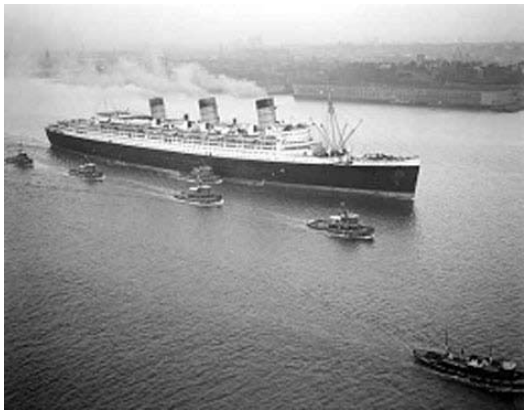

***Fig. 4** - Tugs assisting Queen Mary in the 1930s*

The development of steam engines is reflected in the increased towing power, twin-screw tugs are built with the Kort-nozzle propellers. Manoeuvrability of such tugs is much better than those with classical single-screw propulsion sy-

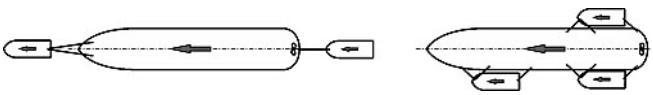

Fig. 5 *- The difference between American and European method of the ship-tug cooperation*

stem, which makes the cooperation with ship easier and safer. Nevertheless, the number of tugs necessary for handling the biggest ships increases and several are needed simultaneously to aid the large ocean passenger liners (Fig. 4).

There are also differences in the operating methods: Europe prefers tug on a towrope, USA develops a technique based on tug at the ship side (Fig. 5).

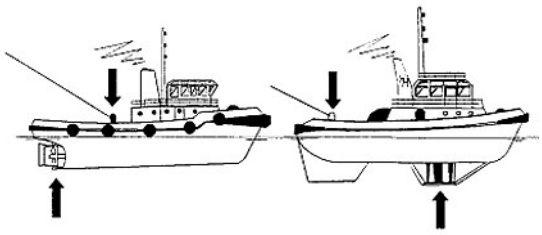

Fig. 6 *- Conventional tug and tractor - different points of propulsion acting upon the tug hull*

However, a real revolution is made by introduction of new types of propellers: the Voith-Schneider propeller or various types of a propulsion column under the hull. Tugs with propeller placed before the centre of towing pull are called tractors (Fig. 5 and 6). They have good manoeuvring capability and allow to use new methods in the ship-tug cooperation. The towing power is also increasing.

The threat to the natural environment that an oil spill carries caused the development of a new class of tugs - escort tugs. They are very effective and relatively fast (10-12 knots). This is necessary in order to be able to assist large tankers for tens of miles in their trips in restricted waters (in straits and among rocky islands). Escort tugs improve the ship manoeuvrability, they become also a „sheet anchor" in case of the propulsion or steering system breakdown. The requirement of escorting the ships carrying hazardous cargo is becoming a rule. The operating method of an escort tug is shown in Fig. 7 and 8.

Fig. 7 *- Tug in escorting operation. The marked ship steering force is generated by the tug skeg*

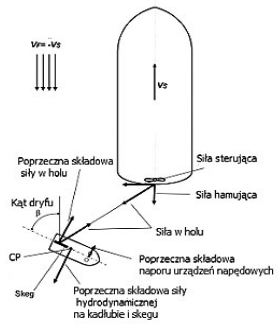

Fig. 8 *- Force distribution on an escort tug during assisting a ship, in the indirect assistance method*

The steering forces at the maximum tug speed may reach a value of 140-150 tons.

Manoeuvrability tests with free models

Free model tests are carried out on a lake, pond or in other sufficiently large water space. The water depth usually corresponds to the deep water conditions as it is extremely difficult to find a large natural shallow water area.

Nowadays, the aim of tests is to determine the ship manoeuvrability characteristics, although in many centres the open water resistance and propulsion as well as seagoing quality tests have been carried out for long years. Also the non-conventional units: hovercraft, hydrofoils etc., were often tested in the open water conditions, as they were too big to be tested in typical towing tanks.

A part of the ship manoeuvrability tests involves manoeuvres in restricted water areas, mainly in ports and port approaches. The aim is to verify a given port and waterway configuration from the point of view of navigation safety. In such case the cooperation of ship with tugs, particularly a large ship manoeuvring in heavy weather conditions, is of essential importance. It is not possible, even for units very well equipped with additional steering devices, to manoeuvre on their own in ports and fairways. Therefore, the quality of tests will to a large extent depend on the reliability of representation of the cooperation with tugs, including also the interaction between tugs and the hull.

Representation of the cooperation with tugs

From the manoeuvring point of view, a tug means an additional force controlling the ship movement, applied to the hull through the towrope or the point of contact between the tug hull and ship hull. It should be performed in a way ensuring maximum effectiveness of the manoeuvre. The tug impact force depends on the tug type, propulsion system configuration and to some extent on the quality of it's crew. The effective steering force will also be a function of the relative tug position, motion parameters and usually is much smaller than the tug bollard pull.

The first free tests in the Experimental Centre in Ilawa, aimed at the verification of a port water area layout, were carried out in 1975. They pertained to the Northern Port in Gdansk, which was built in a 1:24 scale on the Lipowa island. The port water area and a substantial part of the approach fairway had the depth adequate to the adopted scale. That provided proper depth of water under the keel and the hydrodynamic reactions on the ship hull. The tug and the number of units cooperating with the ship turned out to be a problem. Simple calculation of the necessary pull force for a 7° B wind and the assumed water depth yielded the number of 4. As the cost of purchase of the tug model remote control devices exceeded the financial resources of the project, a simple method of the tug impact simulation was applied.

A weight equal to 90% of the tug bollard pull was suspended on a block fastened to a wooden tug hull model in the same scale as the ship model. The tug position was changed manually - „skippers" were employees of the then Division of

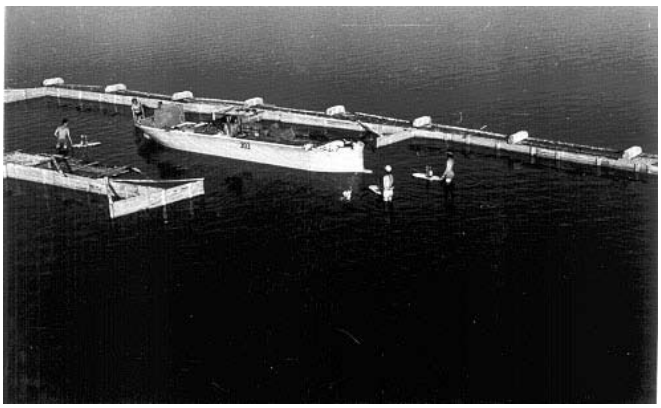

Fig. 9 - Model tests aimed at the verification of port water area layout in the Northern Port in Gdansk, Ilawa 1975.

Hydromechanics. Such solution prevented excessive towrope forces from appearing but did not allow to monitor the interaction between tug and ship. The trajectory was recorded by a photographic method - the ship position was registered, every fixed number of seconds, in the same frame. Fig. 9 presents that test methodology.

The following year, with the same methodology, verification was carried out of the shipyard basin configuration in the newly designed shipyard in Ustka. The maximum size of a ship to be hauled out from Ustka was determined as 400 000 DWT, the water depth map in the whole shipyard and port area was also maintained.

Later, the Ship Hydromechanics Division activity in the ship manoeuvrability field was more and more directed towards training in the ship manoeuvring. The first training models were built equipped with the tug operation simulation systems, good measurement instrumentation allowed to use them also for research work, which was a frequent case. „WARTA" - model of an LCC ship was built in 1980, „SZCZECIN" - a Panamax ship model in 1983 and „GDYNIA" - a Ro-ro ship model in 1987. The time of construction (end of the 1970s) was not good for execution of the tug operation simulator. The tug towing power was replaced by tubular rudders (thrusters) installed in the training-research model bow and stern at the points as close as possible to the centre of towing pull. Therefore, the tug impact force configuration was limited: perpendicular to the ship axis to PS or SB (see Fig. 11). This allowed to use a tug for pushing a ship to the quay or pulling from the quay, also turning a ship in the manoeuvring basin by two tugs could be relatively well simulated. Represented was the tug bollard pull, decreasing with the increasing model speed (like the tubular rudder thrust), also taken into account were some time constants, e.g. passage of the tug from one ship side to the opposite. In the „Warta" model the bow thruster could be rotated by an angle approximately equal to the operating angle of the bow tug on the towrope. It was a considerable step forward which made it possible to use a tug as assistance in the port approach fairway, in narrow passages etc.. A diagram of tug impact forces is shown in Fig. 10.

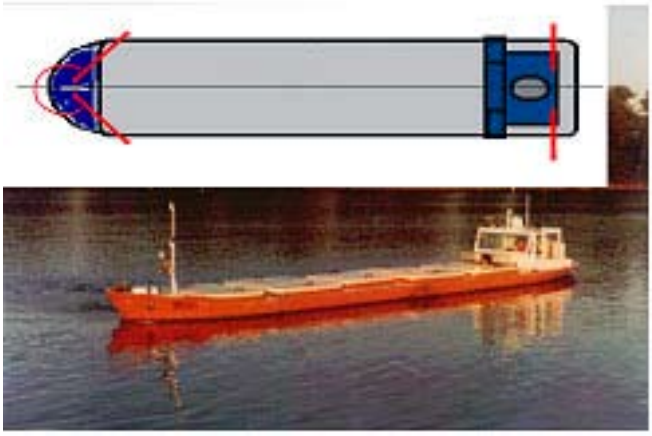

Fig. 10 - The training and research model „Warta" equipped with the first tug cooperation simulators. State in 1983

Fig. 11 - Training model „Szczecin" equipped with a bow thruster and stern thruster. They had a tug operation simulation option

The increasing requirements regarding trainees as well as research orders connected with dimensioning of the port water areas have necessitated the design and implementation of a new generation of tug simulators. As before, the tug impact force is generated by the steering devices: thrusters or Schottel propellers with a 360° rotation capability, which significantly widens the scope of possible tug cooperation representations. However, the greatest qualitative improvement has been coupling of the tug simulator with GPS, sending precise information to the model about its position in relation to the surrounding objects (quay, shallow water spots etc.). That allows to generate virtual tug profiles changing their position in accordance with

Fig. 12 - Control panel of a tug simulator and a monitor screen with transitory tug positions

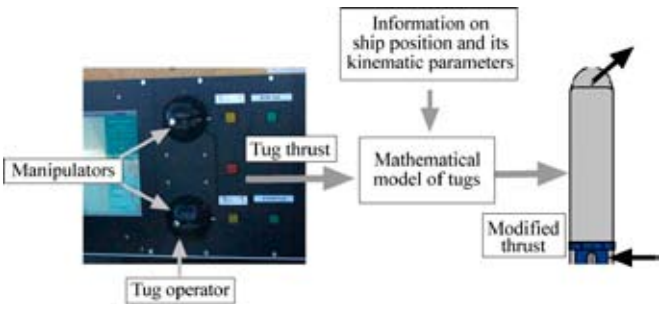

Fig. 13 - Determining the thrust force of the steering devices representing the tug operation

changes in the thrust generating device control settings. This is only a short step from using a simplified mathematical model representing the dynamics of a specific type of tug, including its interaction with the ship hull. Available are the towrope operating tugs or the ship side tugs (the American method), twin-screw or tractor type.

However, the steering device generated force limitations (mainly due to the Coanda effect) and some problems with manoeuvring in very shallow waters were the reasons for seeking different solutions allowing to implement all the aspects of the ship-tug cooperation. Particularly important appeared the escorting function, which in the indirect assistance method (see Fig. 8) requires considerably greater impact forces. After an analysis of methods used in Ilawa and abroad (remotely controlled tug models, fan generated force, additional propellers behind the hull on outriggers etc.) it was decided to use the simplest method: building of a manned tug model in the same scale as the big training and research models. Nowadays, escort tugs are even more than 50 m long and the analysis showed that a model could be built without significant outfit limitations. The tug model tests were carried out in 2005 and now work is in progress on the hull and propulsion system. In the second half of 2006 the prototype will be put into operation in the Foundation Centre on Lake Slim. Fig. 14 below presents the original escort tug used as a reference solution in the propulsion and skeg positioning (skeg first). But the type of propulsion on the tug model is entirely different.

***Fig. 14** - Escort tug of the BUKSER OG BERGING company and the escort tug model under construction in the Foundation workshop in Ilawa, May 2006*

Calculations confirm a possibility of generating by the tug a force allowing to obtain the steering force of up to 150 tons on the training model. It is assumed that the value of forces generated on the tug model hull and skeg and transmitted through the towrope to the ship will be continuously monitored.

Summary

It is difficult these days to imagine a ship manoeuvring in restricted waters without assistance of tugs, in spite of the development of various additional steering devices. Many port administrations simply prohibit to use fully those devices in the vicinity of hydrotechnical structures, for safety reasons, e.g. during pushing a ship to the quay. Therefore, only tugs and their efficient and effective cooperation with the ship may secure safe navigation.

The research work and training should represent as fully as possible all the aspects of that cooperation, including the interaction between ship and tug. It seems that building a physical model of a tug operated by man, in spite of all the possible scale effect reservations, is a proper way of solving all the problems of the open water tug-assisted manoeuvring investigations.

Practical measurement of trajectory in open water model tests

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Abstract

The common GPS technology – used at sea or in motor vehicle traffic - does not meet the measurement quality requirements of the present day model tests. It is necessary to use special receivers performing very precise real time measurements. Specialised microprocessor controllers allow to substitute a fallible and inaccurate ship model operator by computers. They guarantee practical execution of precisely defined tasks and their full repeatability. Owing to the coordination of the GPS geodesic technology, computing power of the present day miniature processors and radio communications - test automation, unmanned models, quick analysis of results and control from shore have become feasible.

Keywords: *open water model tests, GPS, practical measurement, trajectory*

INTRODUCTION

Since the beginnings of the model tests, the struggle for precision of measurement systems has been a constant feature and one of serious problems is determining and recording the position of a unit on water.

At first, position of a model during manoeuvring tests was determined in relation to some fixed points on water (buoys, leading marks, poles) and this technique is still used as auxiliary measures.

Then analogue instruments came – optics, photography, film...

One of recording techniques used then were „frame-by-frame" photographs of a manoeuvring model in a defined time interval. A tower was constructed for that purpose in the Ilawa Centre. Photographer would climb up and make a series of model photographs.

Fig.1*. Frame-by-frame photographs of a 105,000 DWT OBO ship model trajectory. Mix of 13 frames.*

Another version of the photographic technique were night photographs. A strong source of light was installed on the manoeuvring model and the ship model motion trajectory was marked on the photographic plate.

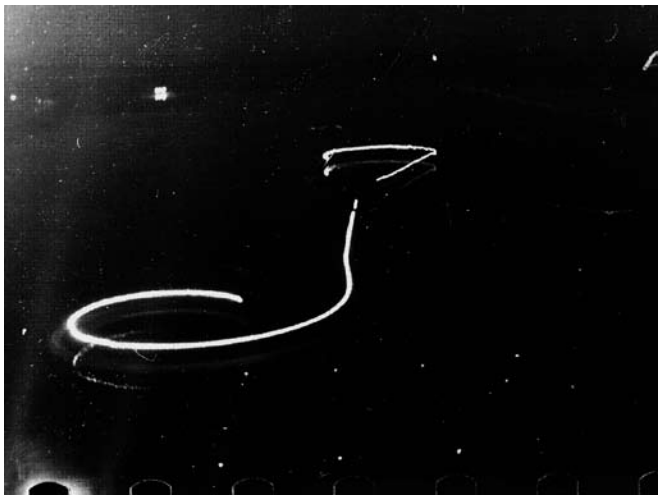
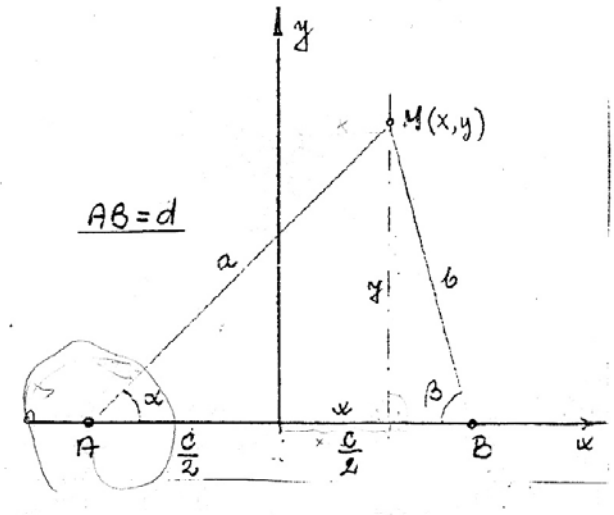


Fig.2. *Night photographs of model tests, 29.08.1977. Turning manoeuvre test.*

An example of tests of a 105,000 DWT OBO ship performed in 1977 is shown in Fig. 2.

As it can be seen, buoys with lights were placed in the test



Drwg. 1. *Measurement principle of the model trajectory*

area and the model position was oriented in relation to them, which allowed later analysis of the manoeuvring qualities.

The accuracy of those measurements was approximately one meter. Therefore, at the times of the development of electronics the method of angle measurements was implemented.

Principle of operation of the electronic trajectory measurement systems

Calculation of the coordinates of a tested object was performed by the mathematical method of intersection, consisting in measurement, from two points A and B ashore, of the direction angles α, β to the model (Drwg.1).

With known length of base C, the model M position coordinates (x, y) can be determined. In the system of coordinates shown in Drwg. 1, position of the model M (x, y) will be

$$x = \frac{c}{2}\left(\frac{tg(\beta) - tg(\alpha)}{tg(\alpha) - tg(\beta)}\right) \quad y = c\left(\frac{tg(\beta) \times tg(\alpha)}{tg(\alpha) + tg(\beta)}\right)$$

expressed by the formula:

Measurements of angles α, β were performed, at different times, visually (by means of all sorts of telescopes) or electronically (infrared cameras). Initially the tracking system was manual, with the use of special levers or gears, in the last version electric motors were used. The angle measurement transducers also changed, from electric selsyns to the optical Gray code pulse counters, in order to reduce the measurement error.

History of the trajectory recording systems

The first model bearings were taken by means of an ordinary sight with a sighting notch, then by means of special levers (arms) the measurement was transferred directly to paper on a drawing desk. Also the technique of plotting the measurement points on paper evolved, first it was only a pen (Fig. 3) and then an electric spark from generators (Fig. 4).

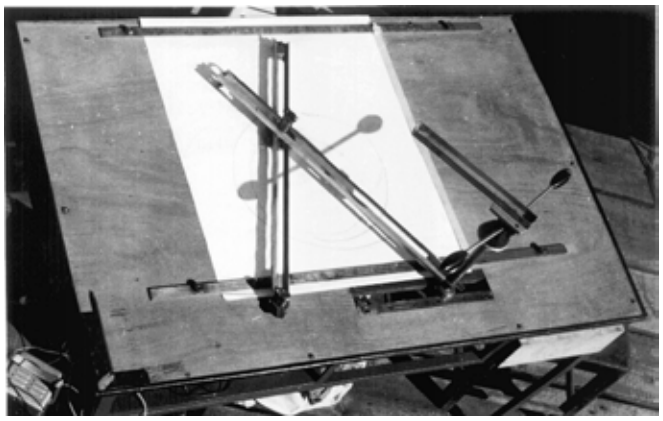


Fig.3. The first measurement table – Torograph – designed by E. Adelman

The improved version of torograph (Fig. 4) had optical telescopes for tracing the model.

The direct measurement arm was on the paper. Another tracing arm, controlled by a follow-up selsyn, was under the paper.

High voltage pulse from the generator burnt model motion traces in the paper at the crossing point of the two arms.

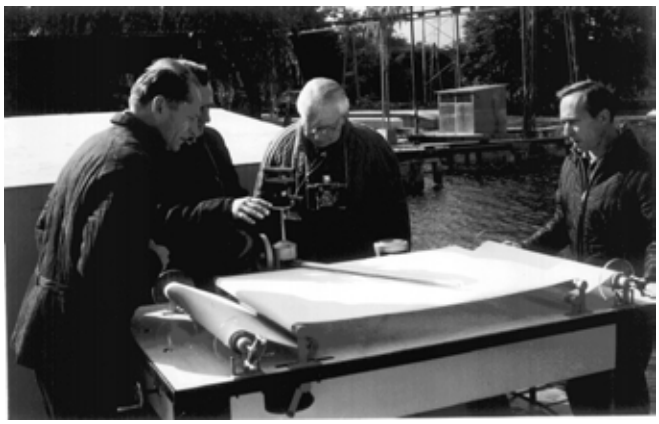


Fig. 4. *Improved version of torograph with optical telescopes and trace burning*

At a 41.5 m distance from the main torograph table, operator observed the model through a telescope and positioned the parent selsyn (Fig. 5). The selsyn electrically transmitted the directional angle information to the tracking device in the torograph table and the position was printed.

Fig. 5*. Parent selsyn transmitting angle information – first version without telescopes*

The next improvement of the torograph in 1988 was replacing the selsyn by an electronic angle transducer and collecting data in a Z80 type computer. But observation was still performed by means of an operator-controlled telescope.

Fig. 6. *Model tracking point with an optical telescope and angle transducer*

The transducer data were analysed in the XT personal computers and the first automatically plotted trajectories were produced (Fig. 7).

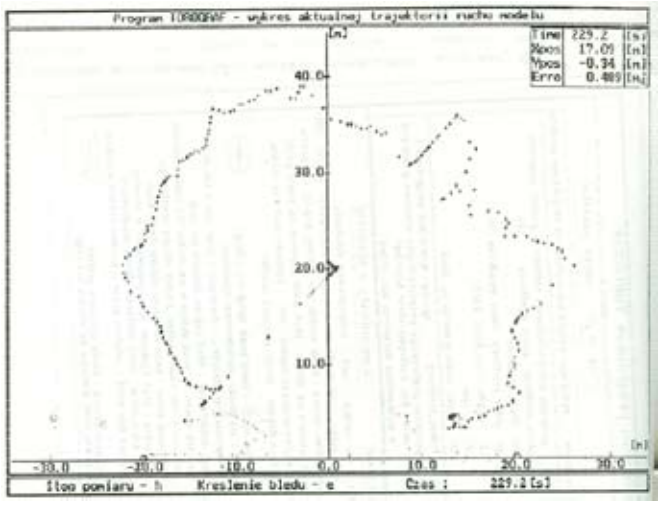
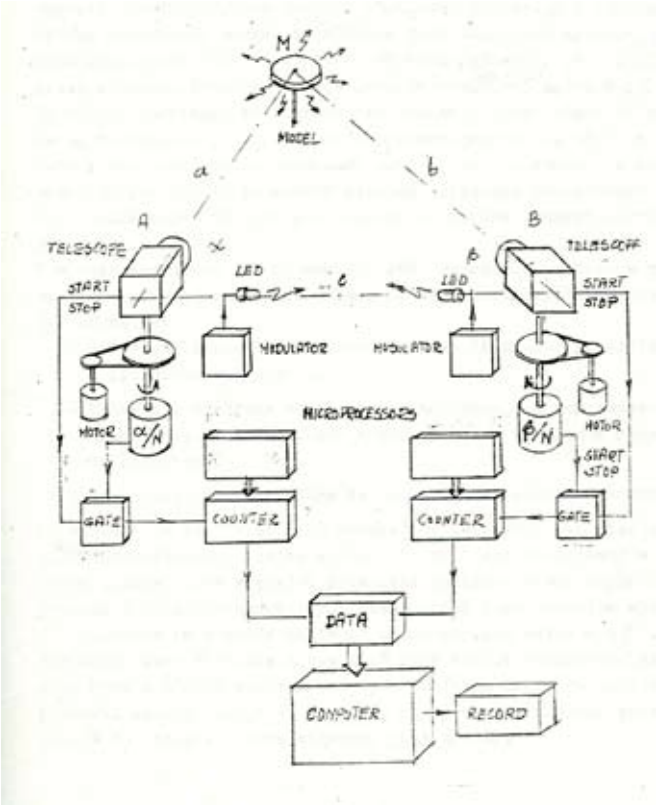


Fig. 7. First computer printouts of trajectories obtained with the angle transducers

Full automation of the bearing taking process was achieved in 1990 when optoelectronics were used for model tracking. The system was built in the Optoelectronics Department of the Warsaw University of Technology Telecommunication Institute. The object tracking was performed with two direction finders with movable telescopes, sensitive to infrared of a specific spectrum and frequency (Fig. 8).

***Fig. 8**. Fully automated model tracking stand*

The infrared radiator was placed on the model and rotating telescopes tracked its position. The angle transducer, coupled with the telescope, was sending information on the model angle and an AT286 computer recalculated it into the model position. The operating, visualization and data recording system was developed in the Foundation for Navigation Safety and Environmennt Protection. Block diagram of the system is presented in Drwg. 2.

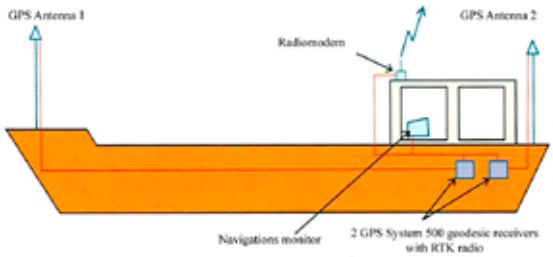


Drwg. 2. Recent fully automated version of torograph

The angle transducer precision was electronically improved and bearing angles were given with 1.8' accuracy. A satisfactory quality of the model position measurement was achieved, at a 20-30 cm level.

Present day research tracking systems

The present day GPS receivers operating in the Real Time Kinematic (RTK) mode give a 3D position determination precision at an 1 cm level. Installing two GPS RTK receivers on a ship model allows to determine the ship position and orientation. Position may be displayed currently on the ship model and that information may be transmitted, through a radiomodem, to the main control stand. The first design of such system is shown in Drwg. 3.



Drwg. 3. First version of GPS SR530 receiver-based tracking system

The first tests were carried out in the Foundation for Safety of Navigation and Environment Protection on 29.05.1999.

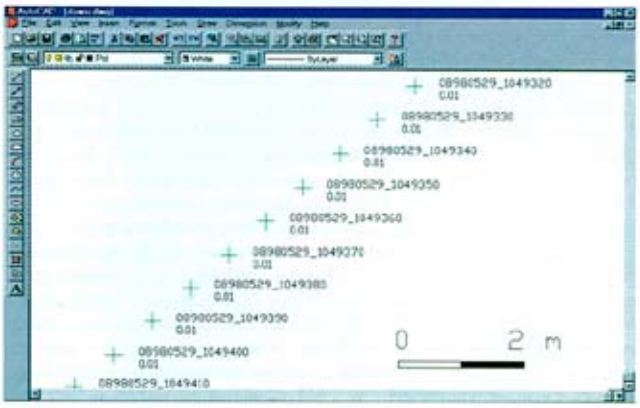
All the at that time available GPS receivers (Leica, Trimble, Zeiss and Aztech) were installed on the model, which was full of the GPS antennas – Fig. 9.

Leica of Switzerland introduced a new generation of the

Fig. 9. *Testing of various GPS systems*

GPS System 500 geodesic receivers. This new receiver solution allowed to determine position in the RTK mode and set a new satellite geodesy standard in the GPS systems. The new CleartrackTM Technology ensured higher accuracy even in very difficult conditions, e.g. wooded lake shores.

Measurement results from the Leica GPS System 500 were converted to the DXF format and imported to Auto-CAD for presentation. A section of the tracking path, displayed in Auto-CAD, is shown in Drwg. 4.



Drwg. 4. *A GPS SR530 model trajectory displayed in Auto-CAD*

Each model position is displayed with a cross symbol and it's description contains measurement time and accuracy in meters. Along the whole path, System 500 delivered data every 1 second with an 1 cm accuracy.

This is a satisfactory result for the contemporary open water model tests.

The latest GPS positioning system

The system has been developed in the Foundation for Safety of Navigation and Environment Protection. It consists of GPS receivers, gyrocompass, radiomodems, an MC68000 deck computer and a base PC for data display and recording.

The most recent Leica series 1200 GPS receivers are equipped with the newest generation AX1202 dual frequency GPS antennas, designed with the use of new military technologies and characterised by a sub-millimetre drift of the phase centre, very good resistance to the reflected and mispolarised signals and also improved tracking of low satellites. The new Leica GX1230 receivers are adjusted also to operation in the VRS and FKP virtual reference station system. They will be adjusted to receiving corrections from the being developed ASG-PL Polish reference network. When the GPS system reaches the configuration allowing to receive new L2C and L5 signals, the receivers will be adjusted to operation with those frequencies. At present, a too small number of satellites does not allow to perform measurements with those frequencies and they are not used in measurements.

The Leica GX1230 receivers are adjusted to receive corrections from the WASS/EGNOS satellites.

Fig. 10. *New Leica GX1230 GPS during an underwater test*

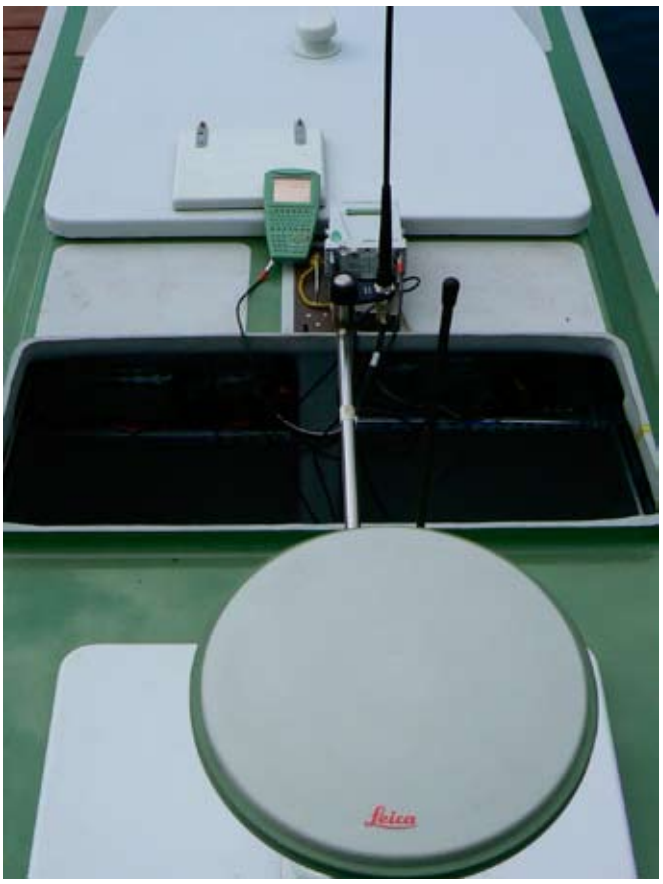


Fig. 12*. GX1230 system installed on a model*

The new GX1200 receivers have an IP67 dust and watertightness standard (temporary submergence to 1 m depth), which makes them suitable for operation in most difficult field and weather conditions. A new magnesium alloy casing makes the receiver resistant to fall from 1 m height on a hard surface.

The new GX1230 set allows to work in the GPS RTK real time technology and in the static mode and to achieve the vector measurement accuracy of 5 mm + 0.5 ppm.

The test system consists of the GPS GX1230 for position recording and an Anschutz STD22 gyro-compass for model direction orientation. The analogue-digital transducers provide information on the rudder position, engine operation parameters, velocity in relation to water, thrusters etc.. All the data are collected in a PC, displayed on a monitor installed on the model and sent via a modem to the observation centre.

In the foreground can be seen a dual frequency GPS AX1202 antenna, behind it on the same mast two radio antennas, the first for receiving the GPS correction to the RTK system, the second for data transmission to the shore. Further on deck is a GX1230 receiver and a programming terminal.

Introduction of new methods of the test model position recording and common use of the PC-class computers caused changes in the test model control and measurements. Loop and magnetic recorders were no longer used and the man-controlled manoeuvring were abandoned. One of the first changes was introduction of the remotely controlled models in the model tests of free motion on waves.

The control system elements were based on ready made remote control devices and miniature own design elements - a strong steering gear and an electronic power transmission

Fig.13. *Model tests on waves*

system, adjusted to the model scale in terms of power and reaction time. Those elemens were a basis for the measurement system development.

A gyro was used once for heel measurements in free motion on waves. Measurement results were recorded in a prototype miniature magnetic dual-channel recorder. It precisely changed the analogue signals into frequencies. A basic difficulty was very limited space, which forced non-typical solutions.

The wave height measurement with calculation of a mean and effective wave height was taken by means of a wave sounder. The sounder was fully automatized, the measurement process consisted of starting the measurement cycle by radio

Fig. 14. *Steering gear and power transmission system*

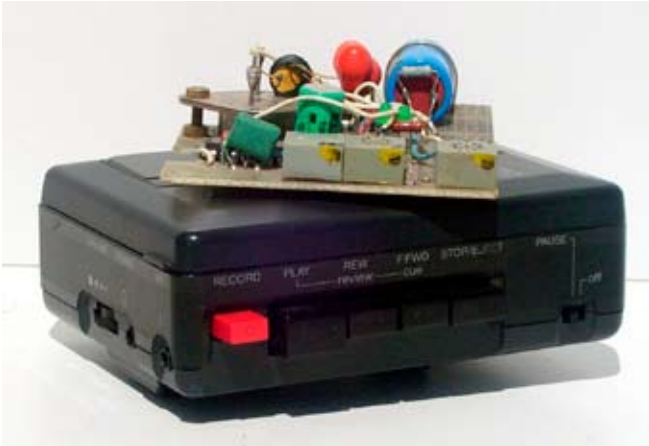


Fig. 15. *Miniature magnetic recorder*

and after its completion the results were recorded and the sounder became dormant. Sounder would remain in water in the test area for many days.

Another teaching measurement system was the „Z80" deck measurement system. Measurements included the main engine revolutions, rudder position, bow turning mechanism position, thruster revolutions. The rudder and steering gear control modules were added for tests. Measurement results were

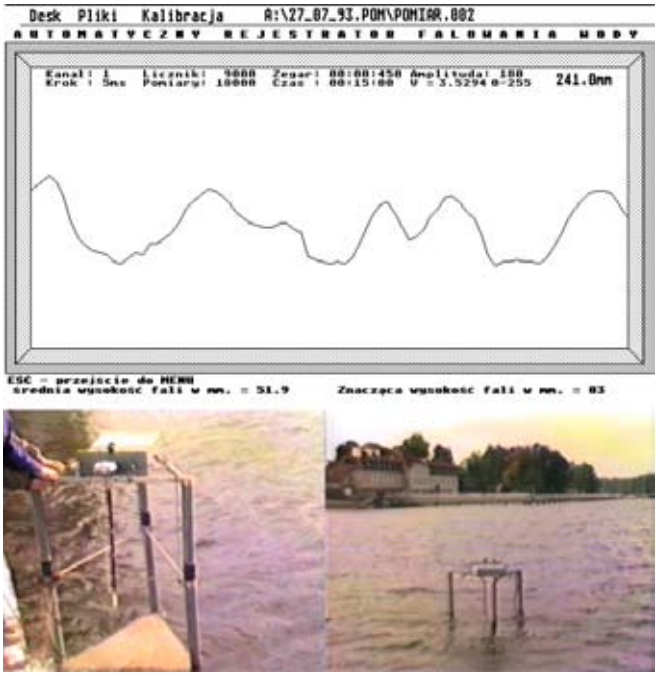


Fig. 16. *Sounder software and view of a sounder on water*

transmitted by radio to the base computer on shore, where the optical positioning system data were also collected. The Z80 measurement system together with the optical bearing finders was used in the catamaran model tests on Jeziorak lake and in the Maritime Academy own investigations where the base computer was on the model and the position data were transmitted from shore to the model.

The system is still in operation and is used for training and presentations of practical measurement methods to the GUT students (the GPS receiver-based positioning system is now in use).

For the needs of a simple spiral test, consisting in stabilising the model angular velocity in changing rudder laying conditions, a precise angular velocity measurement system

was developed, based on a precise steering gear and a course gyro with accurate angle measurement. Those devices used GRAY transducers with a 12-bit accuracy. Measurement was considered correct when results of five time intervals, from the current moment on, were identical. Those requirements could be met with an ideal weather, large water space and plenty of time. Even a slight wind or a shallow water had an impact on the model angular velocity.

An outstanding achievement in the measurement system development is the M68 Automatic Measurement System together with its modifications. It is characterised by a modular structure where basic subassemblies and measurement cards are selected according to needs of the standard or extended tests.

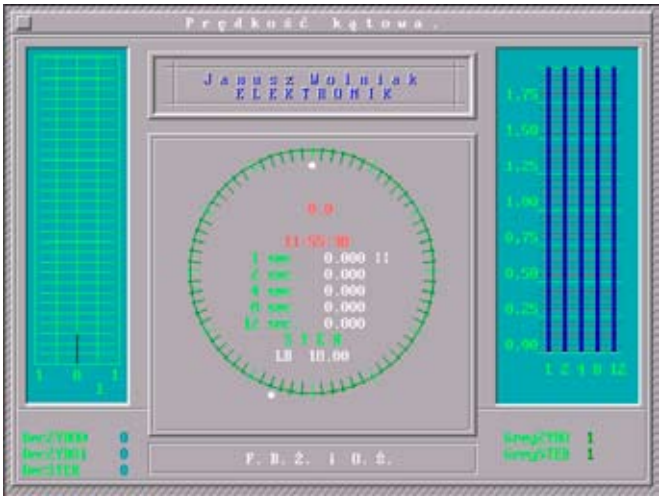


***Fig. 17**. Screen of the angular velocity measurement system*

This system allows to perform manoeuvring tests fully automatically, without human intervention. The system collects measurement data of the test itself and of additional gauges. The collected data may be retransmitted as needed.

***Fig. 18.** Selected subassemblies of the M68 measurement system*

The defined tests are the following:

Circulation test, Exit from circulation test, Circulation with acceleration test, Circulation without propulsion test, zig-zag test, free backing test, crash backing test.

The measurement system allows to carry out non-standard measurements, for instance:

Circulation tests with rudder laid in 45 or 70 degrees and exit from circulation with rudder in 0 position, asymmetrical zig-zag test with departure from course of 10 degrees for rudder laid in 5 degrees.

The set test parameters are rudder direction, rudder angle, reaction to departure angle, main engine revolutions. The parameters are set for a required speed.

The control and measurement accuracy is 12 bits for a range, actual accuracy depends on the steering gear, propulsion system and gauges used.

The system is universal and allows to perform the ship manoeuvring tests either under full remote control without human intervention or locally with base computer on the tested model. System modifications in the form of exchangeable A/D and D/A measurement cards or additional memory cards allow to perform tests on various units. Apart from the standard models, tests were also carried out on twin propulsion and controllable pitch propeller models or models with azipods or combustion engine.

- The operator's supervision includes:
- selecting the test type and parameters,
- directing the model to the measurement area,
- checking the model speed and its possible correction,
- switching the system to the automatic manoeuvring test mode,
- supervising proper execution of the test,
- normal or emergency completion of the automatic manoeuvring test.

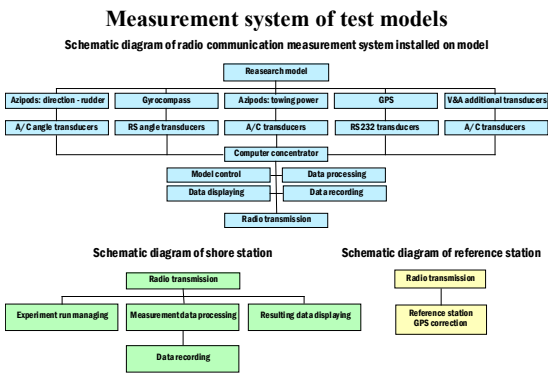
Modified versions of the M68 Automatic Measurement System were used as a basis for the development, for teaching purposes, of tug simulators on the training models.

***Fig. 19.** View of the models during tests*

Combining the teaching and research applications allowed to use the teaching systems with properly selected measurement parameters for research purposes. An example is the tug operation supervision system with additional control and measurement channels, used by a research group from the Maritime Academy.

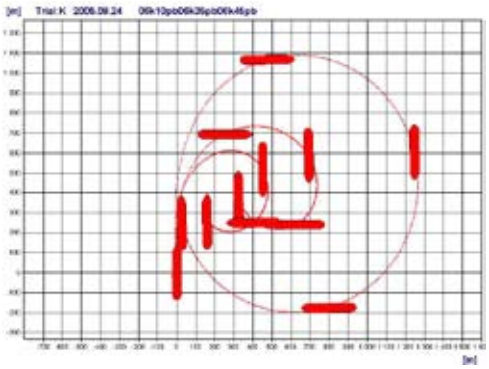
The present measurement system allows to trace the course of experiment on the model and in the measurement centre on shore. Software ensures immediate analysis of measurements,

***Fig. 20.** Model with a teaching system prepared for measurements*



Drwg. 5. *Block diagram of an up-to-date test model measurement system*

storing the results and presenting them on paper or on any other data medium - Drwg. 6.

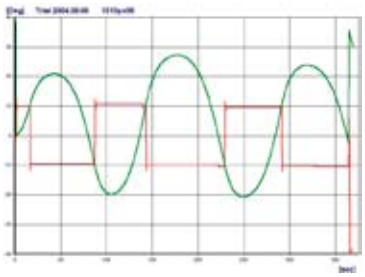


Drwg. 6. *Trajectory diagrams generated by the positioning system – gas carrier model 10o, 35o, 45o turning test*

The GPS position data, gyrocompass data and the MC6800 controller information are collected in the deck computer, which performs the following functions, depending on the type of measurement:

- steering the model (in the zig-zag test, Drwg. 7),
- sending information to shore (radio modems),
- data display for the model operator,
- preliminary data recording.

The system is now used in everyday operation of the Ship Handling Centre in Ilawa on Silm lake.



Drwg. 7. *Deck equipment diagrams generated by the system – 10º/10º zigzag test*

Future development of research systems and popular bearing taking systems

Commonly used bearing taking systems, depending on a version, achieve positioning accuracy up to 3 m.

Historically, it has been as follows:

- 100 m: position determination accuracy up to 2 May 2000, when the position access limiting signal was switched off,
- 10 m: practical accuracy achieved by the undisturbed GPS signal receivers,
- 5 m: GPS accuracy achieved with a DGPS differential correction signal receiver,
- 3 m: accuracy achieved with a WAAS/EGNOS signal receiver,
- 0.01 m: accuracy achieved with a local reference station signal receiver.

Drwg. 8. *Accuracy of the GPS systems*

At present, the accuracy of specialist systems is 5 mm. These are specialized geodesic receivers, e.g. Leica GX1230, using a local reference station signal. Such systems are very expensive and configuration is taylor-made for a specific application.

The future belongs to the European Galileo system, which is planned to be fully operational in 2010. Galileo is by definition a civilian system, controlled by an international team of specialists to guarantee continuity of its operation. The present GPS or GLONASS systems are of a military origin and they do not guarantee a correct and continuous operation. Galileo will make the satellite signals available in 95% of the urban areas (now the GPS is capable of covering only 50% of those areas). The system will also offer greater transmission band widths, ensuring better accuracy and stronger signal. This will allow to use satellite navigation also in buildings and in tunnels.

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The ship control system for trajectory tracking experiments with physical model of tanker

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Abstract

This paper presents a cascade system which stabilizes the transverse deviation of the ship in relation to the set path. The ship's path is determined as a broken line with specified coordinates of way points. Three controllers are used in the system. The primary controller is the trajectory controller. It generates the set value of heading for the course control system or angular velocity for the turning control system. The course control system is used on the straight line of the set trajectory while the turning controller is used during a change of the set trajectory segment. The characteristics of the nonlinear controllers are selected in such a way that the properties of the control system with the rate of turn controller are modelled by the first-order inertia, while the system with the course keeping controller is modelled by a second-order linear term. The presented control system was tested in Matlab-Simulink environment. The results of tests performed on a lake are presented and discussed.

Keywords: *Nonlinear control, ship control, track keeping*

INTRODUCTION

Ship trajectory tracking is a programme control task. The trajectory along which the ship is bound to move is determined on a horizontal plane, in the system of geographic coordinates X_0Y_0, as a broken line with defined x_ky_k coordinates of the way points (Figure 1). The required trajectory can be a safe trajectory, which leaves aside all areas threatening with collision, or a trajectory resulting from sailing directions and regulations in the water region. It can also have a form of an orthodrome, approximated by rhumb-line segments. Usually, the trajectory parts between adjacent way points are approximated by straight line segments, with the attributed directions Ψ_k measured from the X_0 axis (north). The ship has to cover each of these line segments with a given constant speed. After introducing an additional right-handed system of XY coordinates fixed to a current trajectory segment, ship trajectory tracking is reduced to the stabilisation of transverse deviations of the hull centre y on the minimal level.

Kinematical model of the process

Let us assume that the origin of the XY coordinate system for the current trajectory segment (k-th segment) is in line with the coordinates x_ky_k of its ending point. Then the transverse deviation from the trajectory is given by the formula:

$$y = -(x_r - x_k)\sin(\Psi_k) + (y_r - y_k)\cos(\Psi_k) \quad (1)$$

where Ψ_k is the directional angle of the current trajectory segment, measured from the north, and x_ry_r stand for coordinates of the hull centre in the earth-fixed coordinate system X_0Y_0.

With u and v representing, respectively, the longitudinal and transverse components of the ship speed vector, (both fixed to the hull), and Ψ standing for ship's course measured from the X_0 axis, the rate of change of x_ry_r coordinates in the X_0Y_0 coordinate system is given by:

$$\begin{aligned} \dot{x}_r &= u \cdot \cos(\Psi) - v \cdot \sin(\Psi) \\ \dot{y}_r &= u \cdot \sin(\Psi) + v \cdot \cos(\Psi) \end{aligned} \quad (2)$$

while the rate of change of x,y coordinates of the hull centre in the XY system is given by:

$$\begin{aligned} \dot{x} &= u \cdot \cos(\Psi - \Psi_k) - v \cdot \cos(\Psi - \Psi_k) \\ \dot{y} &= u \cdot \sin(\Psi - \Psi_k) + v \cdot \cos(\Psi - \Psi_k) \end{aligned} \quad (3)$$

These kinetic relations define the motion of the hull in the calm waters. In case a sea current is present they have to be complemented by the current speed components.

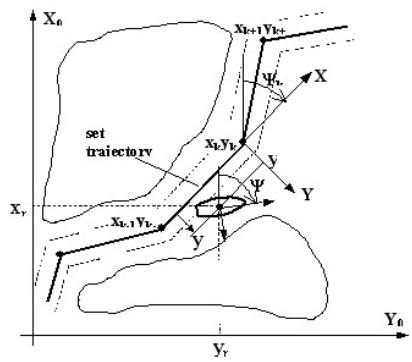

Fig. 1. *The trajectory-fixed coordinate system*

Steering System - Controllers

Stabilisation of the transverse deviation from the trajectory is obtained using a control system having a cascade structure, shown in Fig. 2. The main controller is a trajectory controller, also playing the role of a decision making system. It determines which, out of the two remaining controllers, is to be used for trajectory tracking. Along the straight trajectory segments it generates the assumed value $\Psi_k+\Delta\Psi_y(t)$ for the course control system. The correction $\Delta\Psi_y(t)$ depends on instantaneous scale of deviation of the hull centre from the assumed trajectory. Along trajectory parts that require large course changes a turning angular velocity controller is used. The supervising controller generates the assumed constant value of the angular

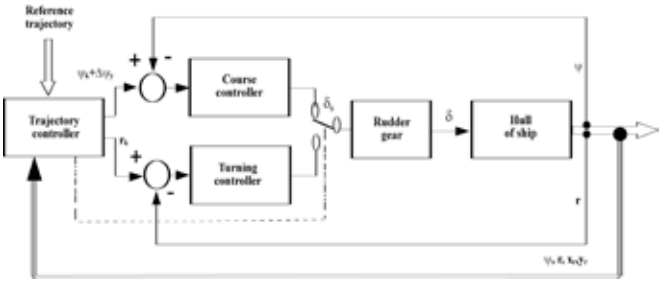

Fig. 2. Block diagram of the control system

velocity of turning and passes to the angular velocity control system. It can also generate varying values of the angular velocity in response to the speed changes of the hull translation, in order to obtain stability of the turning radius.

Linear algorithms, which are usually used in ship autopilots, can keep the stability of a course control system on a directionally unstable ship. However, a global stability requirement for controlling such a ship needs strong derivative action of the controller. High value of the derivative gain coefficient compensates the unstable pole of the object within the range of small rudder angles. It is, however, unfavourable for large rudder angles and large course deviations as it limits the turn rate, thus extending the settling time. These difficulties can be avoided by using a controller, the parameters of which are a function of the course deviation. Error deviation thresholds, which determine the changes of controller parameters, are usually selected heuristically.

Isidori [2] has proposed a simple algorithm of non-linear control. The algorithm can be most easily synthesised using a simple non-linear model of ship's dynamics. Let the object (controlled ship) be modelled by a Norrbin model defined by:

$$T \cdot r + a_3 \cdot r^3 + a_2 \cdot r^2 + a_1 \cdot r + a_0 = k\delta \tag{5}$$

where: δ - rudder angle, r - angular velocity of hull,
T, k, a_i, - parameters of ship dynamics,
The 3rd-order polynomial:

$$H_N(r) = a_3 r^3 + a_2 ı \tag{6}$$

describes the non-linear manoeuvring characteristic generated by Bech's reverse spiral manoeuvre. For course-unstable ships $a_1 = -1$ while for those course-stable ones $a_1 = 1$.

The parameters of this model were also determined with the aid of the recorded results of manoeuvre trials of the model tanker performed on the lake [5]. A general concept of non-linear control is explained in Figure 3.

The course and turn rate determine the actual state of the ship. Here, a static-state feedback control mode is applied. The control is defined by a non-linear function of state variables. The dynamics of the steering gear is omitted during control synthesis. This simplifying assumption is fully acceptable, as it does not create significant errors in cases when the time-constant

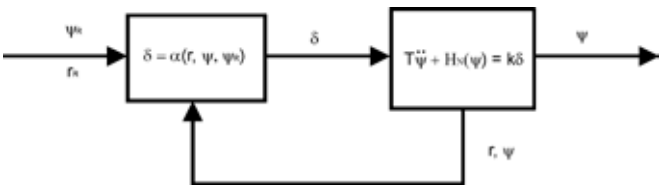

Fig. 3. Schematic diagram of the non-linear control system

of the ship dynamics is much larger than the equivalent time-constant of the steering gear [6]. The instantaneous component of the course control error:

$$e = \psi_R - \psi \tag{7}$$

where:

ψ_R – denotes desired course of the ship, is assumed to satisfy the following differential equation in the transient state:

$$\ddot{e} + \beta_1 \dot{e} + \beta_2 e = 0 \tag{8}$$

Parameters β_1 and β_2 can be determined using the natural frequency ω_n, and the relative damping factor ξ, of a closed loop system. They are equal: $\beta_1 = 2\xi\omega$, and $\beta_2 = \omega n^2$. Placing the error definition from (7) into (8), and then into the dynamics model defined by (5), and setting $d\psi/dt=r$ gives:

$$\delta_\psi = \frac{T}{k}\left[\beta_2(\psi_R - \psi) + \beta_1(r_R - r)\right] + \frac{1}{k}H_N(r) \tag{9}$$

assuming that $d^2\psi_R/dt^2 = 0$.

This equation defines the structure of the non-linear ship course controller. The advantage of the controller is its ability to vary the derivative action, adjusting it to non-linear characteristics of the unstable object. Moreover, the control law described by (9) allows to define the characteristics of a closed loop control system in a direct way using the natural frequency of the system and the relative damping factor.

For large course changes, the reference rudder angles generated by the controller are larger than the maximum rudder angle. Then the rudder angle has to be limited, and changes of error in the control system are not defined by (8) any longer.

It is desirable for large course changes that the course change be performed at a constant turn rate. The instantaneous component of the turn rate error $e_r = r_R - r$ is assumed to satisfy the equation:

$$\alpha_1 \cdot \dot{e}_r + e_r \tag{10}$$

where r_R is the required turn rate and α_1 is a time-constant. Placing the Norrbin model defined by (5) into (10) we arrive at the formula that determines the rudder angles during the turn rate stabilisation period:

$$\delta_r = \frac{T}{k \cdot \alpha_1}(r_R - r) + \frac{1}{k}H_N(r) \tag{11}$$

For continuous operation of the ship control system, conditions for switching between course-keeping and rate of turn controllers have to be defined.

This function is executed in the system by the trajectory controller. Along the straight trajectory segments, small deviations from the assumed trajectory are recorded and the course of the current trajectory segment $\psi_k+\Delta\psi_k$ is stabilised. The correction $\Delta\psi_k$ is a function of an instantaneous deviation y of the hull centre from the assumed trajectory. Let us assume that the transverse trajectory deviation y changes non-periodically (exponentially) during the steering:

$$y(t) = y \cdot e^{-\frac{t}{T_y}} \tag{12}$$

Then, after placing to (3) and neglecting the second term $v \cdot \cos\Delta\Psi_k$ (which is small along a straight line trajectory segment) we arrive at:

$$\Delta\psi_y(t) = -\arcsin\left(\frac{y(t)}{T_y u}\right) \tag{13}$$

$$\psi_R = \psi_k + \Delta\psi_y = \psi_k - \arcsin\left(\frac{y(t)}{T_y u}\right) \tag{14}$$

As a result, the course assumed for the course control system will be equal to:

$$\psi_R = \psi_k + \Delta\psi_y = \psi_k - \arcsin\left(\operatorname{sign}(y(t)\cdot\min\left(\left|\frac{y(t)}{T_y u}\right|,1\right)\right) \tag{15}$$

After analysing the results of the simulation tests the presented formula was modified by limiting the correction range to ±90 deg.

Due to certain inertial characteristics of the object, ship trajectory tracking along the segments including course change requires starting this manoeuvre at an appropriate time instant. If it is started too late, it leads to strong overshoot of the control system. Optimisation of the steering process, or in-advance steering with sufficiently large steering horizon solve this problem. In practical execution, this task can be solved by changing, at a proper time instant, the position of the XY co-ordinate system (Figure 1). The time instant at which the position of the XY co-ordinate system is to be suddenly changed to match the next trajectory segment can be most easily defined by the time instant when the ship nears the tuning point by a certain distance referred to as the advance distance l_{wy}. The manoeuvre advance distance is a function of dynamic characteristics of the ship, its speed, turning abilities, the shape of the assumed trajectory and special requirements concerning the shape of the real trajectory of ship's motion. Figure 4 presents selected cases of possible trajectories of ship's motion for positive and negative manoeuvre advance distances. The negative advance distance means that the manoeuvre is started after the turning point has been passed by.

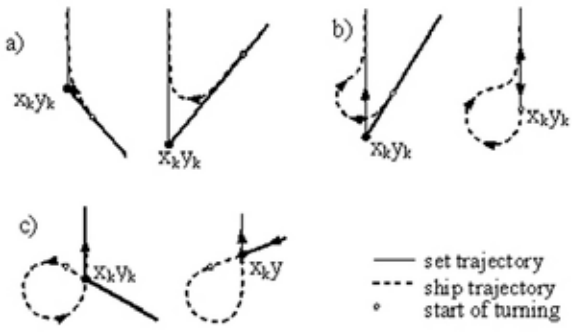

Fig. 4. Examples of the assumed and real trajectories of the ship

During trajectory tracking along straight line segments, the scales of course, rudder angle, and angular velocity deviations are small. Therefore in those situations switching on the turning controller gives no benefit. For large reference course changes, the turn rate that is reached when the course controller is switched on corresponds to the maximum rudder angle and is usually larger then the rudder angle corresponding to the required turn rate. Therefore, in those cases the turning controller is to be switched on as it generates smaller rudder angle than the course controller. Generally, the object is to be controlled by that controller in the control system, which calculates smaller commanded rudder angle. The condition for using a rudder angle generated by one of the two controllers is the following:

$$\delta = \begin{cases} \delta_r & \text{if } \delta_r \le \delta_\psi \quad \text{turning controller} \\ \delta_\psi & \text{if } \delta_\psi < \delta_r \quad \text{course controller} \end{cases} \tag{16}$$

The above switching condition can be applied for steering, during which the real trajectory is inscribed into the arms of the angle created by two adjacent segments of the assumed trajectory (Figure 4a). For the remaining variants of steering (Figure 4b and c) the switching condition is the following :

$$\begin{aligned} &\psi - \psi_k \ge -k_p \cdot y \quad \text{for } y < 0 \quad \text{turning controller} \\ &\psi_k - \psi \ge k_p \cdot y \quad \text{for } y > 0 \quad \text{course controller} \end{aligned} \tag{17}$$

Hardware Setup

The tanker „Blue Lady" model was used for tests of the control system on the lake. It is a physical model of the tanker, done in scale 1:24, which is usually used for training navigators at the Shiphandling Centre of the Foundation for Safety of Navigation and Environment Protection, on the lake Silm near Ilawa [3]. Basic characteristics of the model are collected in Table 1. The shape of tanker and general diagram of the control system is shown in Figure 5.

Item	Ship	Model
Length overall	330.65 [m]	13.78 [m]
Beam	57.00 [m]	2.38 [m]
Draft – full load	20.60 [m]	0.86 [m]
Displacement – full load	323 660 [t]	22.83 [t]
Draft – ballast	12 [m]	0.5 [m]
Displacement – ballast	176 000 [t]	12.46 [t]
Speed	15.2 [kn.]	3.1 [kn.]

***Table 1** Parameters of the Ship and the "Blue Lady" model*

The control system consists of two PC-type computers, Anschütz Standard 20 gyro-compass, DGPS receiver Leica System 500 as well as an ultrasonic anemometer for measuring speed and direction of wind. Current levels of the control signals are measured and passed, in feedback, to the concentrator via 12-bit A/D converters. The concentrator, the design of which bases on the M6800 microcontroller, sends measurement data and receives control signals via RS232 link. The two RS 422 serial links with NMEA 183 standards are used to connect of gyro-compass and DGPS receiver. Due to the presence of lake waters which cause the varying humidity and temperature, that surround the research environment, all actuator, as well as control and measuring signal lines are galvanically separated.

The basic component of the real-time system software is the Matlab-Simulink environment, with the toolboxes of Real Time Workshop, xPC Target, Control System Toolbox, Signal Processing Toolbox, and System Identification Toolbox. Predominant idea of building the software was to employ MATLAB's power into control algorithms development process. This software give opportunity to use the built-in procedures of control, signal processing, and many more algorithms collected in toolboxes. The user is also separated from the hardware and software

level problems and can use high level MATLAB language and Simulink graphical programming [4] to test his own ideas instead of spending hours coding C. The dedicated drivers (controllers) for serial ports RS232/ RS422 with NMEA183 protocols were written in C language and implemented to Simulink diagrams in the form of S-functions [4]. Thus the user has an easy access to input and output signals at the Simulink diagram. Toolboxes RTW and xPC target as well as C compiler are used for creating the kernel of the real-time system and the control programme.

After compilation, the kernel and the control programme are loaded to one of the IBM PC deck computers via ethernet connection. This connection is also used for initiating, stopping, logging, and changing parameters in the control-and-measurement algorithms started from the level of the Simulink scheme, installed on the other PC. Selected signals of the already started process can be monitored and recorded in the real-time system and then, after the process has been completed, imported to the Matlab level.

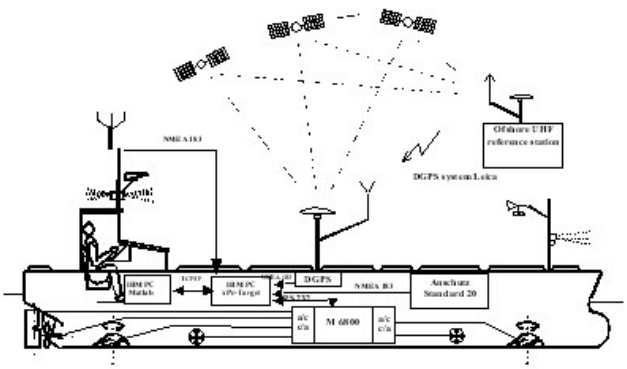

Fig. 5. General scheme of the control system on the "Blue Lady" training boat

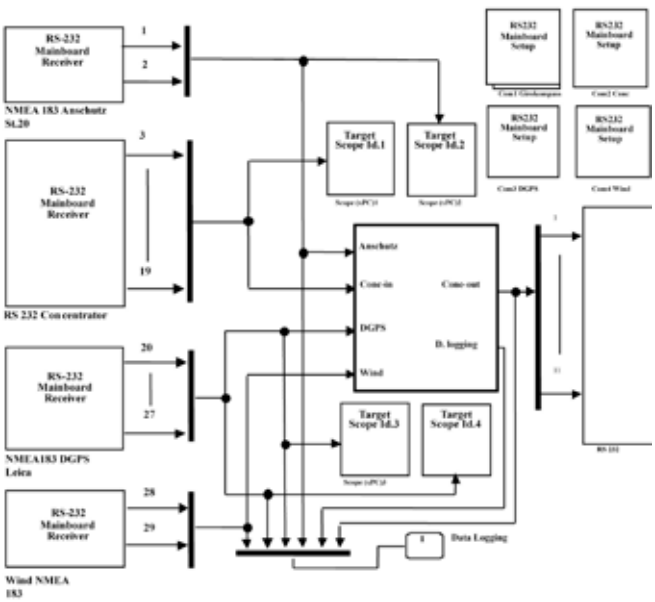

Fig. 6. General block diagram of the Simulink control system on the"Blue Lady" tanker model

A general block scheme of the developed software is given in Figure 6. The examined controller is placed in the central block. The controller can use signals received from input ports and generate output signals to control the model actuators.

Results of the Experiment

The tests of operation of the control algorithm were performed for various speeds of the model tanker, and for various disturbances. Figures 7 and 8 show the obtained trajectory and selected time-histories of the course, angular velocity, transverse deviation from the reference trajectory, and rudder angle during steering the model tanker along the assumed trajectory that included turning manoeuvres with various angles and course stabilisation on a straight trajectory segment.
The presented trajectories correspond to trials at the model speed equal to „half ahead" 0.96m/s and the set parameters of controllers of the course $\beta_1=2\xi\omega=2\cdot0.4\cdot0.1T$, (T=48.5 sec) $\beta_2=\omega^2=(0.1T)^2$ and angular velocity $\alpha_1=0.1T$. The angular velocity of the turning was stabilised at the different level of range 0.5 to 1.3 deg/s while the advance distance of the turning was chosen individually for each manoeuvre.

Conclusions

On the basis of the performed trajectory tracking experiments the following conclusions can be formulated :

- The presented algorithm of ship trajectory tracking reveals good dynamic characteristics

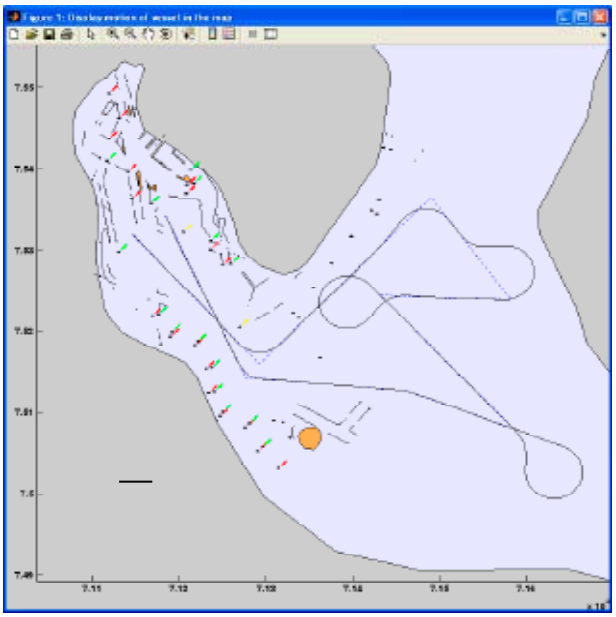

Fig.7. Simulation results of trajectory tracking.

- During synthesis of trajectory tracking, dynamic characteristics of the course and angular velocity control systems are modelled by characteristic equations of the second and first order, respectively. Therefore they can be easily modelled using, for instance, natural frequencies and damping factors of the control system, or the time constant of the angular velocity stabilisation system.

- Using different turning manoeuvre advance distances and set different turning velocity, one can obtain various shapes of the trajectories: either inscribed into the arms of the angle created by two adjacent segments of the assumed trajectory, or going beyond that area.

- The accuracy of trajectory tracking along the selected trajectory segments was not worse than 1m.

- The proposed method of switching the controllers is relatively simple. In case the course change is small during the trajectory segment change manoeuvre, the controlled ship does not reach the required angular velocity fast enough. That is why the turning controller switches on for a short time period only

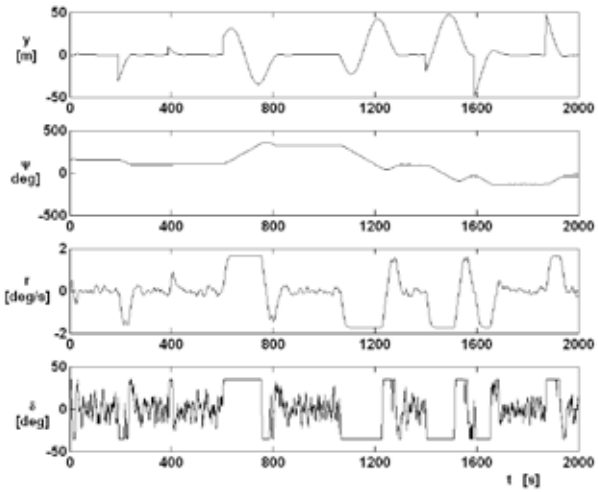

Fig. 8. *Time-histories of transverse deviation from the trajectory y, the real course Ψ, angular velocity r, and rudder angle δ during the steering of the model tanker along the assumed trajectory*

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Classification of Elemental Manoeuvres Observed during Ship Handling Training Employing Manned Ship Models

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Abstract

The paper presents a concept of elemental manoeuvres that may be used for analysis of ship handling training (including the training with manned model ships) and for simulation of complex manoeuvring scenarios. It shows a set of postulated elemental manoeuvres. A fuzzy clustering method is introduced and applied for the classification of manoeuvring patterns. The fuzzy clustering algorithm is used for the extraction of elemental manoeuvres from the records of ship handling manoeuvres of LCC model ship. The best set of variables for the extraction of elemental manoeuvres consists of normalised ship velocities and controls.

Keywords: *Manoeuvring, Elemental manoeuvres, Fuzzy Clustering, Trajectory, Manned models*

INTRODUCTION

The complex task of ship handling – the manoeuvring of ships – has to be analysed at various circumstances to discover and to provide control models constituting the task. These control models are looked for by people assisting the ship handling training (Figure 1) by people creating ship manoeuvring simulations for various design purposes and for people designing ship control systems themselves.

Fig. 1. *Ship models manoeuvring at the Ilawa Research and Ship Handling Centre*

The ship handling training that uses manned ship model simulation technology is more efficient when the instructor may rationally analyse the sequences of controls employed by the trainee and the results of these control actions on the model ship responses. The understanding of these relations helps in the explanations of the model ship behaviour to the trainee. The questions that arise when analysing the sequences of ship's manoeuvres consist of the following: How to evaluate the manoeuvres? What are the quality criteria of the performance in a specific manoeuvre? Which fragments of the training should be repeated and why the execution of these fragments was judged as a sub-standard one? What control strategies are used by trainees – ship masters and ship pilots – during ship handling? It would be of importance when aiding such analyses to discover, to describe and to verify the existence of manoeuvring patterns that are employed by pilots and masters during manoeuvring planning and execution. The manoeuvring patterns would allow to focus on individual parts of the whole manoeuvring scenario and to analyse manoeuvres of different ships within various environments using a common framework of manoeuvring patterns. These manoeuvring patterns will be presented in the paper and they are called elemental manoeuvres. Figure 1 shows a snapshot from a ship handling training – a ship is passing through bent waterway – the trainee has to follow the designed track, proceeding through connected straight – line segments and changing ship's course when moving from one waterway segment to another.

Other problems arise when one uses ship handling manoeuvring computer simulations for ship design, harbour assessment or waterway safety studies. The control models used for simulations should be understandable and easy to explain to pilots, ship masters and people ordering the simulations. It is possible when a control model has a direct reference to the practice of ship handling onboard a real ship. Figure 2 shows a simulation model for the assessment of limiting wind condition (maximum wind speed) for a given ship with specified

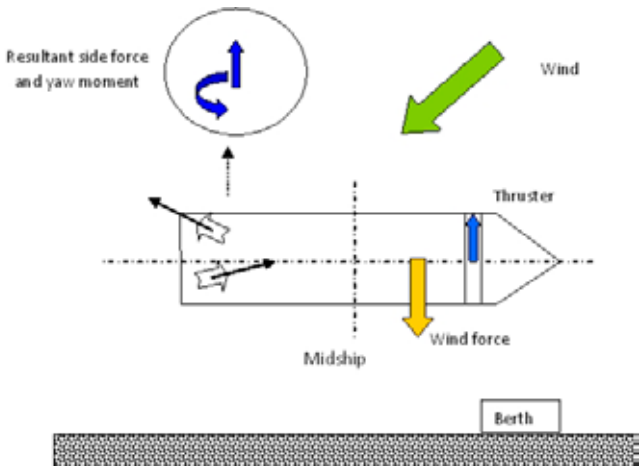

Fig. 2. *Model of control in a manoeuvring computer simulation (for ship design)*

azimuthing propellers and bow thruster – the model assumes position keeping and constant heading: the question is whether such a pattern is used for manoeuvring and whether assumed controls (propellers' angles and bow thruster settings) would be used in reality.

Another problems arising in manoeuvring computer simulations are related to the questions like: Does the control model used in simulations refer to the control strategy employed onboard a real ship? How to show and to prove to customers ordering the simulations that the employed control model is used in reality by pilots and ship masters? What structure should the control model for simulation have?

The problem that is the subject of the research presented in the paper is the following: to present the concept of elemental manoeuvres and subsequently to discover and to point out the elemental manoeuvres (manoeuvring patterns) appearing in recordings of ship handling manoeuvres; and to do this in some automated (programmed) way that would allow to use such a method for processing of many data records gathered during ship handling training employing manned ship models.

The concept of elemental manoeuvres was first mentioned by Kose et al [1][2][3] for analysing the manoeuvring in harbours. It was also used by Sousa et al [4][5] for simplification of control schemes for ROV (a creation of a set of simple controllers for a set of simple tasks).

The paper is organised as follows. First the author presents the concept of elemental manoeuvres (manoeuvring patterns). Next the study objective is presented. It is followed by the description of the methodology used for discovering the elemental manoeuvres – a data clustering method is used. Next the author shows the results of clustering on sets of real data – the effect of selection of clustering variables, number of clustering centres and the interpretation of clustering in terms of fuzzy rules. Finally, the author discusses the results of the study and shows the direction of future research.

The Concept of Elemental Manoeuvres

We at the Foundation for Safety of Navigation and Environment Protection recognise that the complex manoeuvring scenario consists of simpler manoeuvring tasks. These simpler tasks are generic for different types of ships – these simple tasks become a kind of parametric templates that are used by the master or the pilot to manoeuvre the ship – the pilot or master follows some learned patterns while adopting the controls to the actual manoeuvring situation and the ship system at hand.

During ship handling training we gather the following information about the ship model state:

- The ship model trajectory information,
- The information about model ship's heading (attitude),
- The information about the propeller revolutions, rudder deflection and tugs' action (control state).

These data are used for velocity and acceleration estimations.

The information gathered is quite complex and the amount of data is significant - Figure 3. Therefore we strive for automation of the information processing when presenting the information to instructors and trainees.

It is desirable to create control models – templates of ship control – that would describe the ship manoeuvres occurring during ship handling. These manoeuvring templates would represent simple manoeuvring tasks. The simple tasks would serve as building blocks that might be assembled into a complex manoeuvring scenario (bottom-up synthesis approach) or that might be used as elemental blocks which the complex scenarios would be divided into (top-down analytic approach).

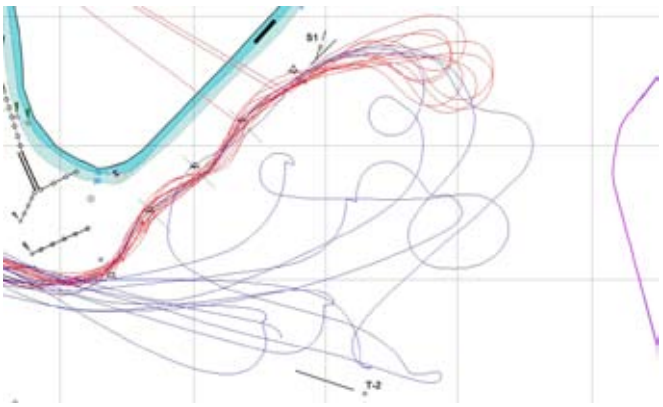

Fig. 3. Part of tracks recorded during the first day of a ship handling course.

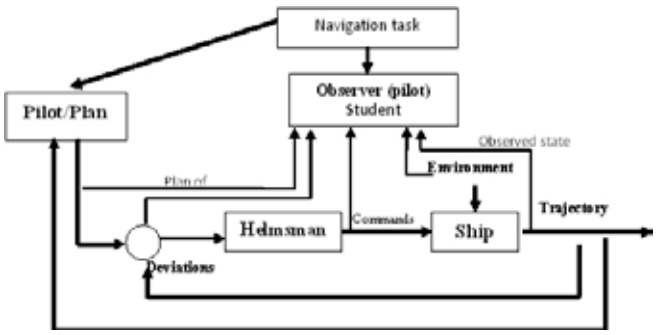

Fig. 4. Model of hierarchical control system in ship handling - with the aspect of the trainee learning

Figure 4 shows that the ship handling tasks have some control structure. We know that people (e.g., pilots or ship masters) perform complex tasks using learned procedures and patterns. Similarly, a direct control of a system (e.g., a ship by a helmsman) relies on some earlier learned behaviour (procedures, patterns and reflexes). Not all learned procedures are obvious to an expert (pilot) – therefore it is important to us to show them the patterns and to relate the ship controls and observed ship's responses to these manoeuvring patterns.

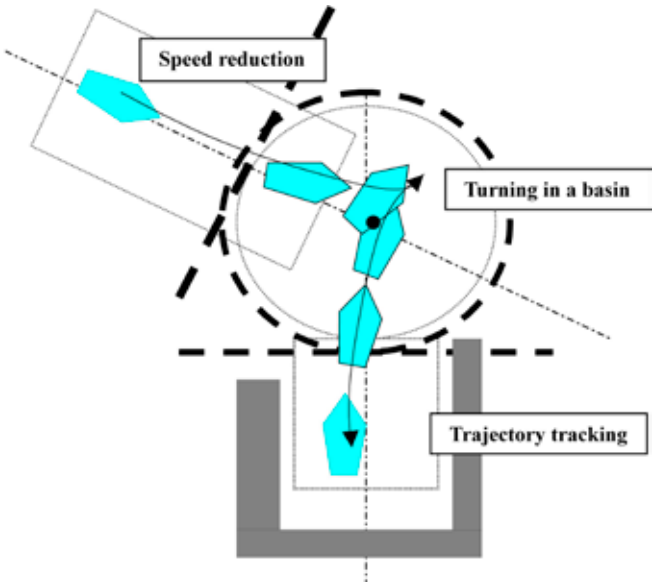

Fig. 5. Manoeuvring scenario separated into three simpler, elemental tasks.

Here we introduce the concept of elemental manoeuvres. The complex manoeuvring scenario can be divided into series of simple manoeuvring tasks – as in Figure 5 - called elemental manoeuvres. This example shows that the approach to the basin, turning and entering the basin may be separated into simpler tasks.

Through the observation of the recorded manoeuvres and applying the control engineering approach one may deduce an initial, hypothetic list of elemental manoeuvres.

The elemental manoeuvre is a ship handling task where one may easily discern the following features, arising from the analysis of the ship model control process:

- It has a well defined manoeuvre objective – allowing to present the art of ship handling as a sequence of rational tasks and to determine the control objective in every task,
- It has well defined initial and final state, allowing to create the control trajectories leading from the initial to the final state,
- It has defined the control strategy – accounting for the available control devices - that should be used to reach the manoeuvre objective,
- It has defined the control objective and the performance criteria of the control process.

It is also possible to create a set of standards for the realisation of the elemental manoeuvre and a set of boundary constraints for performing the elemental manoeuvre (for example, constraints limiting the manoeuvring space, limits on allowable ship model speed, or limits on allowable power of control devices like tugboats). By applying the elemental manoeuvre concept it is possible to obtain the following objectives in ship handling training support and in manoeuvring simulation analyses:

- To isolate a relatively small set (5-6) of elemental manoeuvres, representing a rich world of ship handling procedures, which in turn allows to analyse the complex ship manoeuvres and to define the standards for manoeuvre execution parameters which are directly related to the ship handling task,
- To divide a complex manoeuvring scenario into a set of simple elemental manoeuvres, which helps in the analysis of manoeuvres performed by a trainee by focusing on a well defined manoeuvring templates,
- To generalise the analysis across ship types – through employing the elemental manoeuvre concept for various ship types we may concentrate on patterns and templates common for these various ships and to define the templates specific to a given ship type,
- To define the templates for standards of performing of each of the elemental manoeuvres - the templates are the methods for the evaluation of the manoeuvre execution; the definition of such templates (methods) allows to assign specific numerical values that describe the criteria of manoeuvre execution for a specific ship.

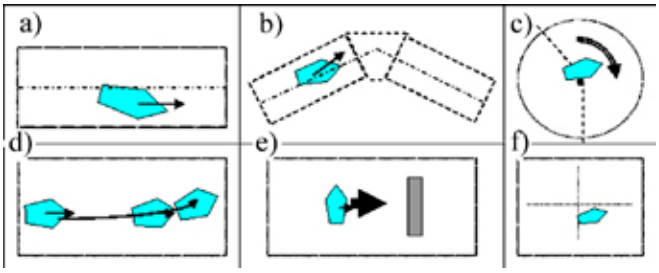

Fig. 6. *Sketches of proposed elemental manoeuvres*

Figure 6 shows proposed elemental manoeuvres. The list of elemental manoeuvres is as follows:

a) Course – or track – keeping,
b) Course change during advancing of the ship,
c) Turning the ship at close to zero advance speed (in place),
d) Stopping the ship (advance speed reduction),
e) Moving the ship sideways (crabbing, for example, toward a pier),
f) Maintaining a prescribed ship position (station-keeping at zero advance speed).

One needs to verify the posed above hypothesis about the elemental manoeuvres. In particular, one needs to check, whether such manoeuvring patterns exist in the recorded ship handling time histories. Also one checks the number of such elemental manoeuvres and their parameters. Another interest lies in fact how to recognise the elemental manoeuvre in time history of a ship handling scenario.

Figure 7 shows registered tracks, recorded during ship handling training performed onboard LCC and VLCC model ships (tankers). There are marked example areas with hypothetical elemental manoeuvres – the shape of the trajectory and the knowledge of the control of the ship suggests that such manoeuvring patterns (turning at speed, turning in a basin at zero speed, course-keeping and crabbing). It would be of interest to find the confirmation of such hypotheses and to show a tool for doing this in an automated way.

Research on Discovering of Elemental Manoeuvres

Below are presented the methodology and results of investigation on discovering of elemental manoeuvres.

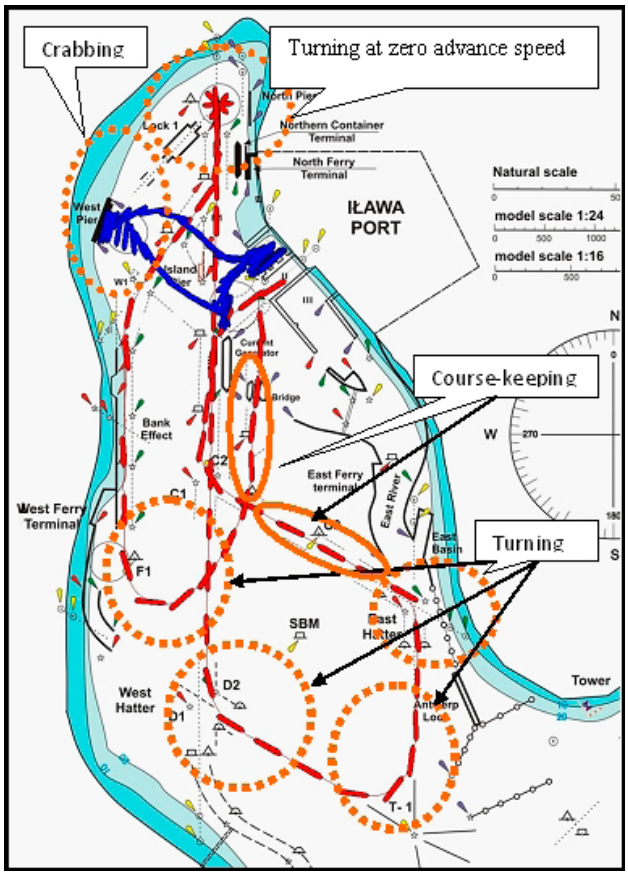

Fig. 7. *Trajectory of tanker model ships with marked potential elemental manoeuvres.*

Purpose of the Research

The objectives of the research are as follows:

a) to present the concept of elemental manoeuvres of ships with application to ship handling training and to manoeuvring simulation,
b) to attempt an extraction of elemental manoeuvres in real observed ship manoeuvring sequences (from ship handling training onboard manned ship models),
c) to evaluate the effectiveness of one of specific methods of data grouping (clustering), namely the C-means clustering algorithm, when applied to such a problem:
   a. can the method point out different data sets that might be assigned to specific elemental manoeuvre,
   b. which data (variables) are best suited for the elemental manoeuvres pattern discovery,
   c. how this particular method performs in the task (can it find out unique data patterns? Does it miss some data patterns?).

The Research Method

The method originates in the analysis of a phase space of ship's state and control vectors. When observing data in properly selected phase space one may discover distinct groupings of data. For example, a ship maintaining its position and heading during station keeping will have all linear and angular velocities components close to zero, so when one constructs a phase space using velocity components then all phase trajectories will group around the origin of the phase space system. When proper phase space representation is selected then one may use a data clustering algorithm for grouping of the data into separate data sets that can be identified within the phase space due to their distinct locations.

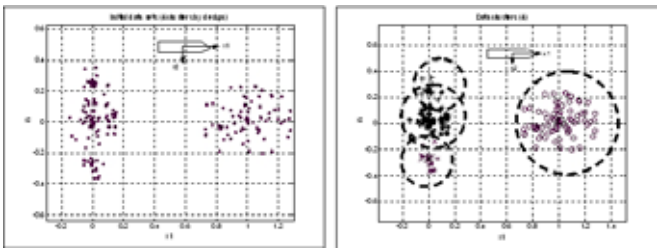

Fig. 8. *Example of clustering method: data (left), identified data cluster (right).*

The phase space in the presented problems will contain ship model kinematics (variables like velocities and accelerations) and control variables (propeller revolutions and rudder deflection angles).

An Example of the Clustering Method

A simple example is given. The data about a hypothetic ship motion consist of 2 components of ship's velocity: surge x1 and sway x2. These data are artificially generated and they are grouped in 4 clusters. The objective is to characterise the ship's motion. Figure 8 shows the data and it can be seen that the data may be grouped into following subsets:

a) motion ahead (large values of surge velocity x1, small absolute values |x2| of sway velocity),
b) motion sideway (small values of surge velocity x1 and large absolute values |x2| of sway velocity),
c) other transient data.

To find the data clusters a procedure fcm from MathWorks MATLAB FuzzyToolbox is used. The clustering method selects data points to become so called cluster centres and next assigns the remaining data to one of clusters as to minimise the total sum of distances between centres of clusters and their data points.

Figure 8 shows the action of the MATLAB procedure fcm. On the right figure one can see the identified 4 data clusters – as it was designed in the original data set. However, the procedure of clustering may not be able to work properly – its result depends on proper indication by the user of the number of data clusters: if the number is incorrect then the localisation of the cluster centres is wrong. The procedure subclust may help in selecting the proper number of data clusters, but here one may also face the incorrect prediction of the number of clusters. Also, even when the number of data clusters is correctly predicted then fcm may give incorrect data – depending on the data characteristics – if the clusters overlap, then the "wrong" location of centres may be assigned. Therefore the results of clustering must be verified by other means.

The Details of Data Analysis Method

The data that were analysed are the so called "night exercises" records of : LCC "Warta" and VLCC "Blue Lady" , as shown in Figure 9.

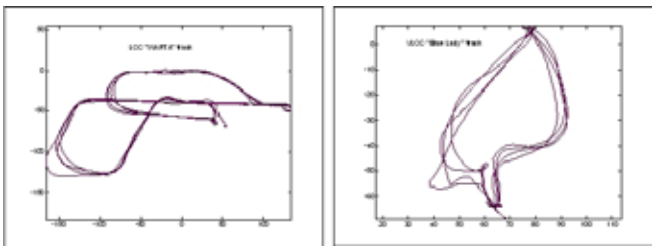

Fig. 9. *Examples of recorded tracks used for the cluster analysis*

The variables that were taken into account during cluster analysis were the following: components of the model ship linear velocity, model ship angular velocity, components of the model ship linear acceleration, model ship angular acceleration, rudder deflection angle, propeller revolutions.

The analysis method was the C-means clustering algorithm (fcm function from MATLAB Fuzzy Toolbox), together with developed software for data processing and for the estimation of the cluster data number (using subclust MATLAB function). Three versions of sub-cluster ing data sets were used to produce the estimation of the cluster numbers.

Data Form for the Analysis

All data were converted into non-dimensional forms. We did it because we searched for patterns that did not depend on absolute values of some motion variables. For example, the crabbing motion is characterised by the drift angle close to 90 degrees, irrespective of the translation speed being 1 knot or 0.1 knots. Similarly, the control variables should be normalised

$$X_1 = [|u'|, |v'|, |\omega'|]$$
$$X_2 = [|u'|, |v'|, |\omega'|, |\tfrac{du'}{dt'}|, |\tfrac{dv'}{dt'}|, |\tfrac{d\omega'}{dt'}|]$$
$$X_3 = [|u'|, |v'|, |\omega'|, |\delta'|, |rpm'|]$$
$$X_4 = [|u'|, |v'|, |\omega'|, |\tfrac{du'}{dt'}|, |\tfrac{dv'}{dt'}|, |\tfrac{d\omega'}{dt'}|, |\delta'|, |rpm'|]$$

using the maximum available control command, so the relative data allow to compare manoeuvres for various ships.

The following rules were used for data normalisation:

a) The velocities and accelerations were normalised using the instantaneous model ship's speed and model ship's length,
b) The rudder deflections were normalised using the maximum rudder deflection,
c) The propeller revolutions were normalised using the maximum propeller revolutions.

Variable Sets for Cl uster Analysis

Various combinations of variables (variable sets) were used for the analysis. We wanted to know which data sets would serve best for the different manoeuvring patterns (elemental manoeuvres) separation. Four variable sets (X_1 – X_4) were selected for the analysis:

Variable set X_1 represents pure kinematics – just velocities. It is less sensitive to errors in the acceleration estimation than the set X_2 which also represents kinematics. The set X_3 represents kinematics and control – it is a set X_1 extended by the vector of control variables (rudder angle and propeller revolutions). The set X_4 represents both full kinematics (set X_2) and the control variables.

The observed data of interest are the following:

a) the localisation of the data clusters on the model ship trajectory (to find the elemental manoeuvres),
b) interpretation of the centres of clusters from the view point of control engineering.

The Example of Data Analysis and Interpretation

The example concerns the manoeuvre of the course change for a model ship proceeding at speed within a waterway. The fcm function shows that there are 2 separate clusters, however, in fact there is just a single cluster, corresponding to the course-change manoeuvre. Figure 10 shows the trajectories and the interpretation of the data using the phase planes of velocities. The phase-plane data show that the rate of turn r' is high for both clusters, while sway velocity v' remains relatively low – it suggests that the data concern course change manoeuvre with large surge (advance) velocity u'. This example shows that the clustering can separate the data, but at the same time care should be taken of the interpretation of the results, since there are possibilities of misclassification.

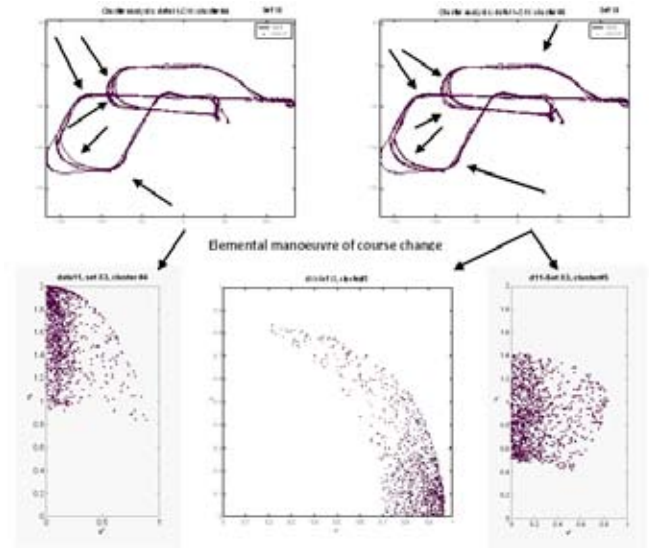

***Fig. 10**. The trajectories of the manoeuvres and the phase planes of clusters corresponding to course-change*

Some of the Results of Investigations

Figure 11 and Table 1 show some clusters obtained through clustering procedure when conducted on the variables consisting of kinematics (velocities) and control (rudder deflection). Figure 11 shows two data sets that may be identified as

***Table 1.** Data cluster centres and interpretation (6 data clusters)*

	u'	v'	r'	δ'	Interpretation
1	0.4560	0.8361	0.1354	0.0760	Turning with small amount of rudder (advancing) – (medium surge velocity, large sway velocity, small yaw rate, small rudder)
2	0.9645	0.1314	0.1696	0.6787	Course-change with large amount of rudder (large surge velocity, small sway velocity, small yaw rate, large rudder)
3	0.2714	0.1874	1.8048	0.0420	Turning with small amount of rudder (advancing) – (medium surge velocity, small sway velocity, large yaw rate, small rudder)
4	0.4974	0.1456	1.6179	0.8393	Turning with large amount of rudder (advancing) – (medium surge velocity, small sway velocity, large yaw rate, large rudder)
5	0.8313	0.2144	0.8504	0.1556	Course-change with small amount of rudder (advancing) – (large surge velocity, small sway velocity, medium yaw rate, small rudder)
6	0.9813	0.1085	0.0972	0.0777	Course-keeping with small amount of rudder (large surge velocity, small sway velocity, small yaw rate, small rudder)

***Table 2**. Data cluster centres and their interpretation (4 clusters)*

Cluster	u'	v'	r'	Interpretation
1	0.4839	0.8272	0.1137	Turning with small advance velocity (in basin) (medium surge velocity, large sway velocity, small yaw rate)
2	0.8176	0.1883	0.9599	Course – change while advancing (large surge velocity, small sway velocity, large yaw rate)
3	0.9832	0.1047	0.1135	Course-keeping while advancing – and course-change (large surge velocity, small sway velocity, small yaw rate)
4	0.3175	0.1655	1.7894	Turning with small advance velocity (in basin, on spot) (small surge velocity, small sway velocity, large yaw rate)

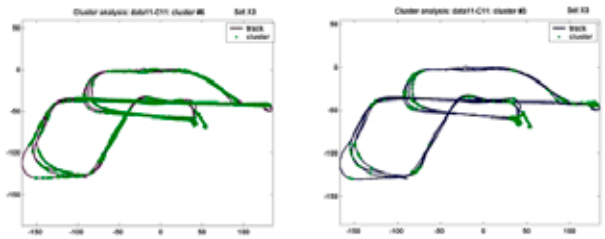

Fig. 11. *Variables (kinematics + control), 6 data clusters; course-keeping pattern (#6) and course-change pattern (#3)*

a course-keeping and course-changing patterns.

Table 1 shows the interpretation that may be assigned to the centres of the data clusters.The separation of the data into 6 clusters works relatively well, especially because the variables include the control data (rudder deflection). However, some data seem still to be misclassified.

More misclassification happens when the clustering variables include only the kinematics (velocities). In this case the best results were obtained with 4 cluster centres. However, as Figure 12 and Table 2 show, the points are more often misclassified. Still the procedure can find different clusters (cf. the Table 2 as it shows the different data and interpretation).

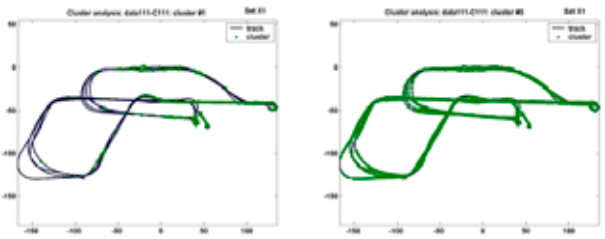

Fig. 12. *Variables (kinematics), 4 data clusters, turning pattern (#1) and course-keeping pattern (#3)*

Conclusions

The clustering analysis confirms the existence of elemental manoeuvres (manoeuvring patterns) in ship handling. It is possible to automate the search for the fragments of records of ship handling representing data from a specific elemental manoeuvre. The fuzzy clustering method (MATLAB implementation of C-means algorithm) has been used and it is capable of classification of ship handling data into clusters representing the elemental manoeuvres.

When selecting the variables for data clustering the best results were obtained using the following sets of variables:

a) the velocities (linear and angular) and controls (rudder angle and propeller revolutions),
b) the velocities (linear and angular).

A great sensitivity was seen of fcm (clustering function) to the the variations of accelerations. Typical of the clustering method is its sensitivity to the number of data clusters – when they are specified incorrectly (the number differs from the observed number of data clusters) then misclassification results.

Other methods of data clustering – specially the ones designed for analysis of time series – might be investigated.

As for the application of the presented approach we see the following:

a) the possibility to classify the manoeuvres performed in selected areas – after the data classification it would be possible to determine whether the timing and the sequence of manoeuvres in the area were correct (it is important when analysing the results of the ship handling training),
b) when connecting the specific elemental manoeuvres to the type of the navigation area and the manoeuvring task (so, when using the concept of elemental manoeuvres in motion trajectory planner) it would be possible to use specific automatic controller for manoeuvring the ship in a given elemental manoeuvre – it is important when developing ship handling simulations.

Further Studies

The author sees the necessity of further studies in the following areas:

a) The use and assessment of effectiveness of other method of data clustering specific for analysis of time series (in this case, for the records of ship handling manoeuvres),
b) The use of neural networks for the data set classifications, in particular, for data that are time series of recorded ship handling manoeuvres,
c) Identification and the determination of characteristic parameters that would describe the elemental manoeuvres appearing during ship handling training,
d) Identification of control models typical of specific elemental manoeuvres.

Literature

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The disturbances of the life raft leeway induced by the fluctuations of wind direction in the life raft coordinate system

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Abstract

The paper presents the results of investigations on the life raft leeway induced by the fluctuations of wind direction. The surface current is one of the main factors determining the life raft leeway, but the recently conducted research confirmed that there are also other elements influencing the perturbations of leeway direction. The field experiments showed diversion of the life raft leeway from the downwind direction. This diversion can be explained by the existing cross wind component. The wind tunnel tests allowed to determine the aerodynamic coefficients in the fluid-state control system. On the basis of the test results the expression for the wind pressure force has been formulated. The mean deviation and median of probability distribution of the leeway diversions from the downwind direction has been determined on the basis of investigations conducted at sea. The models for the life raft velocity dependent on wind velocity, developed for the life raft with drogue and without drogue, are presented in the paper.

Keywords: *Search and Rescue, life raft aerodynamic coefficients, sea investigations of life raft leeway, model of life raft leeway*

INTRODUCTION

The most important element of SAR (Search and Rescue) action at sea is the proper determination of search area. Search area is the part of sea which contains the Datum/Datums. The probability of search object containment in this area is the hightest. There are several factors influencing the Datum and search area dimensions. The most important is the search object leeway. The velocity and direction of the leeway can be expressed by the leeway vector. This vector determines the position of search area. The divergence of search object leeway from the downwind directon has the influence on the search area fuzziness – figure 5.

Definitions of the Search Object Leeway

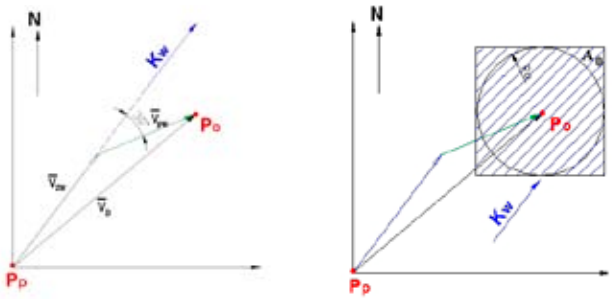
There are severeal definitions used to define the leeway of surface objects published in scientific works and research reports. The leeway definitions that are widely used for the search objects and considered in the paper are as follows:

- Leeway is the movement of a craft through the water, caused by the wind acting on the exposed surface of the craft [4],
- Leeway is the motion of the search object on the water surface induced by wind and waves [7],
- The more general definition is formulated by the author: leeway is the motion of the search object on the water surface, induced by the wind, waves and self object's motions dependent on the operational conditions of the object.

The search area and the method of search area determination recommended by IAMSAR until 2002 is presented in figure 1.

Investigations of life raft leeway in real Sea conditions

The research conducted at sea conditions showed the search objects leeway diversion from the downwind direction [1,2,5,6]. Figure 2 presents the progressive vector diagrams



Where:
Pp – Initial Position
V_{ZW} – Leeway Vector,
V_{PW} – Wind Current Vector,
V_D – Drift Vector,
P_o – Datum,
A_o – Determination Search Area,
Kw – Wind Direction (Downwind)

Fig. 1 *determination of search area recommended by IAMSAR before 2002*

of trajectories relative to the downwind direction for twenty experimental drift runs of 4-6-person life rafts, with deep-ballast system and canopy, in light loading condition. The twenty-degree divergence angles for this leeway category specified by Allen and Plourde (1999) [6] are shown as dashed lines.

One of the factors causing the diversion of life raft leeway from the downwind direction is the surface current, however the laboratory tests and sea investigations confirm that there are additional factors influencing the disturbances of the leeway direction. The most important factor is the cross wind component. Crosswind component of leeway versus wind speed for different operational conditions of life rafts is presented in figure 3. The leeway diversion from the downwind direction of the 10-person life raft is presented in figure 4.

Table 1 presents the observed real position of the 10-person life raft after 8 hours since it was observed at the initial position.

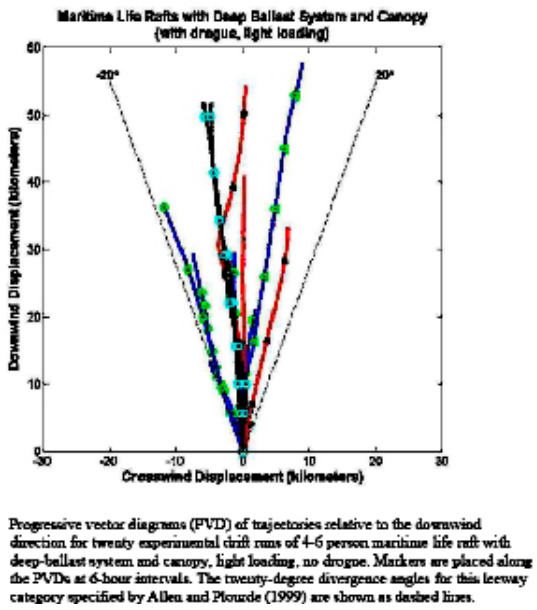


Fig. 2 *Progressive vector diagrams of life rafts trajectories relative to the downwind direction for twenty experimental drift runs [6].*

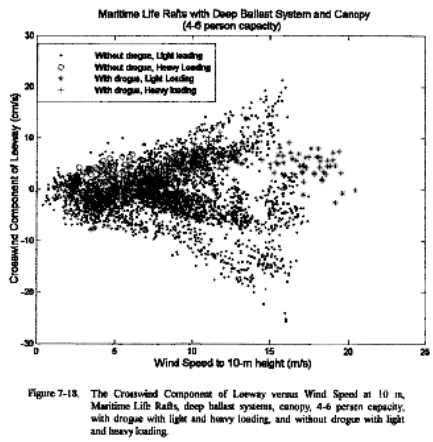


Fig. 3 *Crosswind component of leeway versus wind speed for different operational conditions of life rafts [6].*

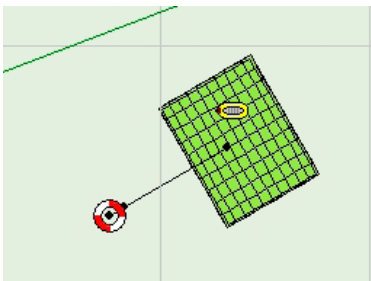


Fig. 4 *The real position of the 10-person life raft diverged from the downwind direction.*

Search area determination

The new method of search area determination, which considered the observed leeway diversions to the right and left side from the downwind direction, follows from the results of research conducted since 2002 [1,2,5,6]. The search area recommended by IAMSAR after 2002 is presented in figure 5.

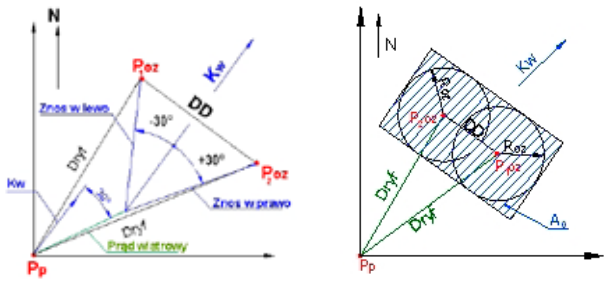


Fig. 5 *Search area recommended by IAMSAR after 2002.*

Apart from sea investigations on the life rafts leeway there were several laboratory experiments conducted for the real 10-person life raft. The results of the laboratory test were used to determine the forces acting on the life raft. Measurements

Fig. 6 *Investigations of wind pressure force of the life raft conducted at Aerodynamic Laboratory of the Air force Institute in Warsaw.*

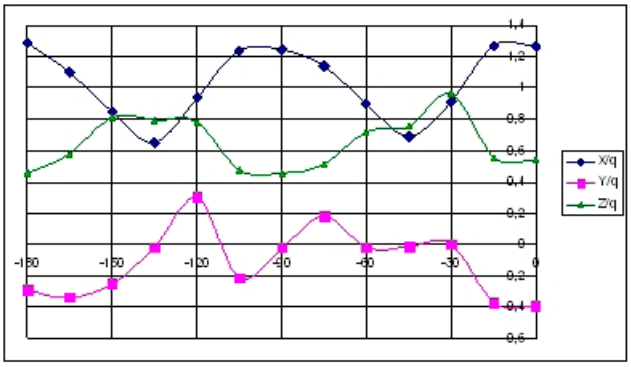


Fig. 7 *Linear aerodynamic coefficients in the fluid-state control system for the 6-person life raft and wind speed of 10 m/s .*

collected during wind tunnel tests allowed to determine the functions of air pressure force coefficiens in relation to the wind direction in the life raft coordinate system. The investigations were conducted at the Low Speeds Aerodynamic Laboratory of

TABLE 1. *The real position of the 10-person life raft observed after 8 hours at the wind speed of 24 knots.*

Search Object	Initial position P_p		Real observed position		Time of drifting [hours]	Downwind direction [°]	v_w [knots]
10-person life raft	φ = 55°20,7'N	λ=017°12,7'E	φ =55°26,5'N	λ=017°24,3'E	8	240	24

the Airforce Institute in Warsaw [1,2,8]. The results illustrating the dependence of the aerodynamic coefficients on the direction of life raft axes in the fluid-state control system are presented in the diagram of the aerodynamic coefficients in figure 7.

The changes of wind pressure force of the life raft, expressed by the linear coefficients in the fluid-state control system, are one of the reasons of the life raft leeway diversion from the downwind direction. Due to this reason the determined search area must be broadened. The broadening is the efect of the uncertainty of determination of wind direction in the coordinate system of the life raft axes.

To make the allowance for the wind direction changes influence (in the coordination system related to the life raft axes) in the expression of the wind force $F_N(v)$ it is necessary to use conditional probability:
where:

$$F_N(v) = P(A_1)F(v \mid A_1) + P(A_2)F(v \mid A_2) + \ldots + P(A_n)F(v \mid A_n) \quad (1)$$

$P(A_i)$ – probability of the wind direction
$F(v/A_i)$ – wind force function dependent on wind velocity for the i-th wind direction

$$F(v \mid A_i) = C_i \cdot F(v)$$
$$F(v) = a_0 + a_1 \cdot v + a_2 \cdot v_2 \quad (2)$$

where:
coefficients a_0, a_1, a_2 are presented in table 2,
v- wind velocity.

The model parameters for the different life raft types and different life raft loadings for the life raft with drogue are presented in table 2.

TABLE 2 *Coefficients of the wind force for the 10-person life raft*

Life raft type	a_0	a_1	a_2
10 persons	-18,4608	3,55045	0,814599

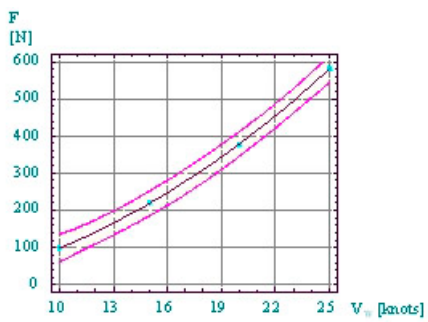


Fig. 7 *Wind pressure force for the 10-person life raft*

The 10-person life raft during the tests conducted in the real sea conditions is presented in figure 8. The investigations of the life raft leeway at sea has proved that the life raft motion induced by wind is diverged from the downwind direction [1,2]. The mean diversion of life raft leeway from wind direction is 8,6° and the median is 11°.

Fig. 8 *10-person life raft during the tests conducted in real sea conditions.*

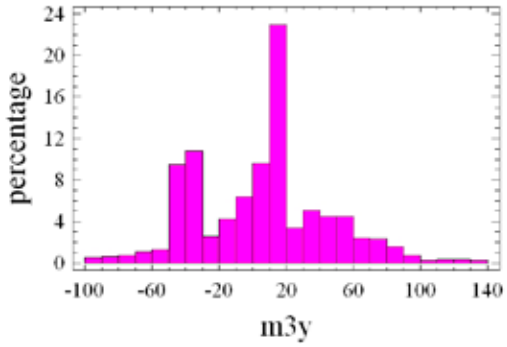


Fig. 9 *Histogram of the life raft leeway diversion from the downwind direction in the coordinate system of the life raft axes.*

For the force F(v) the expression for the life raft leway velocity can be formulated. The model describing the influence of wind velocity on the life raft velocity v_{tr}, for the life raft without drogue, can be expressed by the following polynomial (3):

$$V_{tr}(V_w) = a_4 V_w^{\,4} + a_3 V_w^{\,3} + a_2 V_w^{\,2} + a_1 V_w + a_0 \quad (3)$$

The coefficients of the model for the different life raft types and life raft loadings, with or without the drouge are presented in table 3 .

The model describing the influence of wind velocity on the life raft velocity v_{tr}, for the life raft with drogue, can be expressed by the following polynomial (4):

$$V_{tr6}(V_w) = a_8 V_w^{\,8} + a_7 V_w^{\,7} + a_6 V_w^{\,6} + a_5 V_w^{\,5} + a_4 V_w^{\,4} + a_3 V_w^{\,3} + a_2 V_w^{\,2} + a_1 V_w + a_0 \quad (4)$$

The minimum and maximum life raft loadindg should be considered due to the lack of information regarding the number of survivors inside the life raft during SAR action. Therefore the models for the full loading and minimum loading should be assumed as the upper and lower limits of the leeway velocity changes.

The position of life raft drogue fastening induces the drag force and moment (5) being the additional reason of the

TABLE 3 *Coefficients of leeway velocity for the life raft without drogue*

Life raft type and loading	a_4	a_3	a_2	a_1	a_0
10 persons without drogue 10% loading	-2,7912E-07	3,315E-06	1,6907E-03	-1,0098E-03	0,2221
10 persons without drogue 10% loading	-2,3051E-07	-2,7377E-06	-1,5519E-03	-9,2637E-07	0,26348

TABLE 4 *Coefficients of leeway velocity for the life raft with drogue*

Life raft type and loading	a_8	a_7	a_6	a_5	a_4	a_3	a_2	a_1	a_0
10 persons without drogue 10% loading	-3,77E-15	8,95E-14	4,51E-11	-8,15E-10	-3,06E-07	3,68E-06	1,03E-03	6,19E-03	13,971E-02
10 persons without drogue 10% loading	-2,57E-15	6,11E-14	3,43E-11	-6,18E-10	-2,54E-07	3,06E-06	9,4E-04	-5,64E-03	16,497E-02

leeway diversion form the downwind direction. The drogue fastening position is presented in figure 10 and the drag force is presented in figure 11.

Fig. 10 *life rafft with drogue*

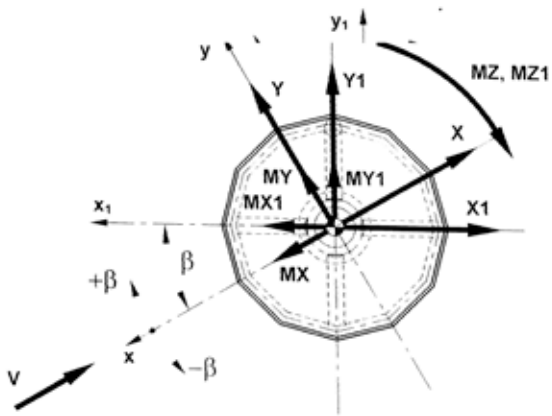


Fig. 11 *Drag force induced by drogue.*

The disturbances which induced the leeway diversion from the downwind direction are as follows:

- Asymmetrical position of the drogue,

$$MZ_D = F_D \cdot y_D \tag{5}$$

- Unequall pressure distribution in the life raft inflation chambers,
- Position of survivors inside the life raft,
- Canopy outline, asymmetrical shape of canopy,
- Shape of underwater body of the life raft.

Conclusions

The investigations conducted at sea and the model tests performed in the wind tunnel allowed to determine the influence of the asymmerical shape of the life raft canopy on the disturbances of life raft leeway velocity and direction. The disturbances have a significant influence on the position and dimensions of the determined search area and the SAR action effectivness.

Acknowledgement

The presented wind tunnel tests were carried out in collaboration with Low Speeds Aerodynamic Laboratory of the Air Force Institute in Warsaw The research was partly conducted according to the research projects No. 4T12C03827 and RDP No. 2288/C.T12-9/98 sponsored by the Polish Ministry of Education and Science.

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Wind effect simulation system in model tests of ship manoeuvrability

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Abstract

Dependence on hydro-meteorological conditions in the test area is an "Achilles' heel" of physical experiment used for assessment of ship manoeuvrability. Aerodynamic forces and moments generated on the ship upperworks distort significantly the measured values. The paper presents new testing tool in the form of physical simulation of wind effect enabling quantitative evaluation of distortion of the measurement results. Another feature of the system enabling compensation of real atmospheric conditions prevailing during the experiment is also presented. The wind effects simulation arrangement includes board data acquisition and processing system, automatic control system and executive system consisting of industrial fans.

Keywords: *ship manoeuvrability, wind, wind effect simulation*

INTRODUCTION

Physical model experiment always entails not only a number of conditions resulting from the laws of modelling, but also some environmental conditions. The ship manoeuvrability cannot be attributed only to the underwater hull, even if the tests are carried out in ideal "no wind" conditions, because there is always a little known effect resulting from neglecting the friction deduction force or aerodynamic effect of apparent wind upon the ship upperworks, the shape of which is a compromise between assumed minimizing and symmetrization of the model surface exposed to the wind, and technical possibility of such realization.

The testing technique presented below, as well as the test equipment designed for this purpose seems to ensure elimination of these undesired effects on the model experiment. Verification of the presented methodology and equipment is based on the mode of operation enabling compensation of the environmental effects on the ship model upperworks. The following scheme of proceeding has been assumed:

- the environmental effect on the ship upperworks will be represented by apparent wind vector,
- compensation of the generated aerodynamic forces and moments will be carried out with use of a set of fans being an integral part of the model upperworks (see Fig. 1).

Fig. 1 *Tested model equipped with a set of fans*

The second mode of testing included simulation of wind effect on virtual model upperworks. In this case the wind was represented by average velocity and function of power spectral density distribution. The upperworks were represented by experimentally found characteristics of a container carrier with full set of containers. In this case the following scheme of proceeding was applied:

- tests were carried out under "no wind" conditions,
- transportation velocity of the set of fans, equal to the model speed, was taken into account in the process of generating the aerodynamic forces and moments.

Input data, necessary for carrying out both operation modes, i.e.:

- model speed and drift angle,
- velocity and angle of relative wind,
- compass course,

came from the board system of data acquisition and processing.

Operation of the fan system was controlled by the control system combined with above-mentioned board system using the library of experimental aerodynamic characteristics of the real and virtual model, as well as control data matrix of the fan motors ensuring proper thrust of the fans.

Aerodynamic data

Wind

Within the confines of the carried out tests, "wind" was assumed as a flat stochastic process represented by turbulent wind velocity and its average angle. In such model the turbulent wind is described by function of power spectral density, by distance from the media parting face, as well as by the harmonic data frequency. Spectral model of wind presented by Ochi&Shina [1] was used in the tests.

Aerodynamic tests

The tests were made in wind tunnel T3 of the Aviation Institute in Warsaw. The following two aerodynamic characteristics of the ship model were used for the tests: (M509 CTO $\lambda = 55$, see Fig. 2A) for the ship with full set of containers, and (M467 CTO $\lambda = 25.7$, see Fig. 2B) used for tests on the lake. Air flow in the layer on the sea surface, velocity distribution, turbulence and boundary layer spectrum were represented during the tests. Reynolds number at the level of $6x10^6$ was used for the tests of M509 model. The upperworks characteristics for M467 model is a compilation of upperworks characteristics in

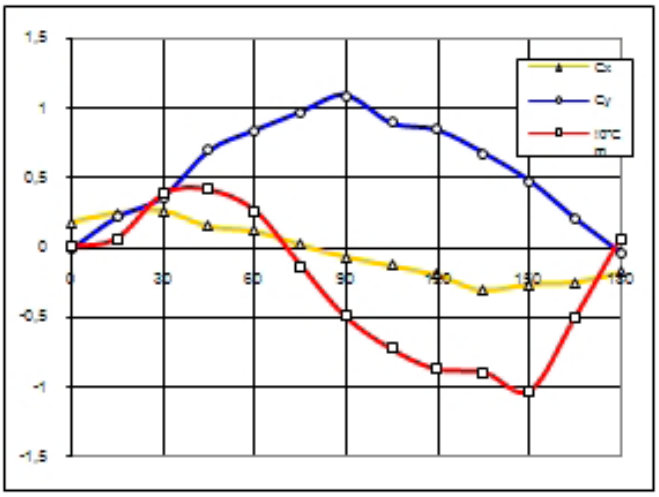

Fig. 2A Aerodynamic characteristics of ship model M509 [2]

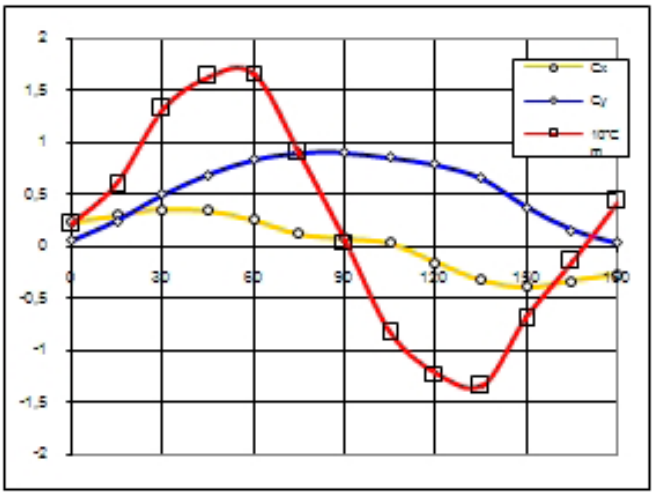

Fig. 2B Aerodynamic characteristics of ship model M467 with the wind simulation system [3]

scale 1:55 for specific freeboard, as well as the characteristics of natural set of fans.

Aerodynamic characteristics of the fan control system were prepared on the basis of the carried out test program, including measuring the fan thrust versus fan rotational speed with simultaneous variation of wind velocity in the tunnel . Within the measuring process in the input function simulation mode, the control system computed the values of signals controlling the operation of fans so that the virtual upperworks were the result of superposition of the following models:

- linear model, based on assumed dimensionless characteristics of the ship upperworks and on dimensionless characteristics of true upperworks of the model with stationary fan executing system,
- non-linear model (taking into account interaction of fans and fan thrust effects on the characteristics of the true upperworks)

Relative heading was measured with an accuracy of 1°. Comparison of assumed characteristics of the model shown in Fig. 3 with the simulation system composed of three fans was considered a proof of correct functioning of the system. Useful results of the tests in the form of matrix of coefficients were saved in microprocessor memory of the control system [4].

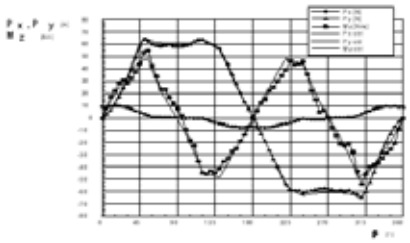

Fig.3 Comparison of assumed characteristics of the ship model in the form of aerodynamic forces Px, Py, Mz (obl), represented by wind simulation system including 3 fans [3]

Board system of data acquisition and processing

The system made by CTO is a combination of standard systems used for supporting ship manoeuvrability tests and of additional systems developed for realization of the present tests. The system includes a subsystem controlling automatically the manoeuvrability tests, pressure directional log, anemometer and special supporting software.

The measurement control system [5] took over the control of the model after a radio signal transmitted by the operator and introducing the model into the start trajectory after getting steady speed and heading of the model. The system enabled recording of the following measured data: model speed, drift angle, model heading, rudder angle, velocity and angle of relative wind. At the same time the system transmitted the data necessary for control of fan simulation system. In the mode of wind effect simulation, the system supported by additional software transmitted expected values of relative wind velocity and angle. These values depended on actual speed and drift of the model, model heading and assumed angle of simulated wind with respect to the resultant heading. Assumed operational frequency of 100 Hz enabled data transmission with the accuracy of heading equal to 0.1 degrees at least.

Pressure log [6] was installed at ¼ of the model length from the model bow. This location and the measuring head lowered to 0.4 m below the model bottom ensured the uncertainty of model speed measurement not exceeding 0.06 m/s, whereas the drift angle uncertainty did not exceed 1.5 degrees for model speed greater than 0.5 m/s and drift angles less than 20 degrees.

Wing anemometer of μAS type, made by Orogenic Institute of the Polish Academy of Sciences, with measuring range 0.2 – 20 m/s ensured an accuracy of 0.5%. The anemometer axis was aligned with the relative wind thanks to a directional fin interconnected with a potentiometer system. The system was statically balanced.

Manoeuvring tests

Scope of tests

The scope of manoeuvrability tests for both modes of operation: compensation and wind effect simulation included standard turning tests, as well as zigzag test [7]. Two angles of simulated and true wind were chosen from the entire compass rose: compatible with and opposite to the model heading during the straight-line phase before the start of the manoeuvre.

Test conditions

The tests were carried out on Lake Wdzydze near the Open Air Test Station of CTO in Joniny. Free running model M467 equipped with a self-propulsion system, as well as with radio controlled manoeuvring and control systems was used for the tests. In order to reduce as far as possible the fan generated heeling moments, the freeboard height was reduced to a minimum value ensuring the model safety with increased metacentric height.

Initial speed 1.85 m/s of the model was assumed. The turning tests were performed with the rudder angle equal to 20°. This value was the maximum acceptable rudder angle because drift angles appearing at rudder angles exceeding 20° caused instability of the pressure log indications. The zigzag tests were made for the rudder angle of 20° and the course change angle of 20°.

Test results

Tests of the true wind effect compensation

Tests of the natural wind compensation effects with the use of this wind simulation system were essential for verification of the correctness of system design assumptions.
The verification of system operation correctness was based on recorded results of manoeuvring tests, when distortion of

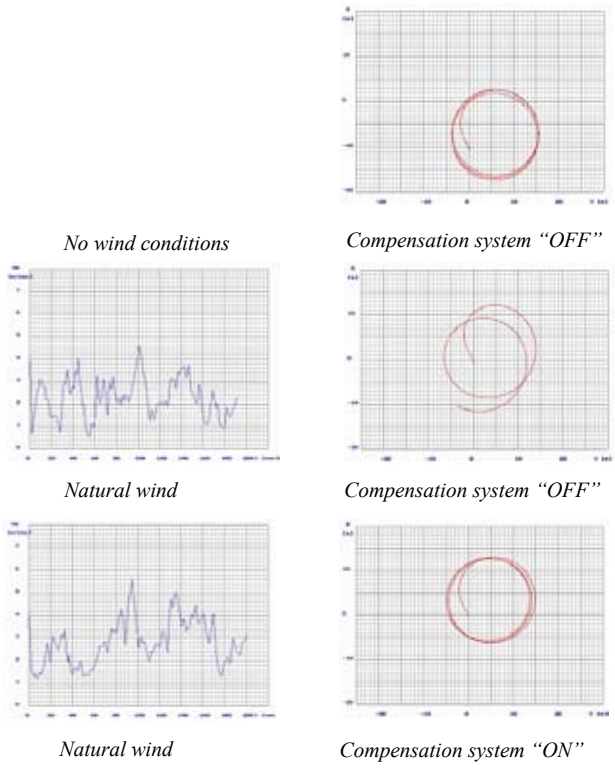

Fig. 4. *Examples of the turning tests*

the model trajectory (in turning test) or changes of heading (in zigzag test) induced by natural wind and compensated by the fan system are insignificant with respect to characteristic parameters of such tests made in "no wind" conditions.
Examples showing functioning of the wind effect compensation system are shown in the form of a record of the turning test trajectory (Fig. 4) and for the zigzag test (Fig. 5).

The presented results show correctness of the proposition assumed during formulation of the scientific project about possibility of the application of additional equipment making the model tests of manoeuvrability independent of the weather conditions.

Tests of simulated inputs

Interesting effect of the simulated wind on the advance (see Fig.6A) and on tactical diameter of circulation (see Fig. 6B) has been shown in a dimensionless form with respect to the values of these parameters for "no wind" conditions. Obvious asymmetry of the changes in these parameters for two different relative angles of simulated wind is a premise for the statement that prediction of the advance on the basis of the mean value may cause 10% error for wind velocity 3 m/s and 15% error for

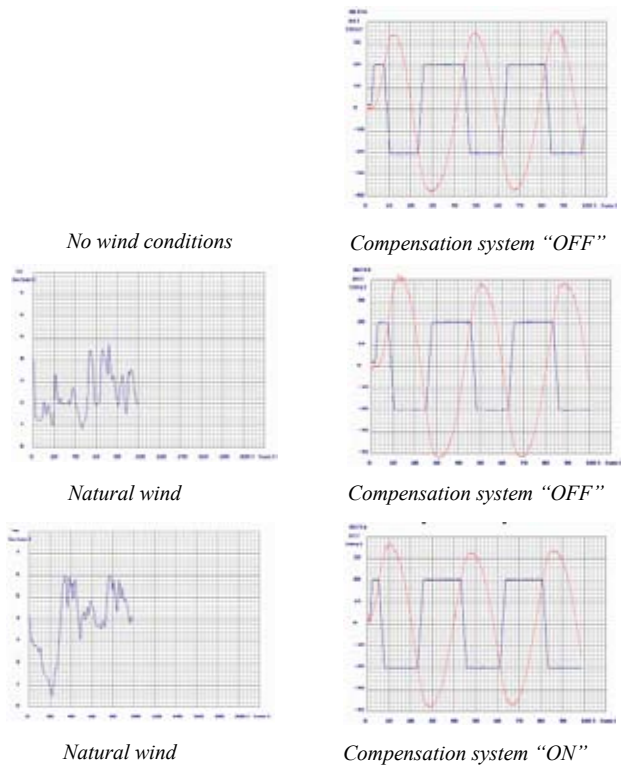

Fig. 5 *Examples of the zigzag tests*

wind velocity 5 m/s. The value of tactical diameter of circulation turned out to be less sensitive to the angle and velocity of the simulated wind and it does not exceed normal dispersion of the measurment results.

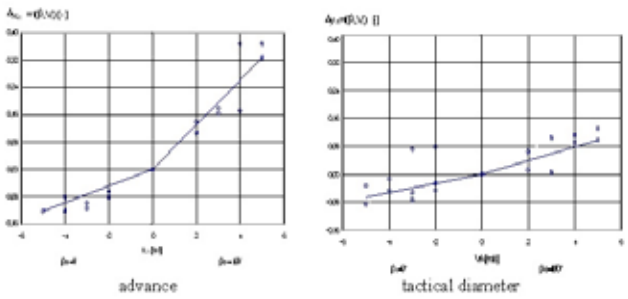

Fig. 6 *Dependence of advance and tactical diameter values on the wind angle and velocity*

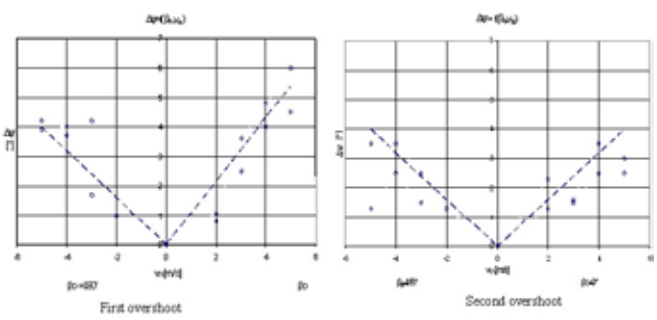

Fig. 7 *Dependence of change of the first and second overshoot angles in zigzag tests on the wind angle and velocity*

The wind velocity and wind angle effect on characteristic parameters of zigzag test is shown in Fig.7. In this case prediction of the overshoots on the basis of the mean value

parameters for two different relative angles of simulated wind does not cause decreasing of measurement errors.

Conclusions

Experiments and test results indicate that:

1. The developed and implemented system of wind simulation can be used without restriction as true wind compensation system and can make up a standard equipment for model tests of ship manoeuvrability.

2. The system, when used for simulation of assumed weather conditions, may be useful in tests aimed at quantitative evaluation of wind effect on chosen manoeuvres.

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Concept of implementation of open water model tests for assessment of safety of ships in damaged condition

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Abstract

The paper presents the preliminary information on the concept of open water model tests for assessment of safety of ships in damaged conditions. The need to develop the concept follows from the fact that the current regulations for assessment of safety of ships in damaged conditions require to consider an influence of many factors coming from different sources. Among the most important factors are those which come from the ship itself and the environment. Of course, the current regulations take into account the impacts which follow from the stages of flooding and progressive flooding but not all the possible impacts are taken into account. The open water model tests may enable to verify the existing regulations and model some phenomena associated with flooding. The open water model tests can be an important alternative method for the assessment of ship safety. The current method and some elements of the new approach to the safety of ships in damaged conditions are briefly described in the paper. A concept of the open water model tests for assessment of the safety of ships in damaged conditions are introduced. Some details regarding the research stand are given. The preliminary programme of investigations is presented as well. Because of the limited space available in the paper more details regarding the concept of open water model tests will be given in the POWER POINT presentation during the Symposium and in the final version of the paper.

Keywords: *assessment of safety, model tests, safety of ships, safety of ships in damaged conditions*

INTRODUCTION

The current requirements regarding the safety of ships in damaged conditions are included in the harmonized SOLAS chapter II-1 parts A, B and B-1 and are still based on the IMO Resolution A.265 (VIII). In comparison with the previous version of SOLAS in these regulations more factors affecting safety of ships in damaged conditions are taken into account. It was possible due to the outcome of HARDER project and extensive work of the IMO SLF Sub-Committee during its 46, 47 and 48 sessions. In May 2005 the IMO Maritime Safety Committee (MSC) approved the revised and harmonized SOLAS chapter II-1 and it will be put into force together with the Explanatory Notes in 2009.

The current regulations are prescriptive in their character and are based on experience. The changes in legislation are difficult to proceed and time consuming. The expectations of the maritime sector are that they will meet new needs and challenges. The current regulations do not enable to meet them and there is no possibility to apply the pro-active approach to safety. Safety still becomes a constraint included in the prescriptive regulations.

The current work on safety of ships in damaged conditions concentrates on development of the Expalantory Notes for the harmonized SOLAS chapter II-1. Although the new SOLAS chapter II-1 is accepted by the IMO MSC Committee there is a necessity to continue the work on modelling the behaviour of ships in damaged conditions because of many reasons. One of them is that using the current regulations the assessment of safety of ships in damaged conditions requires to conduct the computer based calculations of performance of a ship in damaged conditions. The model tests of ships in damaged conditions can be treated as an alternative method and are very usefull for validation purposes when assessment of safety of ships in damaged conditions is done according to the current regulations.

Current method

According to the current SOLAS based regulations the assessment of safety of a ship in damaged conditions is associated with estimation of the subdivision index A value which should be checked against the required subdivision index R value. The design criterion is as follows:

$$A >= R \tag{1}$$

The subdivision index A value should be calculated according to the formula:

$$A=\Sigma pisi \tag{2}$$

where:
- pi - probability of flooding of the group of compartments under consideration;
- si - probability of survival after flooding of the group under consideration.

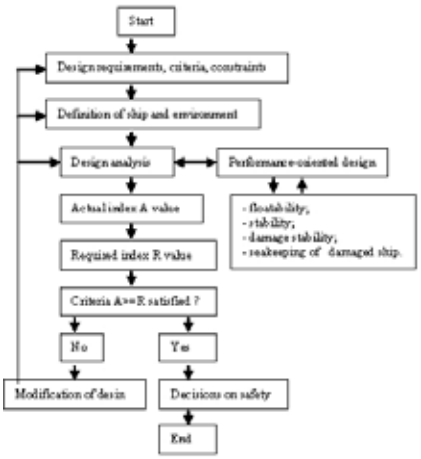

Fig. 1 *logical structure of procedure for assessing the criteria (1) according to the current solas based methodology*

The procedure of estimation of the index A value is associated with conducting the calculations including:

1. floatability;
2. stability;
3. damage stability;
4. dynamical stability of damaged ship;
5. behavuiour of damaged ship in wind and waves (seakeeping of damaged ship).

When predicting the motions of the damaged ships in waves the main contributing factors are as follows:

1. the flooding process;
2. the floodwater effects on the ship motions;
3. mass inertia and hydrodynamic mass effects;
4. potential and viscous damping;
5. restoring effects;
6. wave induced forces.

The performance-oriented design requires assessing the behaviour of a given ship in a given set of environmental and operational scenarios on the basis of her performance in terms of hydromechanical characteristics of a damaged ship in waves. During the design analysis regarding the damaged ship an influence of parameters associated with the hull form, arrangement of internal spaces, loading conditions, position and extent of damage, cargo shift and weather impacts can be taken into account.

The general major parameters associated with estimation of the index A value are the following: hull form, arrangement of internal spaces, loading conditions, position and extension of damage, environment (waves), flooding including the stages of flooding, impacts following from different sources.

The general major parameters associated with estimation of the required index R are as follows: size of ship, number of passengers.

New approach to safety

The new approach to safety is closely associated with the risk-based design. The risk-based design is a formalized design methodology that integrates systematically risk analysis in the design process with the prevention/reduction of risk embedded as a design objective, along the standard design objectives. This methodology applies a holistic approach that links the risk prevention/reduction measures to ship performance and cost by using relevant tools to address ship design and operation. This is a radical shift from the current treatment of safety where safety is a design constraint included within the rules and regulations. The risk-based design offers freedom to the designer to choose and identify optimum solutions to meet safety targets. For the risk-based design safety must be treated as a life cycle issue.

Regarding the current work on safety of ships in damaged conditions conducted at the Chair of Naval Architecture, Faculty of Ocean Engineering and Ship Technology, Gdansk University of Technology it is associated with the development of a method for assessment of safety of ships in damaged conditions which is a performance-oriented risk-based method. Within this method a measure of safety of ships in damaged conditions is either the risk or level of risk.

The risk is defined as follows:

$$R = P * C \tag{3}$$

where:

P – probablity of a hazard occurrence;

C – consequences of a given hazard occurrence.

The risk is estimated using the risk analysis. The risk analysis requires to perform the hazard identification, scenarios development, hazard assessment, risk assessment and risk control.

The risk analysis is combined together with the performance-oriented investigations. It follows from the fact that there is a need to consider all the possible fault trees (sequence of events) to define the hazards, first of all. When the hazards are found, all the possible consequences of an accident should be defined by developing the event trees (another sequence of events). It should be noted that the different consequences may follow from the different hazards or combination of hazards.

Such an approach to ship design and safe operation has been applied for the method presented by the author. Because of the limited space available the particulars of the performance-oriented risk-based method will be omitted in this paper.

Model tests of ships in damaged conditions

Despite all the developments associated with the current regulations regarding the safety of ships in damaged conditions included in the harmonized SOLAS chapter II-1 parts A, B and B-1, there is still a need to apply the model tests of ships in damaged conditions.

The reasons are as follows:

1. model tests of ships in damaged conditions can be treated as an alternative method of safety assessment of ships in damaged conditions;
2. model tests of ships in damaged conditions enable to verify the results obtained using the SOLAS based procedure of estimation of the index A value;
3. model tests of ships in damaged conditions enable to verify the results obtained using the different codes of computer simulation of a ship performance in damaged conditions;
4. model tests of ships in damaged conditions enable to verify and develop the new models for assessment of safety of ships in damaged conditions.

In the early 2004 the 24th ITTC Specialists Committee on Stability in Waves initaiated the study on stability of ships. Between the problems the stability of damaged ships was indicated. The activities were completed at the end of year 2004. The participants of the study were the following:

1. National Technical University of Athens, Ship Design Laboratory, Greece;
2. Ship Stability Research Centre SSRC, Universities of Glasgow and Strathclyde, United Kingdom;
3. Marine Research Institute, MARIN, The Netherlands;
4. Instituto Superior Tecnico IST, Lisbon, Portugal;
5. Korea Research Institute of Ships and Ocean Engineering KRISO, Korea.

The major objectives of the study were as follows:

1. to provide a thorough insight into the fundamental properties of the benchmark numerical methods presented in Table 1;
2. to assess the performance of each numerical method with respect to the available experimental data and the other methods;
3. to assess the overall efficiency of the investigated methods.

The method of study was such that the numerical methods

were assessed by a series of tests of various complexity. The model tests were selected in order to enable to the extent feasible the isolation of the basic component of the problem. The sensitivity of the numerical methods as well as their absolute efficiency were assessed.

Hydrostatic forces by direct pressure integration
Potential strip theory
Potential 3D panel method
Incident wave forces by direct pressure integration
Memory effects
Semi-empirical roll viscous damping
Roll viscous damping analysis in components
Floodwater assumed as a horizontal free surface
Floodwater assumed as moving plane free surface
Internal water motion by shallow water equations
Numerical method
Ship motion degrees of freedom
Flooding by simple hydraulic model

Table 1 *the benchmark methods used during the 24th ittc benchmark study*

The investigations were conducted for the following ships:

1. passenger Ro-Ro ferry (PRR01) of LBP = 170.00 meters (model scale: 1:40);
2. tanker of LBP = 310.20 meters (model scale: 1:82.5);
3. passenger Ro-Ro ferry (PRR01) of LBP = 174.80 meters (model scale: 1:38.25).

The results of study were the following:

1. modelling of the inertia and restoring forces was generally correct;
2. model tests confirmed that the viscous roll damping by semi-empirical coefficients can be usefull;
3. deviations between the results obtained by different numerical methods (Table 1) are caused by the fact that different approaches were used to determine the effect of floodwater on ship motions;
4. there is a necessity to improve the modelling of the flooding process and progressive flooding effects.

Concept of open water model tests of ships in damaged conditions

In Poland, the open water model tests of ships in damaged conditions can be conducted at the Ship Handling Resarch and Training Centre in Ilawa. The objectives of the open water model tests of ships in damaged conditions could be the following:

1. alternative method of safety assessment of ships in damaged conditions;
2. verification of results obtained using the SOLAS based procedure of estimation of the index A value;
3. verification of results obtained using the different codes of computer simulation of a ship performance in damaged conditions;
4. verification and development of new models for assessment of safety of ships in damaged conditions;
5. training of masters, ship officers, naval architects and students.

The logical structure of the risk-based design/operational procedure (method) is introduced in Figure 2. The performance-oriented open water model tests of ships in damaged conditions which can be a part of the entire research activities should cover the following characteristics of ships in damaged conditions:

1. floatability;
2. stability;
3. damage stability;
4. dynamical stability of damaged ship;
5. seakeeping of damaged ship.

The idea of the performance-oriented open water model tests of ships in damaged conditions is based on the following assumptions:

1. all the necessary data regarding the characteristics of the ships used during the tests are generated using the numerical and computer simulation;
2. ship models used during the tests may be as follows:
· struck model (damaged ship);
· striking model;
3. the struck model should always be a full size model;
4. striking model can either be a full size model or a bow-section model;
5. structure of the research stand, equipment and system of indicators involved during the investigations depend on the test variant;
6. the tests should be conducted according to a programme;
7. results of investigations should be worked out and verified using the numerical and computer simulation

Research stand

Fig. 2 *Logical structure of the risk-based design/operational procedure (method).*

The general structure of the research stand is presented in Figure 3.

One of the major characteristics which has to be known to

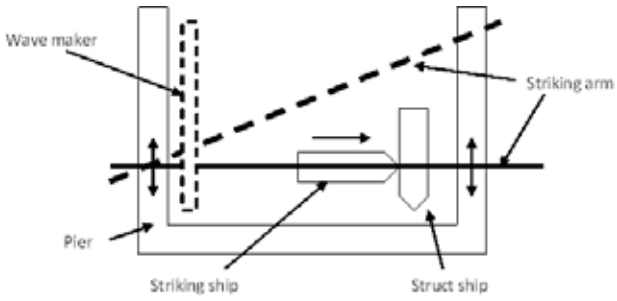

Fig. 3 *General structure of the ship survivability research stand*

determine the energy of the striking ship is the towing force along the striking arm. Using the gravitational dynamometer, the towing force can be calculated according to the formula:

$$F = m\,(dv/dt) + R_T(v) \tag{4}$$

where:
F– towing force;
m – total mass including the mass of model, added mass, mass of weights and mass of inertia of the rotating parts of dynamometer;
R_T– total resistance of model;
v – velocity of model.

Assuming that the total resistance of the model is proporcional to the exponent of velocity:

$$R_T = c_T\ v^2 \tag{5}$$

The formula (3) may be expressed as follows:

$$F = m\,v\,(dv/ds) + c_T\ v^2 \tag{6}$$

where:
s – distance passed by model.

To decrease the distance between the struck and striking models/ships the additional accelerating force has to be implemented according to the formula:

$$F + F_a = m\,v\,(dv/ds_a) + c_T\ v^2 \tag{7}$$

where:
F_a – additional accelerating force;
s_a – distance when the model accelerates.

Solving the formula (7), the distance sa can be estimated.

The general structure of the gravitational type striking arm is presented in Figure 4.

Background for investigations

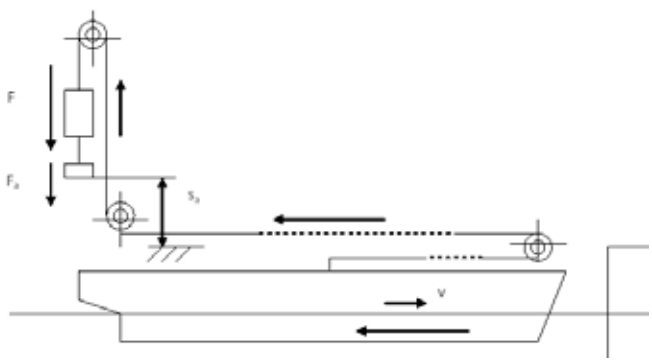

Fig. 4 *General structure of the gravitational type striking arm*

The background of the tests are the risk analysis of collisions, external dynamics of ship collisions, internal mechanics of ship collisions, deterministic and probabilistic analysis of collisions and ship survivability.

During the tests, the model of the ship collision probability can be based on the number of possible ship collisions and can be estimated as follows:

$$P[\text{collision}] = 1 - \exp(-N_{ship\text{-}ship}) \tag{8}$$

where:
Nship-ship – expected number of ship to ship collisions determined as follows:

$$N_{ship\text{-}ship} = P_c\ N_a \tag{9}$$

where:
Pc – the causation probability;
Na – number of possible ship collisions.

The waterway intersection using the definition of collision diameter is taken from Petersen (1995).

The collision risk factors can be divided into three main groups:
1. waterway system including environmental conditions;
2. involved vessels;
3. human factors.

During the tests, the possible consequences of a collision can be as follows:
1. minor damage - economic consequences;
2. severe damage:
3. oil spill – environmental consequences;
4. capsizing – total loss of vessel.

Program of open water model tests of ships in damaged conditions

The behaviour of damaged ships in the calm water conditions have been well investigated according to the damage stability model tests. Such tests enable to determine if a ship would survive or not after flooding of a single watertight compartment or group of adjacent watertight compartments according to its reserve buoyancy, draft and trim and damage stability characteristics.

Predicting the behaviour of damaged ships in rough seas is much more difficult than in the calm water conditions. It follows from the fact that there are a few factors affecting the motion of a damaged ship in waves.

They are as follows:
1. ingress/egress of external water into and out of the damaged compartment or group of compartments under consideration;
2. impact of air cushions;
3. impact of heeling moments from different sources (cargo shift, launching the life saving appliances, passengers behaviour, etc.).

The program of the open water model tests of dynamics of damaged ships should consist of the following tests:

1. intact model tests;
2. investigations of influence of the position (longitudinal, vertical) and extent (shape) of damage on rolling / sway / heave motions;
3. investigations of influence of the quantity of water in damaged compartment on rolling/sway/heave motions;
4. investigations of influence of the quantity of water in damaged compartment under the deck (perforated deck) on rolling/sway/heave motions;
5. investigations of influence of the initial angle of heel due to asymmetric loading on rolling/sway/heave motions during flooding;
6. investigations of influence of the leeward (windward) side, when damage is sealed, on rolling/sway/heave motions;
7. investigations of influence of the bottom damage on rolling/sway/heave motions.

	Stage 1	Stage 2	Stage 3	Stage 4
wind heeling moment	X	X	X	X
action of waves	X	X	X	X
ballast/cargo shift			X	X
Crowding of people		X	X	X
launching life saving aids		X	X	
air-flow bags action			X	X

Table 2 *an example matrix of events during flooding*

Research problems for further investigations

There are many problems included in the regulations which require further development as either the short or long term actions.
Among the problems are the following:

1. intermediate stages of flooding;
2. equalization after flooding;
3. water on deck and progressive flooding;
4. impact of air cushions;
5. impact of the heeling moments due to the cargo shift, passengers behaviour or lauching of the life saving appliances.

When predicting the motions of the damaged ships in waves, the main contributing factors are the following:

1. the flooding process;
2. the floodwater effects on the ship motions;
3. mass inertia and hydrodynamic mass effects;
4. potential and viscous damping;
5. restoring effects;
6. wave induced forces;

Evaluating the performance of numerical methods it can be underlined that regarding the free roll decay of the damaged ship the key results are non-satisfactory. The same applies to the damaged ship motions taking into account the regular (large) wave excitations.

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Open water manoeuvring model tests at the Joniny Test Station, Ship Hydromechanics Division, CTO S.A.

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Abstract

Although the role of computational methods (CFD) in prediction of the hydromechanic qualities of ships grows rapidly, the role of the physical experiment is still very important (if not principal). Concerning the experimental investigations focused on manoeuvring abilities of ships, there are two main approaches to be applied: open water model tests and captive model tests (Planar Motion Mechanism). The paper contains some basic information concerning the first of mentioned methods including the evolution of the measuring techniques, applied equipment and methodology. These changes result not only from technological progress, but also reflect different expectations of our Clients. In the case of mentioned open water manoeuvring model test, its specific character determines a little bit different approach, which combines some strictly scientific objectives, i.e. prediction of the manoeuvring abilities, with commercially attractive and direct demonstration of the results. Thus, in parallel with description of the measuring systems used during the tests (starting from mechanical/optical torograph system to modern laser tachimeter system), evolution of the visualization systems is also presented. In addition, some future trends in the development of the open water tests station in Joniny has been described including experimental work as well as basic/auxiliary equipment.

Keywords: *free sailing model tests, manoeuvring abilities of the ship, manoeuvring tests, model tests*

Figure 1 *That is how it started – preparations for the free sailing model tests in the early seventies*

Foundation of the test station Joniny

The open water test station in Joniny was founded in the early seventies as a part of the Ship Model Basin, Ship Design and Research Centre (Centrum Techniki Okrętowej). In fact the origin of the facility should be dated a little bit earlier, in the sixties – then surroundings of the Wdzydze Lake located about 70-80 kilometres from Gdańsk (see Figure 3) had been chosen as the reserve localization of shipyards' design offices and in parallel first model tests at this localization were carried out (including some experiments with remotely controlled models). Finally, when both design offices (COKBPO and CBKO 2) had joined together into CTO, all experience and equipment was transferred to the newly born organization

Figure 2 *First model tests carried out with assisting auxiliary vessel*

Figure 3 *Localization of the joniny test station (for details of the localization - see www.Pilot.Pl)*

At the early beginnings mainly resistance and self propulsion tests were carried out on the lake – they were carried out by means of an auxiliary vessel (built as a catamaran) which followed the model; and the same idea was originally used for first manoeuvring tests, model was followed by the catamaran equipped with measuring apparatus. But the real impulse for serious manoeuvring investigations was given shortly after the commissioning of the m/s 'Profesor Siedlecki', research

vessel built for Sea Fisheries Institute in Gdynia; due to her poor directional stability it was decided to start intense programme of manoeuvring investigations prepared on the basis of model tests, which were also validated on the real ship. Thus open water test station was activated in the actual form and methodology of model tests carried out by means of remotely controlled models was developed.

Free sailing model tests – advantages and disadvantages

In fact, at the early stage of design, ships are usually not designed and optimised from the point of view of manoeuvring abilities. These abilities are somehow inherited from (for example) resistance/self-propulsion optimisation - thus manoeuvring investigations are realized as the last stage of the programme and they might be considered rather as validation of ships' manoeuvring performance. There are some options for experimental investigations of manoeuvring abilities, e.g. captive model tests, carried out by means of rotating arm or PMM (Planar Motion Mechanism) – this methodology was developed especially for tests in model basins; optionally manoeuvring performance of a ship can be verified on the basis of free running model tests – carried out in special tanks or natural water areas. The last approach has been applied in CTO. What is the advantage of this solution? Unrestricted deep water area, which allows to use the hull models manufactured originally for the resistance/propulsion/sea-keeping tests; application of larger models (6-10m in length and 1.5-3 tons of displacement) reduces the scale effect and makes the model less sensitive to the weather conditions. On the other hand we still strongly depend on the weather conditions: global (we are not able to carry out our model tests during the winter and early spring) and local ones (when the model tests are stopped due to the

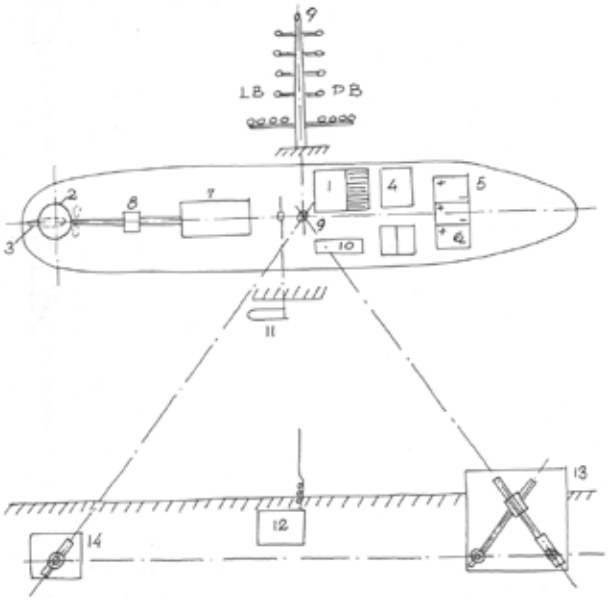

Figure 4 *Description of equipment used for manoeuvring model tests, in the second half of the seventies: radio set with transducers (1), steering engine with the indicator of the rudder position and dynamometer for measurement of the rudder stock moment (2), rudder (3), 5-channel recorder (4), battery of accumulators (5), battery amplifiers (6), driving motor with gear (7), propeller revolution counter (8), mast with signalling system (9), revolution controller (10), leeway (drift) angle indicator (11), 10-channel radio transmitter (12), trajectory recorder with recording desk (13), trajectory recorder with selsyn transmitter (14)*

heavy rains or winds). There is also another important profit coming from free sailing model tests – purely commercial one: the Client can observe the model directly during some typical

Figure 5 *Equipment used during free sailing manoeuvring model tests at the present time*

manoeuvres (specified set of measurements contains usually tests defined in IMO Regulations); thus it gives the general impression about the ship's performance (not only manoeuvring abilities but also about the generated wave system, etc.).

Equipment used for the manoeuvring model tests and its evolution

Systems used during the tests can be divided into the following groups (see also Figures 4 and 5):

- propulsion system (including diesel generator, electric engine(s), shafts, transmission gears, etc. and appropriate stock model propeller(s));
- steering systems (including appropriate rudder(s), steering gear with integrated rudder angle meter);
- measuring systems (including controllers, course-gyroscope, rudder-meter and separate system for recording the trajectory of the model) with associated data collecting system;
- radio control unit with programmable manoeuver controller;
- auxiliary systems for transporting, storing and launching the model.

Although applied systems have been changed many times since the open water test station was founded, this general description is still valid – the configuration of the equipment used during the model tests in the second half of the seventies is presented in Figure 4, while the sketch of actual configuration is given in Figure 5. In the following subchapters some details concerning components of the mentioned subsystems will be shortly described (including its evolution).

Propulsion system

At the early beginnings the system was composed of an electric engine powered by diesel generator located at the auxiliary vessel; power was transferred via cables by means of the special extension arm (as shown in Figure 2). In fact, this solution (with auxiliary vessel following the model) was troublesome because of limitations caused by extension arm; it also required a synchronisation between operator of the auxiliary vessel and the operator of the extension arm.

Therefore, the mentioned system has been modified into the current version of fully independent free sailing model equipped

Figure 6 *Model during the manoeuvring tests, Joniny, in the second half of the seventies*

with the electric engine and power generator located on the model (initially, three batteries of accumulators were used instead of the power generator). Other components are the same as for the self-propulsion or sea-keeping tests – it means system of shaft(s) and propeller(s). The actual parameters of the electric engine are adjusted by means of additional controller; orders are given by the model operator from the radio-console.

Steering system

The model is equipped with a rudder unit (steering engine with dynamometer allowing optional measurements of the rudder stock moment); all steering engines were designed and manufactured in the Ship Hydromechanics Division – starting from the first of the electric-mechanical type up to the last generation built on the basis of servo-mechanism system. In the seventies the model was also equipped with the special rudder position indicator for optical signalisation of the actual rudder and heading angle – it consisted of a set of lamps located on the mast (mounted on the model as shown in Figures 4 and 6). Application of the new programmable Graupner controller has made this system redundant.

Radio control unit with programmable manoeuver controller

Originally, a 10-channel analogue radio-controller (Graupner) for remote control of models (and their systems) was used; later it has been replaced by a new programmable 24-channel controller of the same producer.

Measuring systems

The following values are measured during the tests:

- rudder angle;
- heading angle, turning rate, heel angle;
- position of the model (trajectory);
- rudder stock moment (optionally).

Other values (as speed, drift angles, etc.) are calculated, on the basis of the registered values, directly during the tests. The number of propeller revolutions is derived from the number of impulses from a signal generator installed on the propeller shaft and it is calibrated during the 'measured mile'; rudder angular velocity is set before the tests by means of controller. In fact registration of the measured signals is divided into two independent groups; trajectory of the model is registered independently of the rest and then synchronized. The general schema of the measuring system is given in Figure 7.

At the beginning the rudder angle was measured using two potentiometers mounted on the steering engine, which were connected with a 2-channel amplifier and pen-plotter; similar data acquisition systems were used for registration of the heading angle, while signal was transferred from the air gyro-compass. Both of them were supported (visualized) by mentioned indicator for optical signalisation of the rudder/heading angle. This system was upgraded in parallel with the rudder unit; then first PC computers were applied for registration of the signal (via AD converter cards) - in the nineties rudder and heading angle were recorded on a PC installed on the model. Finally the systems of wireless modems have been applied; thus all data are stored on the same computer and it is possible to observe and assess the registered signal directly during the run.

The trajectory of the model was registered by means of special model trajectory recorder designed and manufactured in CTO, which consisted of two optical viewfinders coupled together with two plotting arms (one mechanically and another one by means of selsyn arrangement, which made the arm follow the finder – see also Figures 4 and 8). During the tests, operators of the viewfinders were constantly following the model's mast; the model's path was visualized by means of a pen-plotter. This system was quite effective, but large group of people were necessary for its functioning; thus it has been

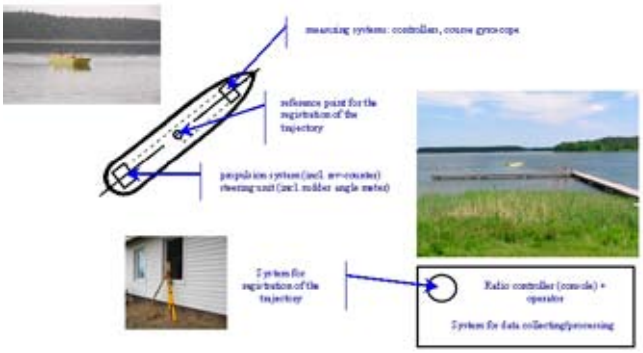

Figure 7 *General diagram of measuring equipment used for free sailing manoeuvring model tests*

improved in the second half of the eighties with additional potentiometers (instead of previous visualization tool) coupled via AD converter to a PC equipped with dedicated home made software. Finally, this system had been phased out a few years ago, when the new GPS system was started. Initially, the model was equipped with additional PC for independent registration of the trajectory signal from GPS; results from both on-board computers were transferred after the test to the data processing computer for synchronization and further analyses. Finally, two years ago a new system built on the basis of optical-laser tachimeter system was started and this solution is used at the present time. Remotely operated tachimeter device follows the

Figure 8 *Model during the turning test, joniny station, in the second half of the seventies*

position of the tachimeter's prism body located on the model (position of the centre of gravity); data are transferred directly to the data collecting/processing computer at the coastal station, for synchronization and further analyses, by means of wireless modems. This system allows the assessment of the correctness of model tests at the early stage, for example during the approach to the zig-zag tests; thus it can be stopped and repeated immediately, if necessary.

Application of the optical trajectory recorders restricted possible test area to the close neighbourhood of the viewfinder stations; moreover obtained results depended strongly on skills of the viewfinders' operators. GPS system was much more precise, while the test area was limited to the range of the differentional station (approx. 300 meters). Actual tachimeter system is limited only by the visibility of the tachimeter device and the tachimeter's prism body located on the model.

Figure 9 *Model of the ship (m/s "Profesor Siedlecki") positioned on the launching carriage*

If necessary, additional signals (up to 16 values) can be registered - for example, forces generated on the propulsors (for podded vessels), then the model is equipped with sets of extensometer blocks.

Auxiliary systems for transporting, storing and launching the model

In general the similar system containing the hangar, small crane with associated carriage and railways is used since the early 1970s for storing, transporting and launching the model; meantime its components have been modernised.

Preparation for the tests, scope of the tests

Model preparation for manoeuvrability model tests covers the following points (activities):

- equipment of the model;
- weighing and dynamic balancing of the model before the tests;
- preparation of the test station;
- transportation of the model to/from the Joniny Test Station.

Before the tests, model is equipped with all systems described in the previous chapters, then it is balanced both – statically and dynamically for proper location of the centre of gravity and appropriate moment of inertia.

During the tests, model is equipped with all appendages including the bilge keels. If the designed propeller is not applied (due to high risk of damaging the propeller during the tests), a stock propeller is selected; in fact set of stock propellers designed especially for manoeuvring model tests have been manufactured at workshops of the Ship Hydromechanics Division.

The manoeuvring model tests are carried out in deep, unrestricted water and at calm weather conditions with the range of parameters (load conditions, approach speed, etc.) specified in accordance with the Customer's request. Appropriate set of tests is preceded by the set of runs on 'measured mile' to calibrate the speed and adjust settings of the main engine controller. The model tests are carried out by means of automatic pilot devices. All signals are registered and synchronized directly during the tests; thus operator of the data acquisition system is able to assess the correctness of the test at its early stage.

In order to verify the manoeuvring properties of the vessel, a typical set of model tests according to the IMO Standards is usually proposed – it consists of:

- turning tests;
- zig-zag tests (20º/20º and 10º/10º);
- direct spiral test;
- stopping tests (inertial, crash-stop).

If requested, some additional manoeuvring model tests can be carried out as:

- modified zig-zag tests;
- reverse spiral test;
- pull-out test;
- special tests (other specified manoeuvres, measurements of additional quantities).

As it was mentioned, first manoeuvring model tests were carried out using additional auxiliary vessel; first 'real' free sailing model tests were controlled manually on the basis of indication given by a system of lights mounted on the mast. Newer generation of equipment enabled to automate the measurements – starting from the course recorder coupled together with the automatic rudder change arrangement; this way zig-zag and spiral tests were carried out, but turning tests and stopping tests were still realized manually. Application of the GPS system and registration of the results on two independent PC units enabled full automation of the tests including further synchronisation of data; then application of the new tachimeter system with system of wireless modems and dedicated home made software has made possible constant observation of the model during the tests.

Although construction of the special manoeuvring tank was planned in the late seventies, successful implementation of the described methodology suspended that tendency; at the present times model tests carried out at the Joniny Test Station seem to be an effective tool for fast and commercially attractive assessments of ship's manoeuvring abilities. In the near future further development of the auxiliary tools is considered including improvement of the dedicated software (allowing to correct the obtained results for actual weather conditions).

Figure 10 *Model during the manoeuvring tests at the present times*

Shape coefficient in the inland vessel resistance prediction

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Abstract

In recalculation of a model resistance into a real object resistance, one of difficult to estimate values is the shape coefficient. There are well known and tested methods of determining the (1+ko) coefficient for sea-going ships. In the case of inland vessels navigating in the limited depth waterways the problem has not been solved completely. The paper presents results of computations of the inland vessel shape coefficient determined by means of numerical methods (MOS). The shape coefficient has been calculated as a function of the block coefficient and block coefficient of the forebody of a barge hull. The calculations were based on five typical shapes of the transport inland vessels and were carried out for different depth to draught (h/T) ratios and different sailing speeds.

Keywords: *shape, ships, inland vessel, resistance prediction, MOS*

INTRODUCTION.

In predicting the ship resistance, the viscous resistance component is determined as resistance of an equivalent flat plate. The specific flat plate frictional resistance is most often determined from the ITTC 57 expression:

$$c_{FO} = \frac{0,075}{\left(\log_{10} Re - 2\right)^2} \tag{1}$$

In order to allow for a space body form of ship, the shape coefficient has been introduced. The form of shape coefficient is given in expression (2):

$$\left(1 + k_0\right) = \frac{c_V}{c_{FO}} \tag{2}$$

The coefficient is a ratio of the hull viscous frictional resistance to the flat plate viscous resistance.

Expression (2) cannot be used for resistance calculations by the classical Froude method as model tests do not allow to subdivide the total force into the normal and tangent resistance components. In practice, formulae are used for the shape coefficient as a function of the hull geometric characteristics. Expression (2) may be used in the CFD numerical methods.

The shape coefficients for resistance calculations in deep water are given by the formulae:

$$k_0 = 18,7 \cdot \left(C_B \frac{B}{L_W}\right)^2 \tag{3}$$

$$k_0 = 0.017 + 20 \frac{C_B}{\left(\frac{L_W}{B}\right)^2 \sqrt{\frac{B}{T}}} \tag{4}$$

The shallow water shape coefficient $\left(1 + k_0\right)$ is taken from Table 1:

Table 1*. Dependence of the shape coefficient on h/T*

h/T	$1+k_0$
>3,0	1,12
2,0	1,24
1,5	1,32

Proceedings of the 23rd ITTC [1] recommend determination of the shape coefficient from:

$$k_{0h} = k_{0\infty} + 0.644\left(\frac{T}{h}\right)^{1.72} \tag{5}$$

During recalculation of the model resistance force into the real object resistance in a restricted waterway, the use of shape coefficients may lead to negative values of the residuary resistance [2].

Numerical calculations, results.

In order to test the influence of shape coefficient in shallow water on the total resistance, flow around the OBM shape with different forebodies was analysed (Fig. 1). A barge of a constant length and the same shape of middlebody and afterbody was used. The analysis was carried out for the draught T =1.6 m and two waterway depths: h =2.0 m and h =2.5 m.

The FLUENT system computations gave the total resistance force and its resolution into a normal and a tangent to the hull surface component. From that the shape coefficient was determined in accordance with formula (2), where c_V was found from

the viscous (tangent) resistance values calculated in the FLUENT system and c_{FO} from (1). Additionally, for comparison, the shape coefficient values were calculated from formulae (3), (4), (5)+(3) and (5)+(4). The shape coefficient (2) depends on the sailing speed and the other formulae make the shape coefficient dependent on the ship hull geometric parameters. The computation results are presented in Tables 2 and 3. Additionally calculations were carried out for two model scales: 1:8 and 1:24. The shape coefficient as described by (2) increases with the increasing sailing speed. It may also be noticed that the shape coefficient increases with model size (decreasing model scale). The shape coefficient (2) variation range is large, equal 1.31 to 0.44 for h = 2.0 m and 1.28 to 0.58 for h = 2.5 m. The main shape parameter in the case of the change of forebody is the block coefficient. It may be assumed that the shape coefficient depends only on the block coefficient of the forebody. When the block coefficient increases, the shape coefficient value decreases.

The shape coefficient increases with the waterway depth h at a constant ship draught T and the increase is greater for greater block coefficient values, e.g. the PION shape, and for smaller block coefficient values, e.g. the PODC shape, it is practically constant or even decreases slightly.

The difference between the shape coefficient extreme values calculated from formulae (4) and (5)+(3) (Table 2) for h = 2.0 m is 47-49% and for h = 2.5 m (Table 3) is 35-37%.

The shape coefficient in Tables 2 and 3 is shown from the smallest to the greatest value acc. to (1). Such order coincides with the shape resistance quality from the best to the worst. The smallest resistance value was obtained from the PODC and OBM shapes and the greatest value from the PION shape. Fig. 2 and Fig. 3 present the total resistance of a model in relation to the total resistance of the OBM model. The OBM shape had the best resistance quality. The results are shown for the 1:8 scale.

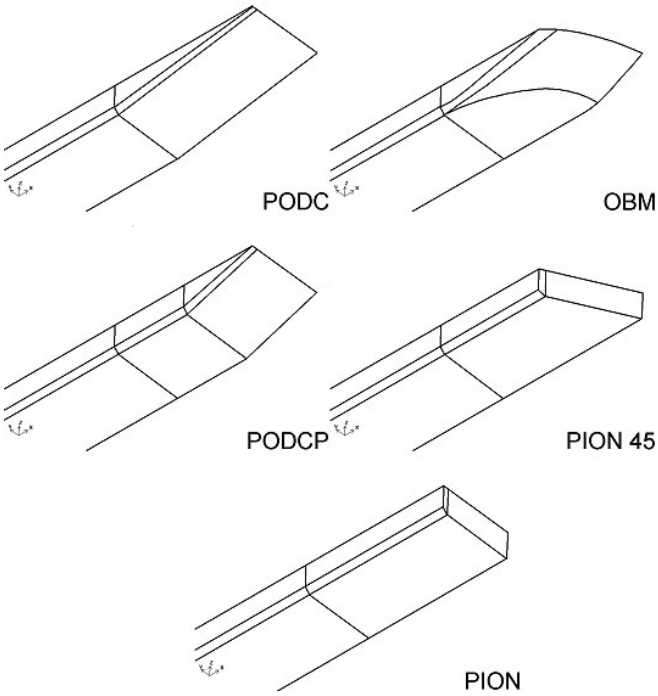

Fig. 1. *OBM with different forebodies*

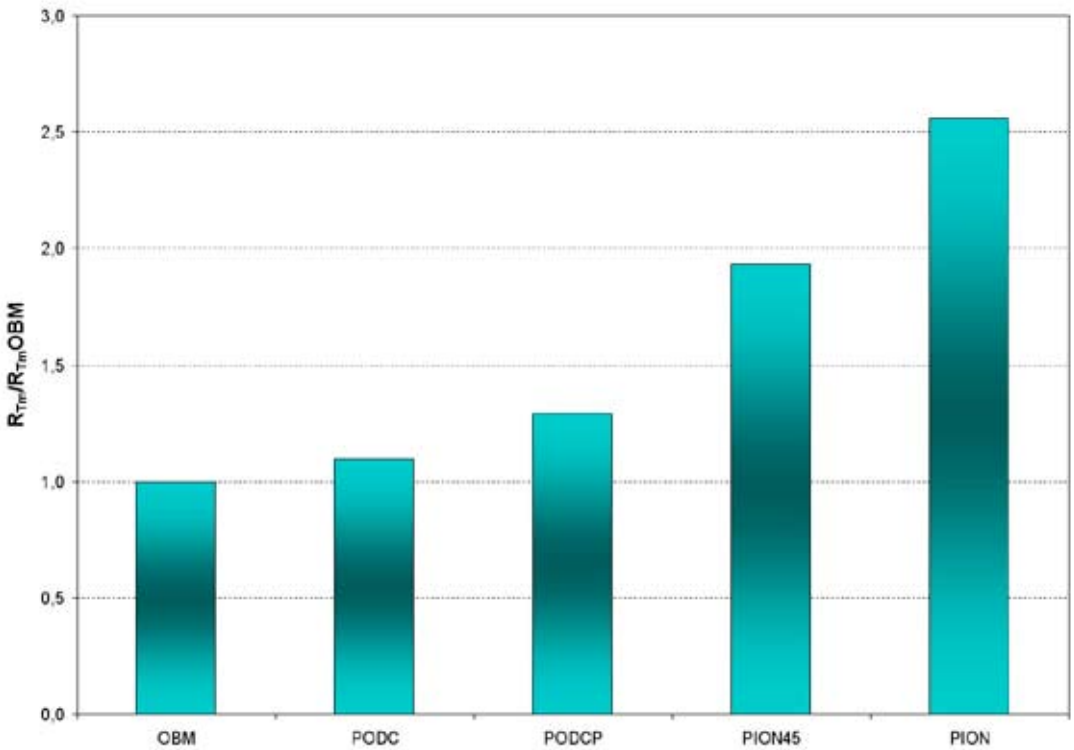

Fig. 2. *Change of the total resistance for the OBM shape with different forebodies. h=2.0 m, T=1.6 m, scale 1:8, Vm=0.491 m/s*

The shape resistance calculations were carried out and shape coefficients determined for the OBM, SFKO, Z1-Z4, B_170, Duisburg [2] barges. From the shape coefficients (2) a "map" of relations with the block coefficient of the forebody CB_D (Fig. 4) and the hull block coefficient CB (Fig. 5) was drawn. All the shape coefficient values for all the analysed shapes with different draught, waterway depth and sailing speed were plotted on the diagrams. Values for different shapes are marked differently. The

***Table 2**. Shape coefficients for OBM – forebodies h =2.0 m and T =1.6 m*

PODC						CB=0,858	CB_D=0,912
scale	V	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$
	m/s	(2)	(3)	(4)	(5)+(3)	(5)+(4)	Tab. 1
8	0,491	1,29	1,24	1,14	1,68	1,58	1,41
24	0,284	1,22					
8	0,687	1,3					
24	0,397	1,25					
8	0,884	1,31					
24	0,51	1,26					
OBM						CB=0,878	CB_D=0,937
scale	V	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$
	m/s	(2)	(3)	(4)	(5)+(3)	(5)+(4)	Tab. 1
8	0,491	1,28	1,25	1,15	1,69	1,58	1,41
24	0,284	1,2					
8	0,687	1,29					
24	0,397	1,23					
8	0,884	1,31					
24	0,51	1,25					
PODCP						CB=0,890	CB_D=0,953
scale	V	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$
	m/s	(2)	(3)	(4)	(5)+(3)	(5)+(4)	Tab. 1
8	0,491	1,19	1,26	1,15	1,69	1,59	1,41
24	0,284	1,14					
8	0,687	1,2					
24	0,397	1,16					
8	0,884	1,21					
24	0,51	1,17					
PION45						CB=0,904	CB_D=0,970
scale	V	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$
	m/s	(2)	(3)	(4)	(5)+(3)	(5)+(4)	Tab. 1
8	0,491	0,73	1,26	1,15	1,7	1,59	1,41
24	0,284	0,7					
8	0,687	0,74					
24	0,397	0,72					
8	0,884	0,74					
24	0,51	0,73					
PION						CB=0,923	CB_D=0,993
scale	V	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$
	m/s	(2)	(3)	(4)	(5)+(3)	(5)+(4)	Tab. 1
8	0,491	0,44	1,28	1,15	1,71	1,59	1,41
24	0,284	0,46					
8	0,687	0,45					
24	0,397	0,46					
8	0,884	0,45					
24	0,51	0,46					

Fig. 4 diagram may be divided into three areas. For the block coefficient value up to 0.96 the shape coefficient is greater than 1, for the block coefficient in the 0.96 to 0.985 range the shape coefficient is greater or less than 1 and for the block coefficient above 0.985 the shape coefficient is less than 1.

The whole diagram has a clear direction. In general, when the block coefficient increases the shape coefficient decreases. When the block coefficient decreases the shape coefficient should approach the value 1, which it will reach with CB = 0, i.e. for a flat plate.

Fig. 5 presents the same results but as a function of the hull block coefficient. Two areas may be distinguished here by the hull shape. OBM and BM Duisburg are motor barges, the other are pushed barges. The diagram shows that not only the forebody

Table 3. *Shape for OBM – forebodies h =2.5 m and T =1.6 m*

PODC						CB=0,858	CB_D=0,912
scale	V	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$
	m/s	(2)	(3)	(4)	(5)+(3)	(5)+(4)	Tab. 1
8	0,491	1,27	1,24	1,14	1,54	1,44	1,31
24	0,284	1,23					
8	0,687	1,28					
24	0,397	1,25					
8	0,884	1,28					
24	0,51	1,26					
OBM						CB=0,878	CB_D=0,937
scale	V	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$
	m/s	(2)	(3)	(4)	(5)+(3)	(5)+(4)	Tab. 1
8	0,491	1,26	1,25	1,15	1,55	1,44	1,31
24	0,284	1,23					
8	0,687	1,27					
24	0,397	1,24					
8	0,884	1,28					
24	0,51	1,25					
PODCP						CB=0,890	CB_D=0,953
scale	V	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$
	m/s	(2)	(3)	(4)	(5)+(3)	(5)+(4)	Tab. 1
8	0,491	1,22	1,26	1,15	1,55	1,45	1,31
24	0,284	1,2					
8	0,687	1,23					
24	0,397	1,21					
8	0,884	1,24					
24	0,51	1,22					
PION45						CB=0,904	CB_D=0,970
scale	V	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$
	m/s	(2)	(3)	(4)	(5)+(3)	(5)+(4)	Tab. 1
8	0,491	0,83	1,26	1,15	1,56	1,45	1,31
24	0,284	0,84					
8	0,687	0,84					
24	0,397	0,86					
8	0,884	0,85					
24	0,51	0,87					
PION						CB=0,923	CB_D=0,993
scale	V	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$	$1+k_0$
	m/s	(2)	(3)	(4)	(5)+(3)	(5)+(4)	Tab. 1
8	0,491	0,58	1,28	1,15	1,57	1,45	1,31
24	0,284	0,59					
8	0,687	0,58					
24	0,397	0,59					
8	0,884	0,58					
24	0,51	0,6					

but also the afterbody shape is important.

The presented shape coefficient "map" shows that the coefficient value may be below one. The classical methods of the coefficient determination will not yield such a value. The use of expression (2) is difficult as it is possible only when the total resistance force is divided into the viscous resistance and normal resistance, which is not achieved in the classical model tests. The above presented results should not be treated as precise, but only as a tendency of the shape coefficient changes as a function of the block coefficient.

The diagrams do not show the shape coefficient as a function of the h/T ratio as the respective results are not unequivocal.

Summary.

- Value of the shape coefficient decreases with the increase of block coefficient and may assume a less than 1 value. These results are significantly different from those obtained from the currently used expressions.
- The value of shape coefficient according to definition (1) depends on the sailing speed, which is not allowed for in the classical empirical formulae. The shape coefficient acc. to (2) increases with the increased sailing speed.
- The greater the shape coefficient value the better the barge shape in terms of resistance (Fig. 2) and (Fig. 3).
- The shape coefficient value increases with the model size (decreasing model scale).
- Relation of the shape coefficient and the h/T ratio for different barge shapes is not unequivocal.

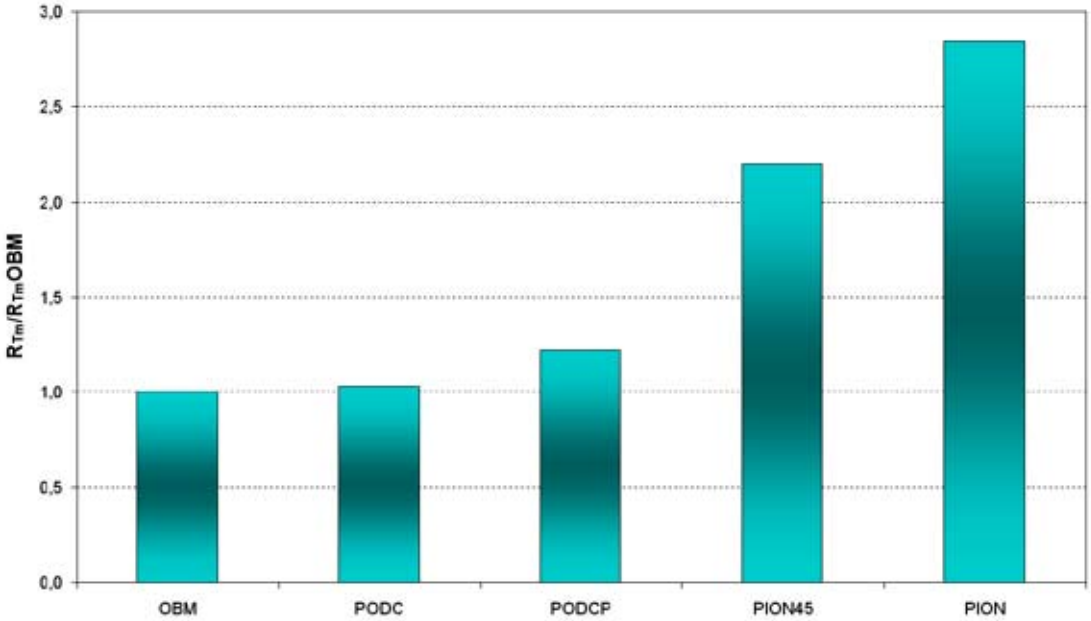

Fig. 3. *Change of the total resistance for OBM with different forebodies. h=2.5 m, T=1.6 m, scale 1:8, Vm=0.491 m/s*

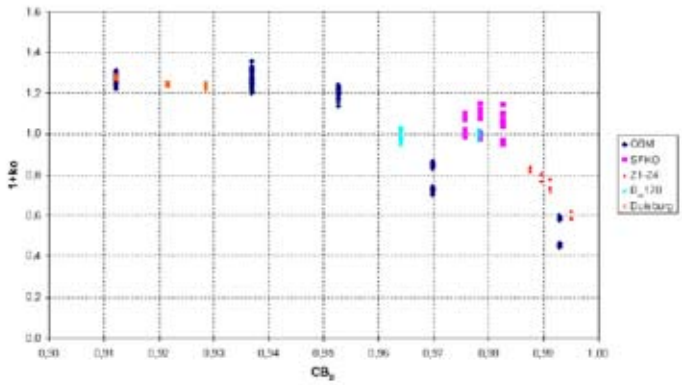

Fig. 4. *The shape coefficient as a function of the forebody block coefficient CBD*

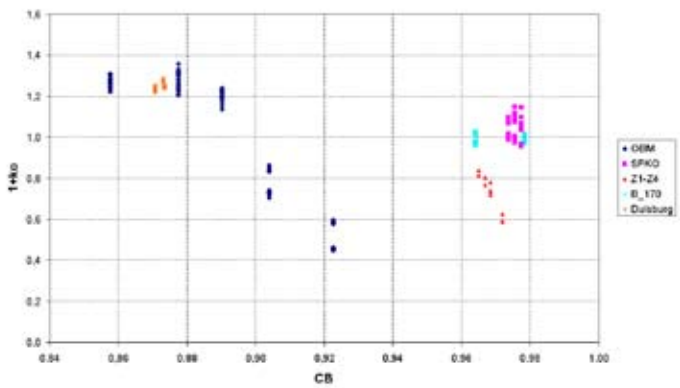

Fig. 5. *The shape coefficient as a function of the hull block coefficient CB*

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NOMENCLATURE:

$1+k_0$ – shape coefficient
c_v – specific viscous frictional resistance
c_{FO} - specific flat plate frictional resistance
c_B – block coefficient
c_{BD} – block coefficient of the forebody
B – ship breadth
L_W – ship length on waterline
T – ship draught
h – depth of waterway

The analysis of hydrodynamic forces and shape of towrope for an underwater vehicle

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Abstract

The paper presents a method of calculating forces in an underwater vehicle towrope as well as its shape under the influence of hydrodynamic forces induced by water flowing round the towrope and vehicle. The rope hydrodynamic loads are calculated from the Morison's equation and the vehicle forces and moments by means of coefficients. An example of calculations for a vehicle has been performed in the Matlab system for one towing speed.

Keywords: *underwater vehicle, towrope, calculating forces*

INTRODUCTION

Ropes and their sets used in the ocean engineering require calculations of shapes and loads. They are characterized by a significant sag, different than in the land applications. The traditional applications in the maritime economy are fishing industry and sea ports. Discoveries of the energy resources under the sea bottom and the inexhaustible quantities of rare metals on the ocean bed have increased the use of ropes in the exploration and production of raw materials.

The main cause of the intensity of forces generated on the sea ropes is considerable difference between the density of water and air. The product of density and motion velocity of those media is equal, respectively:

- for sea water and sea current of a 1-3 m/s velocity → ρv ϵ {1000, 3000} [N/(m3s)];
- for air of 10-50 m/s velocities → ρv ϵ {10, 60} [N/(m3s)].

Taking into account that the hydro- and aero-dynamic forces depend on the second power of medium flow velocity and that the diameter of sea ropes is an order of magnitude greater, it appears that the ratio of forces generated on an average sea rope to those generated on a land rope is in the range {25e3-70e3}. So, the generated loads and forces transmitted by the sea ropes are up to 5 orders of magnitude greater than those transmitted by the land ropes.

The paper concentrates on the towropes of underwater exploration vehicles and similar underwater vehicles, self-propelled and with external supply. In the former, a frequent and significant problem is design of proper diving rudders needed to overcome the forces induced by the flow on the vehicle and on the towrope. Those forces often present also a considerable problem for the vehicle operator. For self-propelled vehicles, the towed set of a safety rope and a control-supply cable may become an even greater problem when the vehicle encounters a sea current of a significant velocity. The induced forces may then be much greater than the thrust forces generated by the vehicle propellers, which threatens the vehicle integrity and safety. The calculations were performed for a vehicle towed with one speed and the best conditions were determined of free towing without a need of using diving rudders (except for balancing the weight and buoyancy forces), which allows a stable motion of the vehicle with the least possible resistance of towing at a given depth.

Analysis of the impact of environment on the underwater vehicle and towrope.

An underwater vehicle equipped with the bow and stern diving rudders and the direction rudder as in Fig.1, is hooked at point B to the towrope, connecting it with the ship. The vehicle, towrope and ship move in the Oxz vertical plane. It is assumed that the vehicle does not turn around the stern-bow longitudinal axis (Gx1 axis), but it turns, by an angle g, around the transverse axis (Gy1) going through the centre of gravity and parallel to the Oy axis. This assumption is fulfilled when the two bow diving rudders and/or the two stern rudders are laid on the same angle. During the diving stage, the operator by laying the diving rudders on the angles, respectively: αH - bow rudders and αST – stern rudders, turns the vehicle by an angle γ and then, operating the diving rudders, keeps that diving angle until the required depth is reached. Then the vehicle is levelled (γ=0). A symmetry of rudder profiles is assumed as well as a linear characteristic of the lift coefficients within the applied angle of incidence range and also a quadratic relation of the resistance force coefficients.

The force generated on the vehicle and its rudders has a horizontal resistance component and vertical lift component generated on the hull and rudders and also vertical gravity and vehicle buoyancy forces, designations given in Fig. 2. Equations of all the component forces and moments are the following:

$$\begin{aligned} R_{x0} &= q_0 * (-C_{DS}(V_S,\gamma) * S_W - C_D(\alpha_H) * S_{pH} - C_D(\alpha_{ST}) * S_{pST}) \\ R_{z0} &= -(\rho_0 - \rho_w) * g * V_0 + q_0 * (-C_{LS}(V_S,\gamma) * S_W - C_L(\alpha_H) * S_{pH} - C_L(\alpha_{ST}) * S_{pST}) \\ M_{Gy} &= -R_L * L/2 * \sin(\beta_0 - \gamma) + C_{MS}(V_S,\gamma) * q_0 * S_W - l_H * q_0 * C_L(\alpha_H) * S_{pH} + l_{ST} * q_0 * C_L(\alpha_{ST}) * S_{pST} \end{aligned} \tag{1}$$

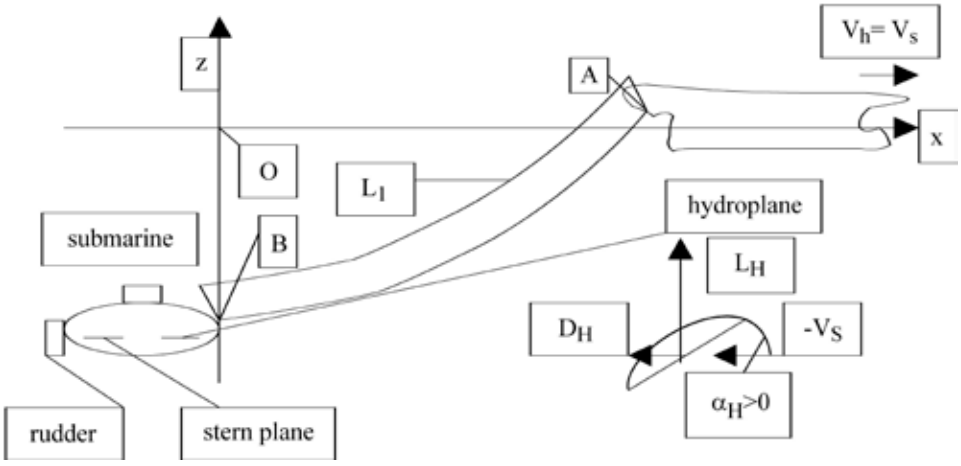

Fig. 1 *Coordinate system Oxyz for the ship and the rope with underwater vehicle.*

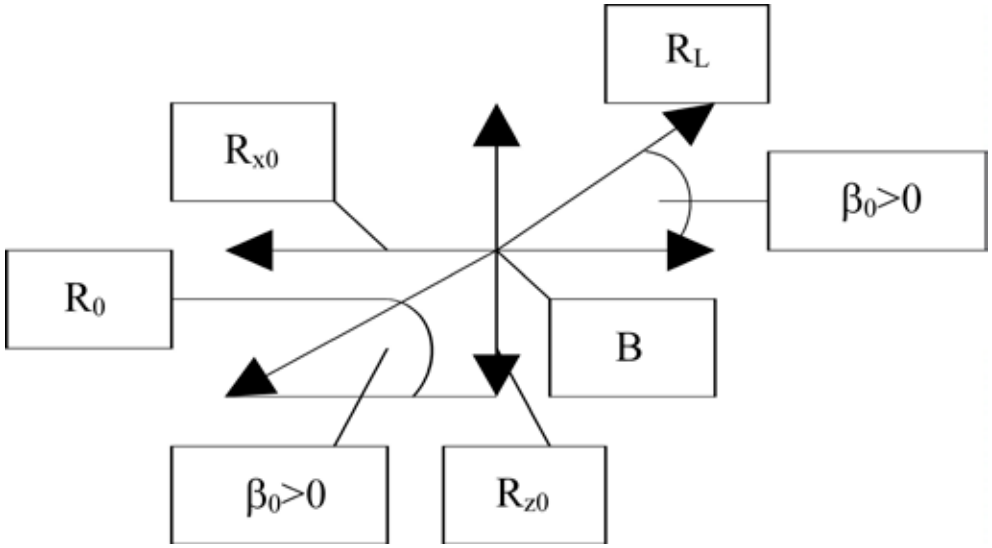

Fig. 2 *The horizontal and vertical components of the hydrodynamic force impact on the underwater vehicle.*

Position of the vehicle centre of gravity, point G, is assumed in its geometric centre and this value (L/2 in formula (1) for the MGymoment) should be changed when the position changes. This is shown in Fig. 3.

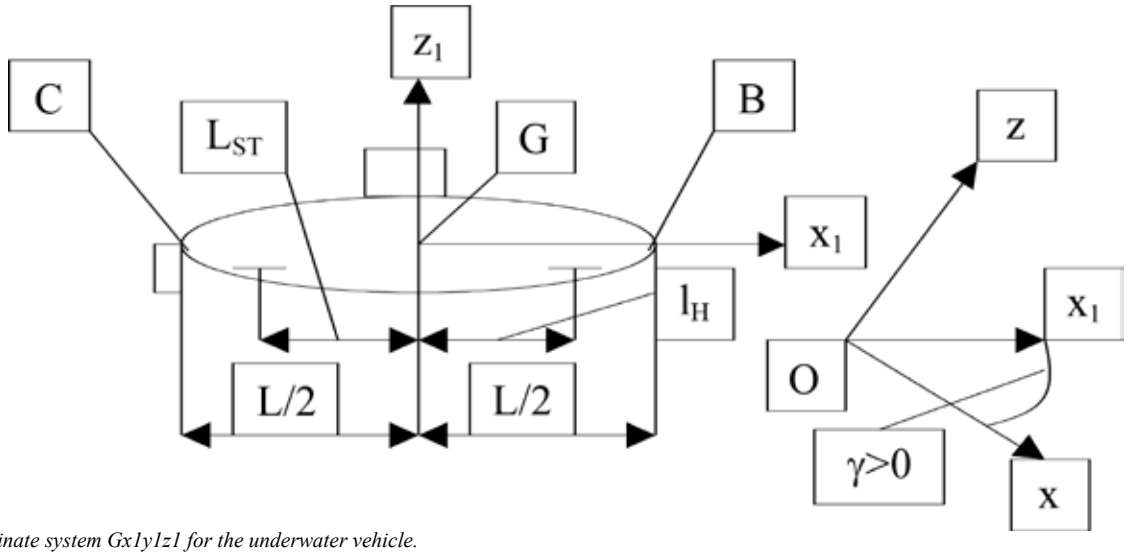

Fig.3 *Coordinate system Gx1y1z1 for the underwater vehicle.*

In the case of small angles of incidence for planes and the underwater vehicle, the lift coefficients may be described as a linear function of the angle of incidence and the resistance coefficients as a quadratic function. Expressions for plane are the following:

$$C_L(\alpha) = k_L * \alpha$$
$$C_D(\alpha) = k_0 + k_D * \alpha^2 \tag{2}$$

Expressions for the vehicle assume the form:

$$\begin{aligned} C_{LS}(V_S,\gamma) &= k_{LS}(V_S)*\gamma \\ C_{DS}(V_S,\gamma) &= k_{0S}(V_S)+k_{DS}(V_S)*\gamma^2 \\ C_{MS}(V_S,\gamma) &= -k_{MS}(V_S)*\gamma \end{aligned} \tag{3}$$

After substitution of equations (2) and (3) to the set of equations (1), the formulae describing the force components and trimming moment have the form:

$$\begin{aligned} R_{x0}/q_0 &= -S_W*(k_{0S}+k_{DS}*\gamma^2)-k_0*(S_{pH}+S_{pST})-k_D*(S_{pH}*\alpha_H{}^2+S_{pST}*\alpha_{ST}{}^2) \\ R_{z0}/q_0 &= -(\rho_0-\rho_W)*V_0*g/q_0+S_W*k_{LS}*\gamma+k_L*(S_{pH}*\alpha_H+S_{pST}*\alpha_{ST}) \\ M_{Gy}/q_0 &= -R_L*L/2*\sin(\beta_0-\gamma)/q_0-S_W*k_{MS}*\gamma-k_L*(l_H*S_{pH}*\alpha_H-l_{ST}*S_{pST}*\alpha_{ST}) \end{aligned} \tag{4}$$

where: RL=R0=(Rx02+Rz02)1/2 ,
β0=arctg(Rz0 / Rx0).

Outside the vehicle submerging and emerging phase, equations (4) get simplified. The vehicle moves in the horizontal position and if the towrope and is also horizontal, then the pull force in the rope has only the horizontal component. Then the vehicle trim angle γ=0 and with zero trimming moment generated on the vehicle the angle of incidence of the bow and stern diving rudders will be equal if their distance from the centre of gravity is equal (lH=lST) and the plane area is identical (SpH=SpST), i.e. then αH= αST. Equations (4) will have a simplified form:

$$\begin{aligned} R_{x0}/q_0 &= -S_W*k_{0S}-2*k_0*S_{pH}-2*k_D*S_{pH}*\alpha_H{}^2 \\ R_{z0}/q_0 &= -(\rho_0-\rho_W)*V_0*g/q_0+2*k_L*S_{pH}*\alpha_H \\ M_{Gy}/q_0 &= 0 \end{aligned} \tag{5}$$

As in such case of balanced motion the vertical component of the force acting on the vehicle must be zero, from the second equation of the equation set (5) we may obtain an expression for such a value of the diving rudder angle of incidence that the corresponding lift force will balance the difference of weight and buoyancy forces. The expression will be as follows:

$$\alpha_H = \frac{(\rho_0-\rho_W)*V_0*g}{2*q_0*k_L*S_{pH}} \tag{6}$$

The resistance of a towed underwater vehicle is given by the equation:

$$R_{x0} = -q_0*k_{0S}*S_W+2*q_0*k_0*S_{pH}+\frac{k_D*S_{pH}}{2*q_0}*\left\{\frac{(\rho_0-\rho_W)*V_0*g}{k_L*S_{pH}}\right\}^2 \tag{7}$$

Then, after an analysis of forces and moments generated on the underwater vehicle surface, the forces acting on the vehicle towrope are described. The expressions here below determine the shape and the internal forces in the rope connecting the underwater vehicle with a sea surface ship. The following boundary conditions of the assembly are known: z(A) - height of the rope fixture at point A on the ship (see Fig. 1) and z(B) - submergence depth of point B where the rope is secured to the vehicle. It is also possible to measure the total tension force in the rope at fixture point A. The assumed rectilinear motion of the vehicle places the rope in the ZOX plane. The state of static equilibrium of the vehicle and rope is sought, neglecting the loads from the wave motion of water particles and the rope elastic strain. The state of static equilibrium is determined by the following actions:

- weight of the rope and underwater vehicle,
- hydrostatic buoyancy force,
- hydrodynamic reactions of the flowing round water.

As, by assumption, the ship tows the rope with constant speed and does not change the direction, the rope axis is a two-dimensional curve.

The following formulae describe the hydrodynamic forces exerted on the rope by the flowing water:

$$\begin{aligned} F_n &= \frac{1}{2}*\rho_W*C_n*V_n|V_n|*d \\ F_t &= \frac{1}{2}*\pi*\rho_W*C_t*V_t*|V_t|*d \end{aligned} \tag{8}$$

Equations of the rope equilibrium will be formulated in accordance with Fig. 4. It presents conditions of equilibrium of the rope loads and internal longitudinal force at an arbitrary point in the direction tangent and normal to the rope axis in the Ozx plane.

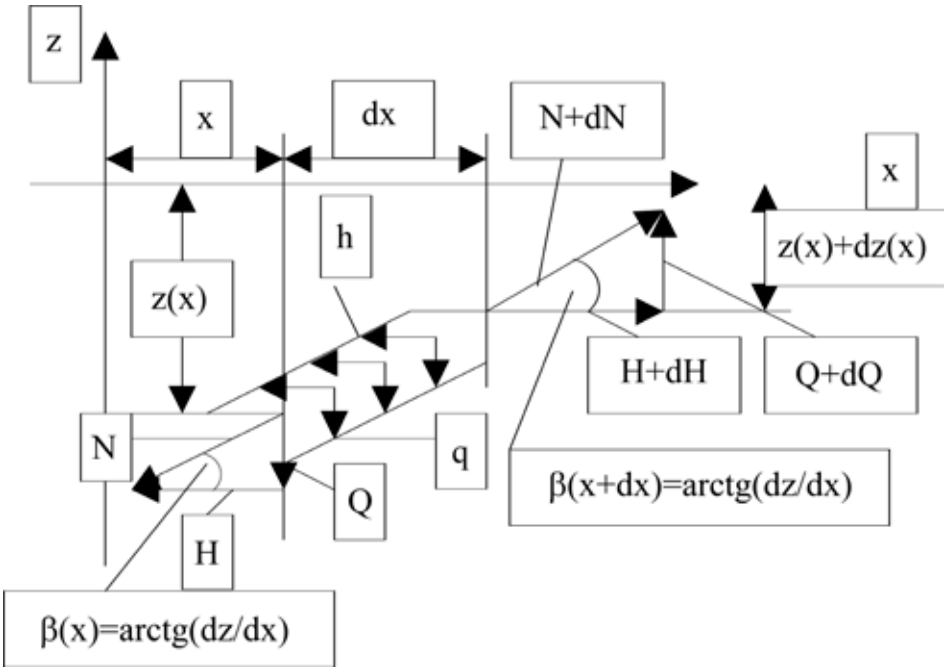

Fig. 4 *The continuous horizontal and vertical load and internal longitudinal force impact on the element of rope.*

The horizontal load on a rope element h is the horizontal component of the hydrodynamic reaction F generated by water flowing round the rope element. As shown in Fig. 4, the value is given by the following relation:

$$h = Fn * \sin\beta + Ft * \cos\beta \tag{9}$$

The continuous vertical load q is a sum of the rope element weight, buoyancy force in water and the vertical component of the hydrodynamic reaction F, given by the following relation:

$$q = (\rho_L - \rho_W) * S_L * g - Fn * \cos\beta + Ft * \sin\beta \tag{10}$$

Equation describing the rope shape is derived from values given in Fig. 4 and from differential relations dH/dx=h, dQ/dx=q and has the following form:

$$\frac{d}{dx}(H\frac{dz}{dx}) = q \tag{11}$$

After differentiating (11) and introducing the coefficients, the rope shape equation takes the form:

$$H * \frac{d^2z}{dx^2} + A_{Fn} * (\frac{dz}{dx})^4 + A_{Fn} * (\frac{dz}{dx})^2 - q_{00} = 0 \tag{12}$$

Solution of the problem

Calculations of the rope shape and forces during towing of an underwater vehicle were carried out by the finite element method in the Matlab computing environment. Own and library computational routines were used. A program was developed to calculate the hydrodynamic forces induced on the vehicle by the flowing-round water, based on the vehicle experimental data. The following boundary conditions were assumed for the calculations:

- at point B (connection of the rope and vehicle) the longitudinal rope tension force is equal to the sum of the towed vehicle resistance and the vertical component induced on the vehicle surface and rudders, mainly on the diving rudders, see Fig. 1 and equations (1);
- at point A (fixture of the rope on the ship) the height z(A) of that point is known and also the total tension force in the rope as well as its inclination angle to the level β(A) can be measured there.

The x(A) coordinate defines the horizontal distance of the vehicle from the ship and it is determined by the rope length L1 and its shape dependent on many parameters, such as: rope material density, its diameter, presence or not of a supply cable, mass (density) of the underwater vehicle, ship speed and also the phase of motion - submergence or emergence or a horizontal motion of the vehicle at a specific depth. Both the shape of towrope and the generated forces depend on those parameters. The calculations allow to solve the design problems and to assist the operator by choosing an optimum rope length for a given

vehicle towing depth etc..

The described method is also applicable to a self-propelled vehicle. In such case a description of forces and moments generated by propellers should be added to the mathematical model. When the self-propelled vehicle performs very complex movements, with turns not only around the Gy1 axis but also around the Gx1 and Gz1 axes, the shape of the rope and the force system will be very complex. In order to be able to perform such complex space calculations, it is necessary to decrease the numerical difficulties of the boundary problem calculations by applying another method described by the author in [2].

Results of calculations

An example of calculations was performed for a vehicle with resistance of approx. 450 N at a speed of 6 knots. In Figs. 5-9 in Appendix I results are presented of the calculations of towing the vehicle with ropes of 50, 100, 150, 200 and 250 m length, respectively. The other data remained unchanged, with the following values:

z(A) = 5 m – height of the rope fixture above the water surface, (Fig.1),
h0 – depth of the vehicle submergence, (Fig.1),
Vs = 6 knots (kn), speed of the ship towing the rope and the underwater vehicle,
ρW =1025kg/m3 – sea water density,
g = 9.81 m/s2 – gravitational acceleration,
d = 5e-3 m – nominal diameter of the steel towrope,
ρL = 7e3 kg/m3 – rope material density,
L1 = 50 m - 250 m – rope length, (Fig. 1),
Cn = 1.2 – coefficient for a round cross-section rope, (equation (8)),
Ct = 2e-2 - coefficient for a round cross-section rope, (equation (8)),
ρO = 1.030e3 kg/m3 – average density of the vehicle material,
D0 = approx. 7.5 kN – vehicle displacement.

The calculation results are presented in Figs. 5-9, which show, respectively:

a - inclination angle of the end of towrope at point B as a function of the vehicle submergence depth h0;
b - vertical force Q (as a function of the vehicle submergence depth h0), which has to be generated by the diving rudders in order to balance the vertical component of the towrope force;
c - total force induced on the vehicle, balancing the rope tension force N, also as a function of h0;
d - values of the rope tension horizontal component as a function of the horizontal coordinate x, for the rope shape corresponding to the maximum tow depth;
e - shape of the towrope at different tow depths in the Oxz plane.

Fig. 5 presents results for a relatively short, 50 m long rope. It can be seen from the values of force Q that free float, understood as floating without the use of diving rudders, is impossible, already for ho = 2 m a force Q = -50 N must be generated by the rudders and it increases for h0 = 21 m to a value of -400 N and is comparable with the total vehicle resistance, see Fig. 5b.

For a longer rope, L1= 100 m, Fig. 6 shows that free float is possible at the depth of ho = 5.5 m but at h0 = 21 m the value of Q = -200 N is two times smaller than that for the L1 = 50 m rope, see Fig. 6b.

For a rope of L1= 150 m, Fig. 7 shows that free float is possible at the depth of ho = 15 m but at h0 = 27 m the value of Q = -120 N is 3.5-4 times smaller than that for the L1 = 50 m rope, see Fig. 7b.

At the depth of ho = 15 m also the total tension force in the rope at point B of rope connection with the vehicle is smallest, see Fig. 7c.

For a rope of L1= 200 m, Fig. 8 shows that free float is possible at the depth of ho = 25 m, see Fig. 8b, but at h0 = 37 m the value of Q = -150 N is 3 times smaller than that for the L1 = 50 m rope at a ho= 21 m depth. At the depth of ho = 25 m also the total tension force in the rope at point B of rope connection with the vehicle is smallest, see Fig. 8c.

Fig. 9 for the rope length L1 = 250 m shows that the vehicle can float freely at the depth greater than h0 = 35 m, see Fig. 9b, but at h0 = 47 m the value of Q = -200 N is 2 times smaller than that for the L1 = 50 m rope at a ho= 21 m depth. At the depth of ho = 35 m also the total tension force in the rope at point B of rope connection with the vehicle is smallest, see Fig. 9c.

These calculation results indicate that it is possible to select an appropriate rope length for the expected submergence depth of the underwater vehicle. Such a rope length will allow the vehicle to float freely, which in turn, with the balanced vehicle weight and buoyancy forces, will allow the vehicle to be towed at a constant depth without the use of diving rudders. This ensures a very stable vehicle motion. When the vehicle weight and buoyancy forces are not balanced, only the difference between them has to be compensated by the diving rudders.

The above shown results of an optimum rope length for given parameters of the rope-vehicle system at the tow speed of 6 knots may be described by a third degree polynomial with the coefficient values as follows:

$$L_1 = f(h_0) = ax^3 + bx^2 + cx + d$$
$$a = 3.6333e-3; b = -0.236688; c = 9.5247358; d = 51.225642 \quad (13)$$

The reverse function has the form:

$$h_0 = f(L_1) = ax^3 + bx^2 + cx + d \tag{14}$$
$$a = -2.666e-6; b = 1.4714e-3; c = -0.059761; d = -0.4$$

Summary.

The calculation results show how easily the forces considerably exceeding the towed vehicle resistance can be generated on the towrope. From formula (13) an optimum rope length can be determined for a given tow depth h0 and formula (14) gives a reverse function. Evidently, the function coefficients will change when the conditions of movement or the rope and vehicle parameters are changed.

Operating a self-propelled underwater vehicle, with external energy supply in difficult conditions of a sea current of changeable direction and velocity, will require performing the vehicle motion simulations allowing to work out the best possible steering procedures.

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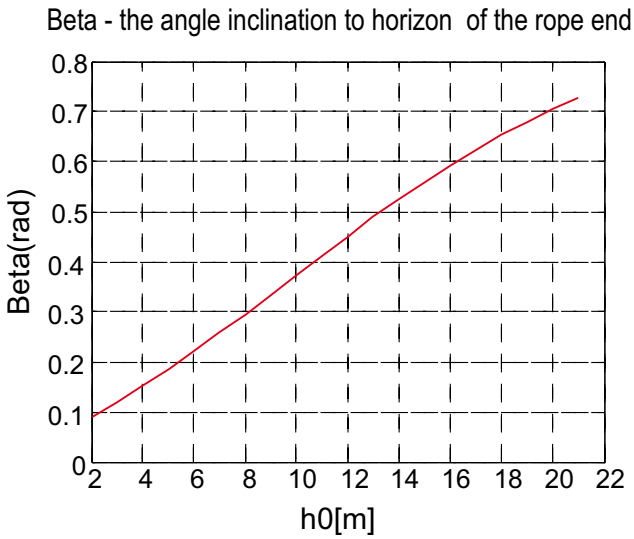
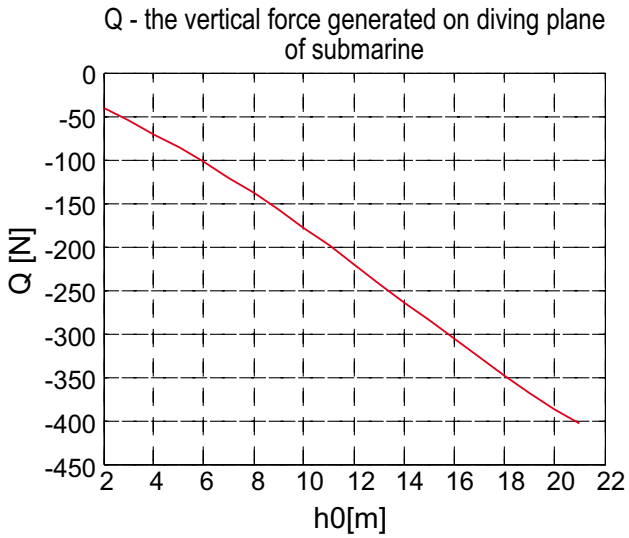
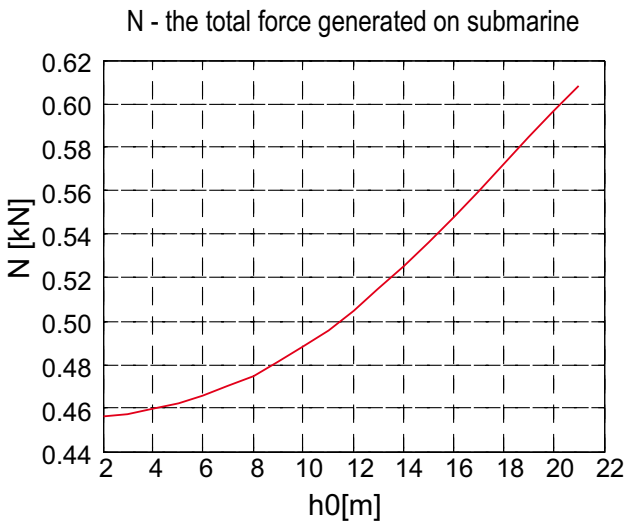
NOMENCLATURE

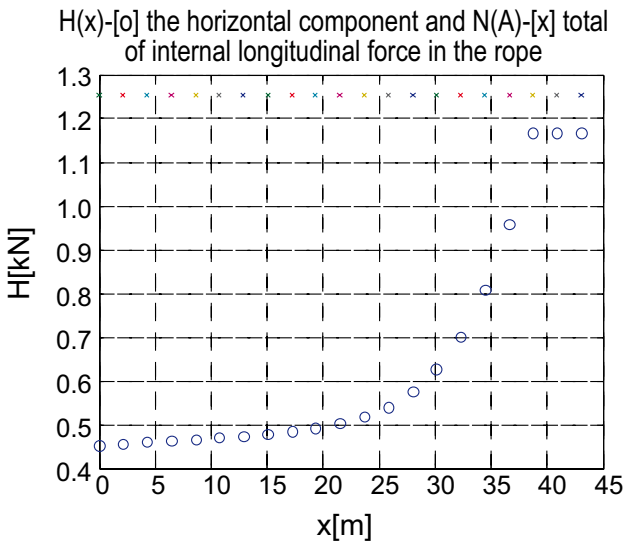
AFn - coefficient of the continuous load normal to rope axis ; AFn = ½*ρW*Vs2*d*Cn
AFt - coefficient of the continuous load tangent to rope axis; AFt = ½*ρW*Vs2*d*π*Ct;
CD(α) – coefficient of the plane resistance with the following relation to the angle of incidence: CD=k0+kD*α^2;
CDS(Vs,γ) – coefficient of the vehicle resistance with the relation to the angle of incidence in the form of a quadratic function: CDS(Vs,γ) = k0S(Vs)+kDS(Vs)*γ^2 , coefficients depend on the Reynolds number and are also a function of the flow speed Vs;
CL(α) – coefficient of the plane hydrodynamic lift force with the relation to the angle of incidence in a linear form: CL = kL*α ;
CLS(Vs,γ) – coefficient of the vehicle-generated hydrodynamic lift force with the relation to the angle of incidence, for small angles, in an approximately linear form: CLS(Vs,γ) = kLS(Vs)*γ ;
CMS(Vs,γ) – coefficient of the vehicle-generated moment with the relation to the angle of incidence, for small angles, in an approximately linear form: CMS(Vs,γ)= - kMS(Vs)*γ ;
Cn ,Ct – dimensionless coefficients dependent on the rope cross-section shape;
d – characteristic dimension of the rope cross-section, for a circular rope the diameter, for a rope-cable set the hydrodynamic forces induced by water flow on the rope and on the cable must be calculated separately;
DH,DST - resistance force generated on the bow and stern diving rudder, respectively;
D0 – underwater vehicle displacement;
Fn – rope continuous load normal to the rope axis, Fn = AFn*sin2β ;
Ft – rope continuous load tangent to the rope axis, Ft = AFt*cos2β ;
g – gravitational acceleration;
G0 – vehicle weight;
h – rope continuous horizontal load;
h0 - submersion depth of the underwater vehicle;
H – horizontal component of the rope tension force;
L1 – towrope length between points A and B;
LH,LST– hydrodynamic lift force generated on the bow and stern diving rudder, respectively
MGy – resultant moment from the hydrodynamic forces acting on the vehicle hull and from forces generated on the vehicle diving rudders and also from the towing force;
N – rope tension force;
Gx1y1z1 - mobile coordinate system connected with the underwater vehicle, moving with speed Vs;
Oxyz – mobile coordinate system connected with the ship, moving with speed Vs;
Ox – horizontal component on the sea surface;
Oz – vertical component;
q – rope continuous vertical load;
q0 – swell pressure;
q00 – coefficient of rope continuous vertical load as a difference of the rope weight and displacement, q00=(ρL-ρW)*SL*g;
RL – reaction in rope balancing the R0 reaction generated on the vehicle, RL = R0;
R0 – reaction generated on the underwater vehicle;
Rx0 – horizontal component of the R0 reaction;
Rz0 – vertical component of the R0 reaction;
SL – rope cross-section area;
SpH,SpST – surface area of the bow and stern diving rudder, respectively;
Sw – wet surface of the vehicle hull;
Vn , Vt – coordinates of the water speed vector projections on the direction normal and tangent to the rope axis, respectively;
V0 – vehicle displacement volume;
Vs – speed of the towing unit;
αH – angle of incidence of the bow diving rudders, positive direction anticlockwise;
αST – angle of incidence of the stern diving rudders, positive direction as above.;
β - angle of the towrope inclination to the level, positive direction anticlockwise;
β0 – angle of deviation of the hydrodynamic reaction generated by water flowing around the vehicle, the direction determines also the angle of towrope inclination to the level at point B;
γ – angle of rotation of the underwater vehicle around the Oy1 axis, parallel to the Oy axis and passing through the vehicle centre of gravity G;
ρL - rope material density;
ρ0 – average vehicle density, weight of the vehicle divided by its volume;
ρW – sea water density;

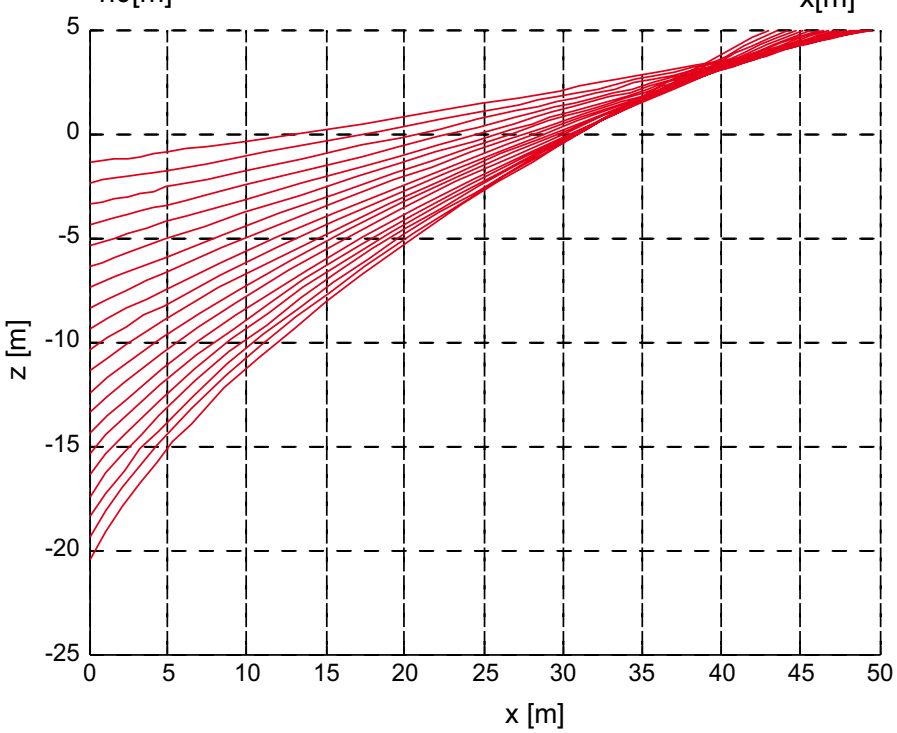
APPENDIX

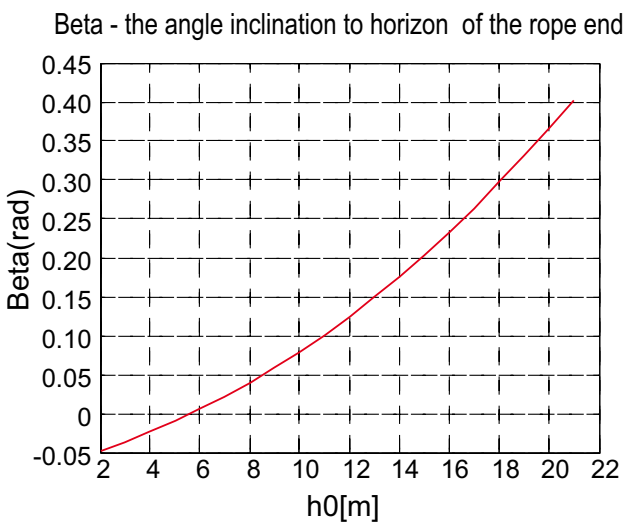

Beta - the angle inclination to horizon of the rope end
Beta(rad)
h0[m]

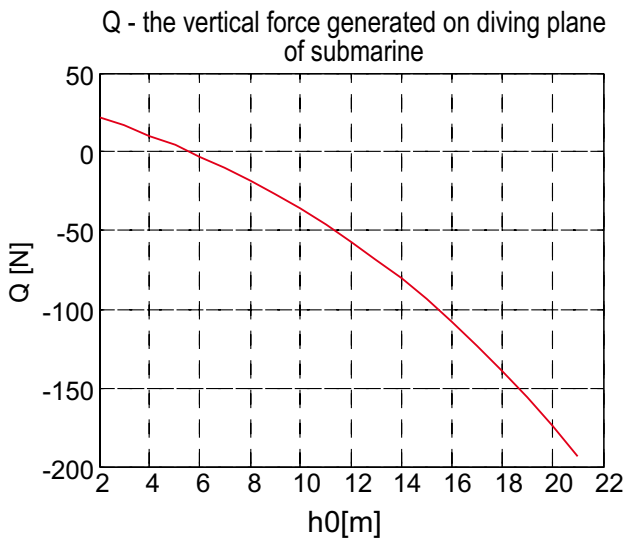

Q - the vertical force generated on diving plane of submarine
Q [N]
h0[m]

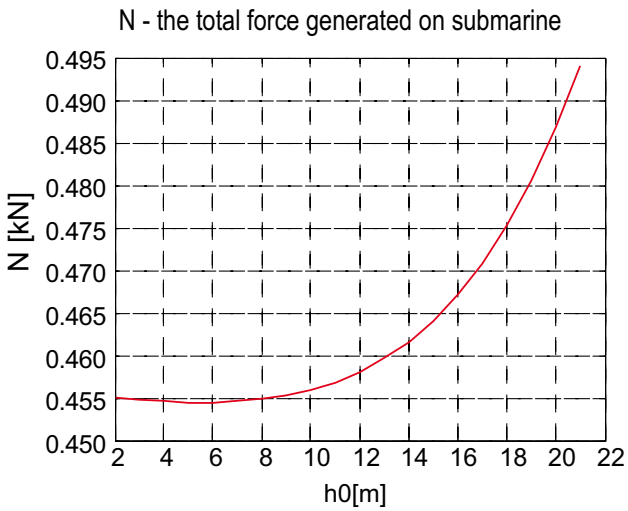

N - the total force generated on submarine
N [kN]
h0[m]

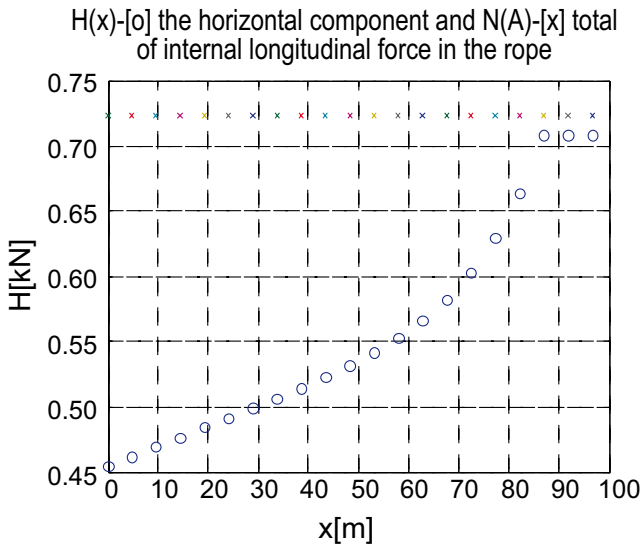

H(x)-[o] the horizontal component and N(A)-[x] total of internal longitudinal force in the rope
H[kN]
x[m]

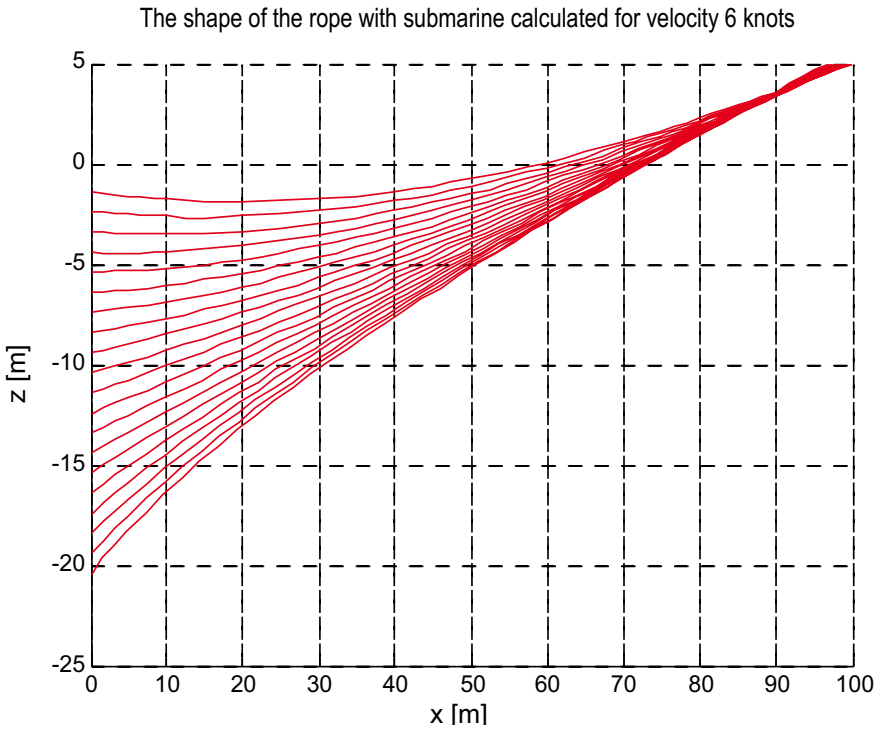

z [m]
x [m]

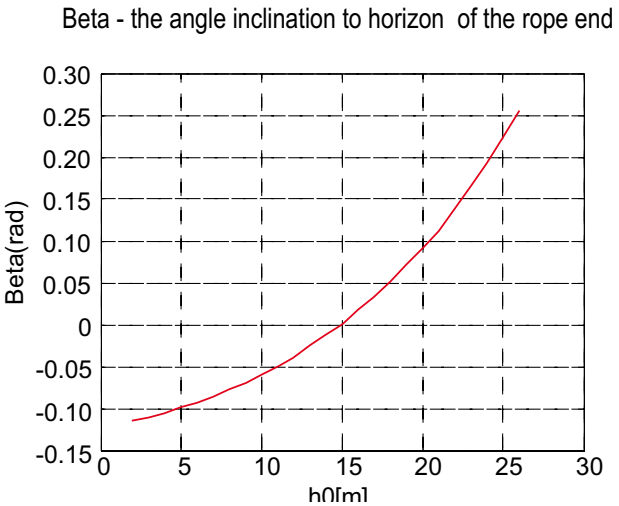

Beta - the angle inclination to horizon of the rope end
Beta(rad)
h0[m]

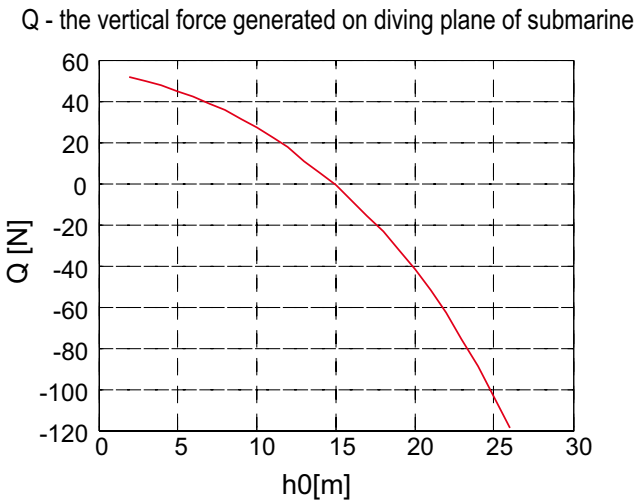

Q - the vertical force generated on diving plane of submarine
Q [N]
h0[m]

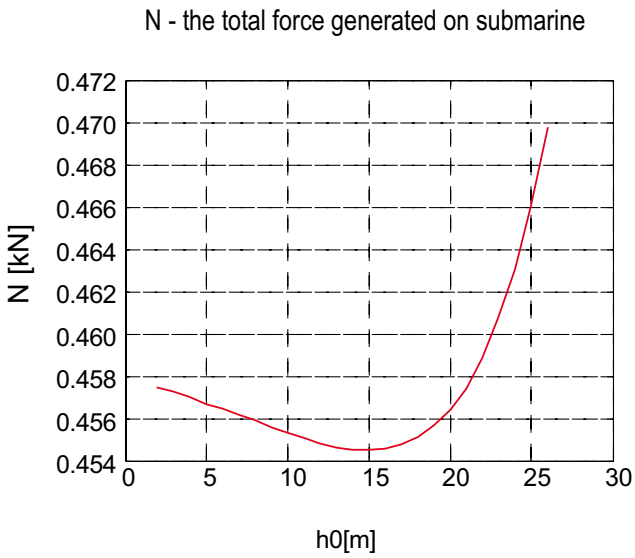

N - the total force generated on submarine
N [kN]
h0[m]

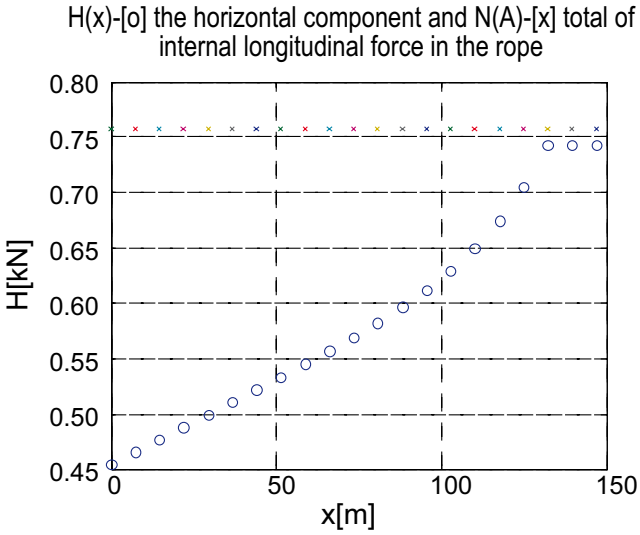

H(x)-[o] the horizontal component and N(A)-[x] total of internal longitudinal force in the rope
H[kN]
x[m]

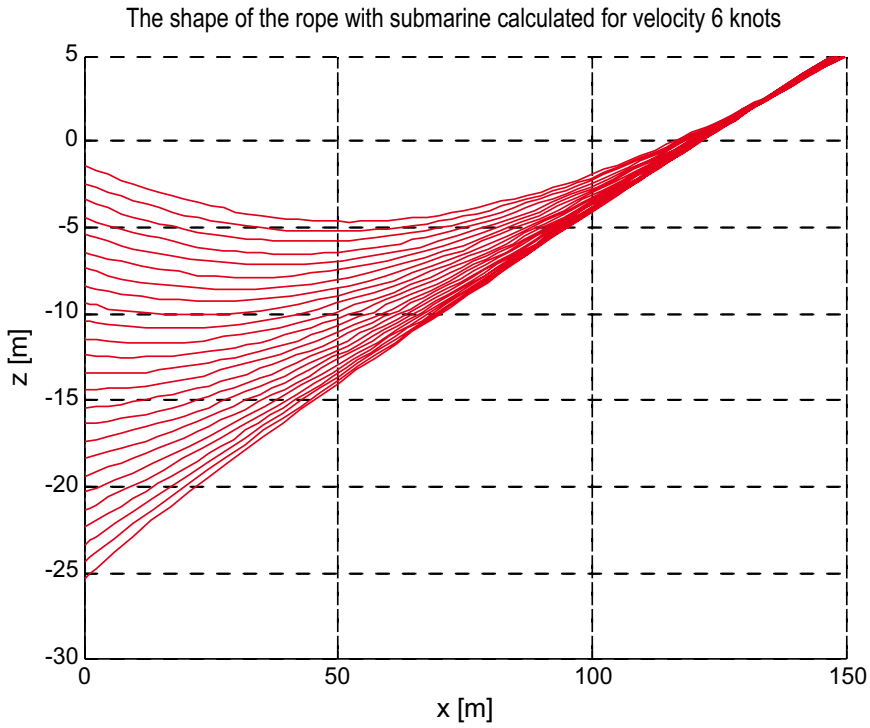

The shape of the rope with submarine calculated for velocity 6 knots
z [m]
x [m]

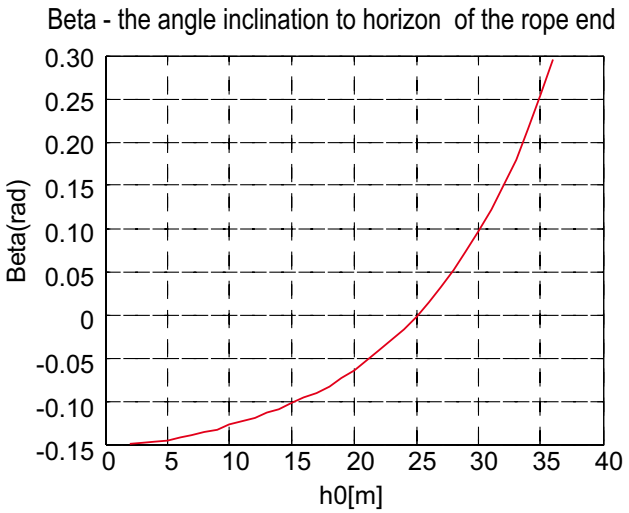

Beta - the angle inclination to horizon of the rope end
Beta(rad)
0.30
0.25
0.20
0.15
0.10
0.05
0
-0.05
-0.10
-0.15
0
5
10
15
20
25
30
h0[m]

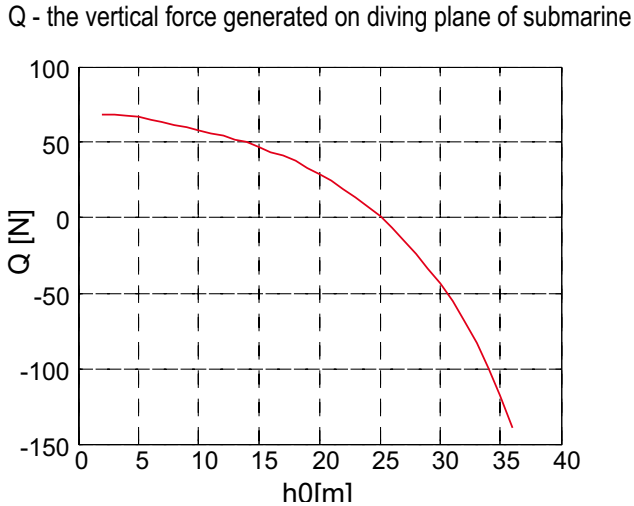

Q - the vertical force generated on diving plane of submarine
Q [N]
60
40
20
0
-20
-40
-60
-80
-100
-120
0
5
10
15
20
25
30
h0[m]

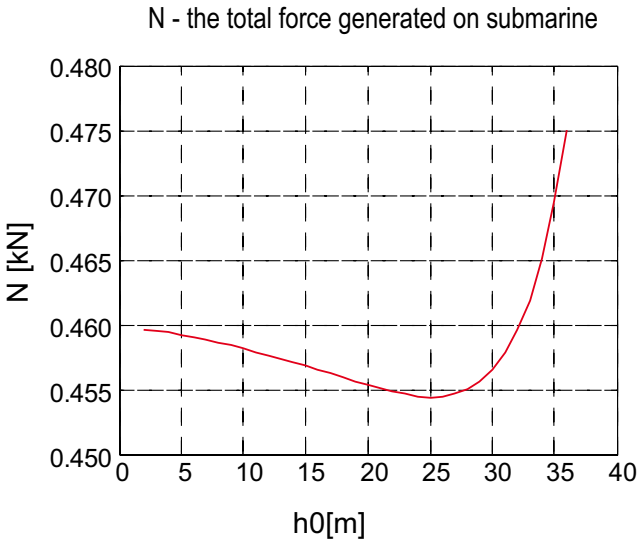

N - the total force generated on submarine
N [kN]
0.472
0.470
0.468
0.466
0.464
0.462
0.460
0.458
0.456
0.454
0
5
10
15
20
25
30
h0[m]

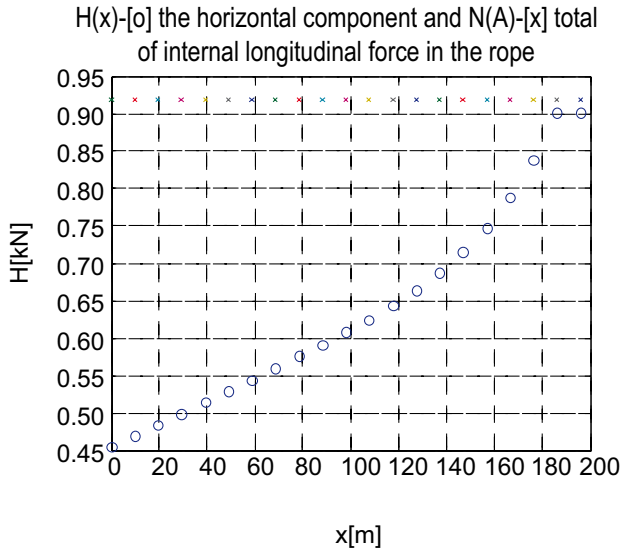

H(x)-[o] the horizontal component and N(A)-[x] total of internal longitudinal force in the rope
H[kN]
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0
50
100
150
x[m]

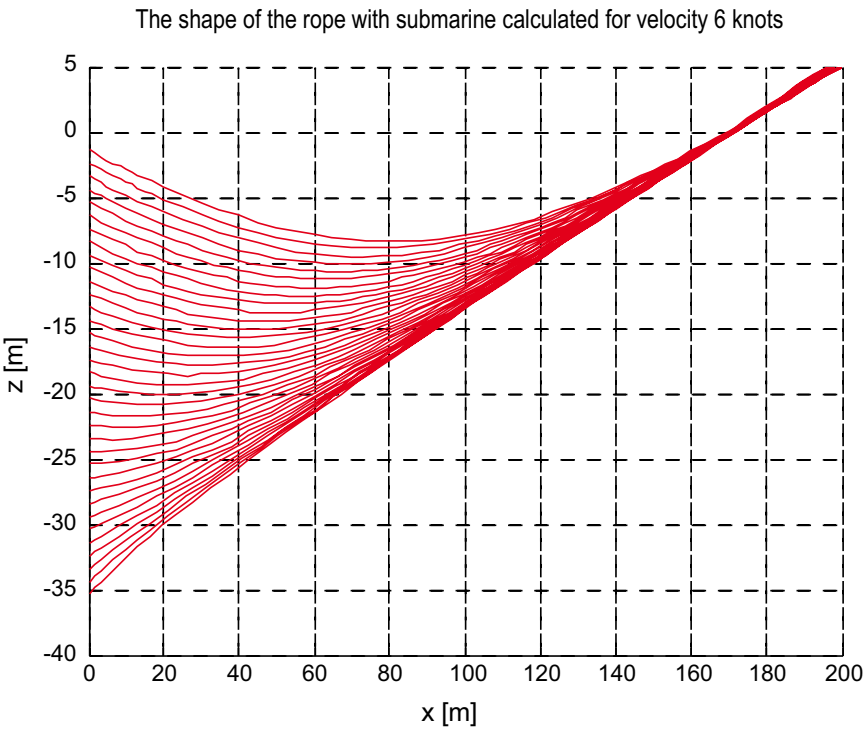

The shape of the rope with submarine calculated for velocity 6 knots
z [m]
5
0
-5
-10
-15
-20
-25
-30
0
50
100
150
x [m]


Beta - the angle inclination to horizon of the rope end
Beta(rad)
0.30
0.25
0.20
0.15
0.10
0.05
0
-0.05
-0.10
-0.15
0 5 10 15 20 25 30 35 40
h0[m]

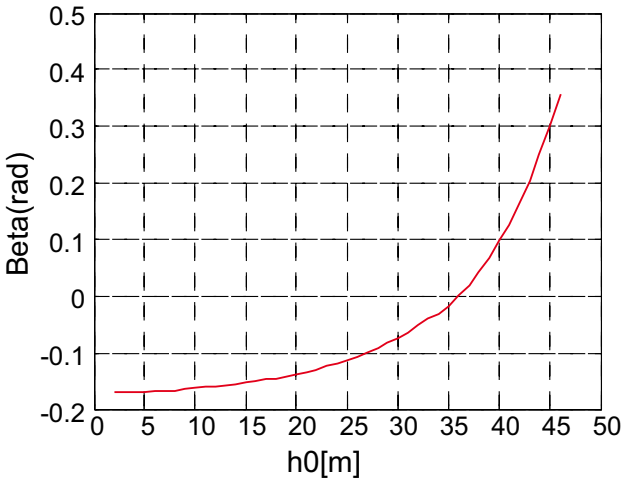

Q - the vertical force generated on diving plane of submarine
Q [N]
100
50
0
-50
-100
-150
0 5 10 15 20 25 30 35 40
h0[m]


N - the total force generated on submarine
N [kN]
0.480
0.475
0.470
0.465
0.460
0.455
0.450
0 5 10 15 20 25 30 35 40
h0[m]

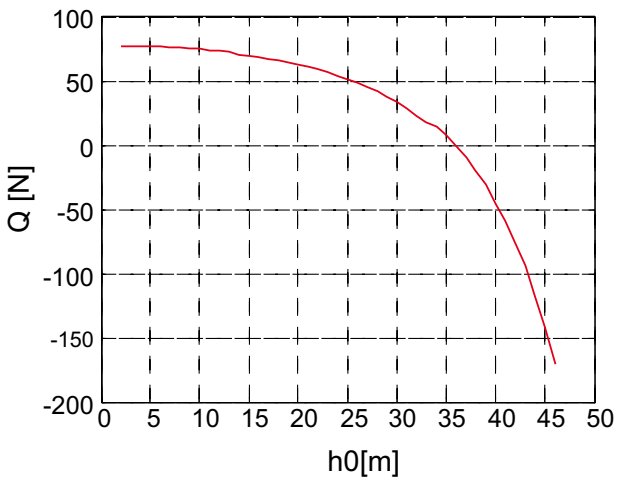

H(x)-[o] the horizontal component and N(A)-[x] total
of internal longitudinal force in the rope
H[kN]
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0 20 40 60 80 100 120 140 160 180 200
x[m]


The shape of the rope with submarine calculated for velocity 6 knots
z [m]
5
0
-5
-10
-15
-20
-25
-30
-35
-40
0 20 40 60 80 100 120 140 160 180 200
x [m]

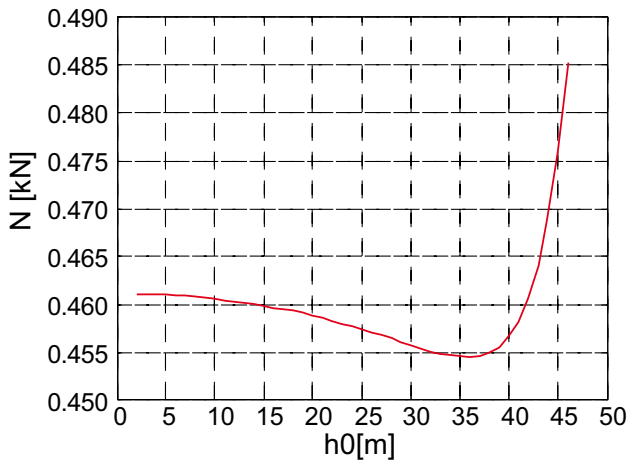
Beta - the angle inclination to horizon of the rope end



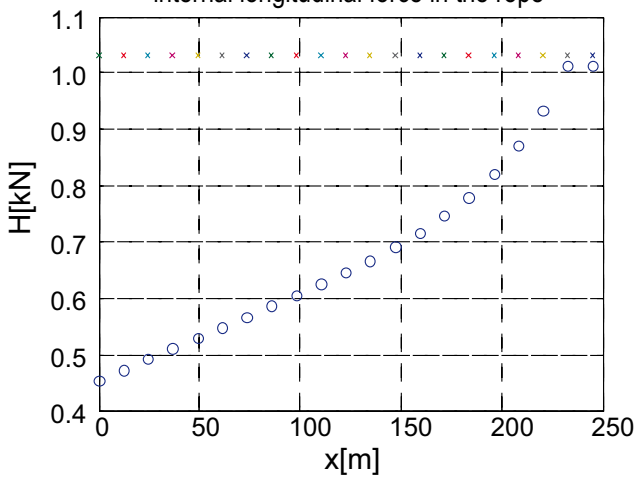
Q - the vertical force generated on diving plane of submarine



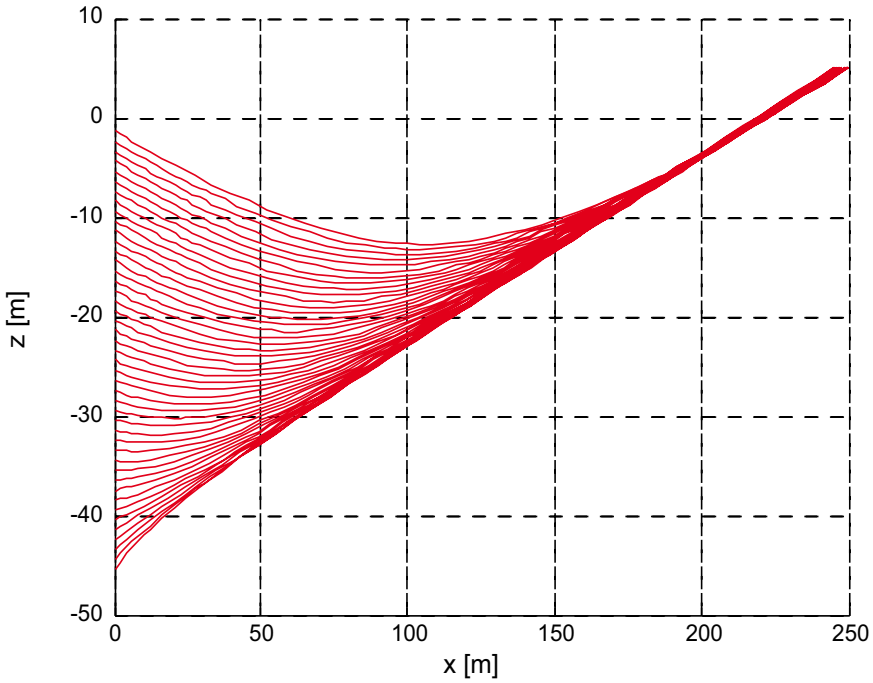
N - the total force generated on submarine



H(x)-[o] the horizontal component and N(A)-[x] total of internal longitudinal force in the rope



The shape of the rope with submarine calculated for velocity 6 knots



Free sailing model tests of evasive action manoeuvre of a river cargo motor barge in shallow waters.

Wojciech Górski,
Maciej Reichel,
Ship Design and Research Centre

Abstract

The paper presents shallow water experiments of a self-propelled, free running model of an inland water motor barge. In accordance with the Rhine Manoeuvring Standards Rheinschiffsuntersuchungsordnung (RheinSchUO 1995, issue 2005), evasive action manoeuvring tests were realised. Model obtained from DST Duisburg Germany was a 5.00 meters long motor barge built to a scale of 1:20 and propelled with an 80 mm diameter ducted propeller. Tests were carried out in the auxiliary towing tank of the Ship Hydromechanics Division in Gdańsk. The experiment consisted of efficiency analysis of different rudder blades with variable rudder profiles and rudder blade areas. In total the evasive action test was repeated for three different rudder profiles, with three different chord lengths and at three different water depths each. For each particular case the total standard manoeuvre time and side rudder force was measured. These results were compared with the RheinSchUO standards. The model tests programme was realised within the EU CREATING project supported in the 6th Framework Programme.

Keywords: *shallow waters, free sailing, inland water motor barge*

INTRODUCTION

Inland waterways transportation in Western Europe has a steadily growing share in total cargo shipping. The similar tendency is expected also in Poland following the increasing road and railway congestion and assuming the infrastructure improvement on our main rivers. Resulting increased number of river ships on waterways raises a danger of collision. Therefore regulatory bodies put special emphasis on safety. With this respect the manoeuvring aspects are one of the key factors for a ship on the river, especially for ships with a long reaction time. Therefore ship designers try to reach the required safety level in an optimal manner.

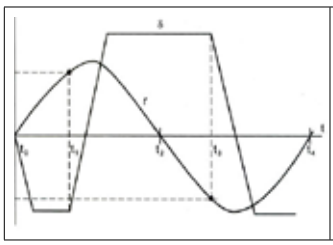
Designers have a wide choice of various steering systems, with different impacts on the overall ship manoeuvring performance. However, the manoeuvring capabilities should be compatible with applicable manoeuvring standards. The knowledge regarding the compliance with requirements should be available as early in the design process as possible. The free running model testing provides the adequate measures for establishing the actual vessel performance with respect to the manoeuvring capabilities in a time and cost effective way (i.e. comparing with the PMM tests). Results of the model tests can be directly compared with appropriate standards providing the requested information at an early design stage.

In the EU project CREATING supported in the 6th Framework Programme a river cargo ship for Rhine was tested. Therefore the model was examined with the obligatory manoeuvring standards of the Rhine Manoeuvring Standards Rheinschiffsuntersuchungsordnung (RheinSchUO 1995, issue 2005), see Fig. 1 and references [1].

The purpose of tests was to make comparative analysis of different rudder blades efficiency by model simulation of the evasive action.

Ship and model data

The hull model No. M654 used for the tests was made of wood by DST Duisburg Germany to a scale of 1:20 and renovated by CTO S.A. It was propelled with an 80 mm diameter ducted propeller model No. P519 manufactured for the purpose of tests in CTO S.A. Before the tests the hull model was ballasted to the draft corresponding to 2.0m full scale.



t_0 – start of manoeuvre
t_1 – time to reach turning speed r_1
t_2 – time to reach turning speed $r_2 = 0$
t_3 – time to reach turning speed r_3
t_4 – time to reach turning speed $r_4 = 0$ (end of evasive action)
δ – rudder angler – angular velocity
r – angular velocity

Figure 1 *Evasive action manoeuvre*

Table 1.1 *Ship and model data*

	Symbol	Unit	Ship	Model
Main data of the M654 ship hull (scale λ=20.0)				
Length between perpendiculars	L_{PP}	m	105.00	5.250
Length of waterline	L_{WL}	m	103.60	5.180
Breadth moulded	B	m	10.50	0.525
Draught: fore	T_F	m	2.00	0.100
Draught: aft	T_A	m	2.00	0.100
Displacement volume	V	m^3	1922.9	0.240
Wetted surface	S	m^2	1364.1	3.410
Block coefficient	CB	-	0.884	
P519 propeller model data				
Propeller diameter	D	m	1.600	0.080
Pitch at r/R=0.7	P	m	1.780	0.089
Pitch ratio at r/R=0.7	P/D	-	1.110	
Expanded blade area ratio	A_E/A_0	-	0.791	
Number of blades	z	-	4	
Direction of rotation		-	right	

In the tests three types of rudders were used – typical NACA

In the tests three types of rudders were used – typical NACA 0015, fishtail and the flat plate. Each of these rudders were made in three versions with different lateral area, so that the ratio of the rudder area to lateral area of ship wetted profilewas in the range of 1.6 – 2.4%.

Table 1.2 *Model rudder profiles*

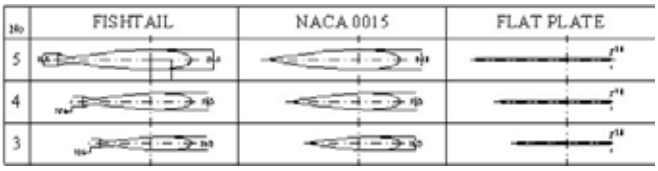


Table 1.3 *Rudder data*

	Rudder area		A_R/LT
	model scale	ship scale	
Rudder No.	mm^2	m^2	%
5	12443	4.98	2.40
4	10043	4.02	1.94

Test conditions

Conditions for evasive action tests for all versions of rudders were identical, corresponding to the Chapter 5 of RheinSchUO 1995 [1].

Table 3 *Tests conditions*

		Ship scale	Model scale
	Approach speed	13 km/h	0.8 m/s
1st test	Max. rudder angle	20°	20°
	Angular velocity	20 deg/min	1.49 deg/s
2nd test	Max. rudder angle	45°	45°
	Angular velocity	28 deg/min	2.09 deg/s

In total the evasive action test was repeated for nine rudders and at three different water depths – 1.3T, 1.6T, and 2.5T.

The number of model propeller revolutions was established at a deep-water condition to reach a speed of 0.8 m/s. During the tests the model speed was not measured but the approach speed was the same for all the test runs as the model was accelerated using the tank carriage with precisely controlled speed.

Because of a short time of manoeuvre the rudder angular velocity was established at .

Apparatus and facilities

Model was tested in a towing tank using free-running model test technique with the assistance of tank carriage equipped with measuring devices, radio controller and data processing computer. The tests were carried out in shallow water. During each run the rudder angle and angular velocity as well as rudder forces were, with the time step of 0.1 second, discrete recorded on a digital unit with associated computer data recording systems. The model was equipped in order to provide full autonomous operation during the tests. For this purpose the following subsystems were installed:

- propulsion subsystem consisting of a ducted propeller model, shafting and 500W AC motor,
- steering subsystem composed of the exchangeable rudder blade, rudder force dynamometer (2-component) and steering gear (stepping motor),
- manoeuvre control subsystem based on an own-developed controller governing the rudder deflection with respect to angular velocity signal obtained from the digital gyro,
- power supply for propulsion and steering system consisting of two batteries, DC/AC converter and electric motor inverter,
- power supply for data acquisition system (AC power pack),
- data acquisition system composed of signal amplifier, analogue-to-digital converter, radio transmitter, radio receiver and data processing computer (the last two items installed on the towing carriage)

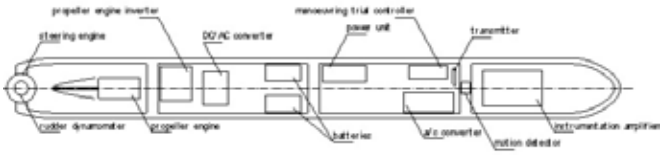


Figure 2. *Pictorial diagram of model outfit*

Performing the test

On a short length the model was accelerated to 0.8 m/s velocity with the help of towing carriage and the propeller revolutions set to the required level. During the acceleration the operator kept the model parallel to the towing tank axis by hand controlling its position using the laser beam projected to the model centre line. When the approach speed was reached and the resistance balanced with the propeller thrust, the model was released and the evasive manoeuvre started with first deflection (20˚ or 45˚).

During the complete manoeuvre the angular speed was measured and compared with limiting value (1.49˚ or 2.09˚ respectively) in the controller unit. The rudder was deflected to the opposite side each time the angular velocity reached the limiting value. Usually three or four turns were performed in the length of the towing tank.

Figure 5. *Model during the evasive manoeuvre test*

Results of experiments

The model test results; rudder angle, angular velocity and lateral rudder force, were computed to the full scale. For all tests six graphs were plotted, each for a different water depth. In all graphs the rudder angle, angular velocity and lateral rudder force were drawn. Example of the results for one rudder is presented below.

Table 4.1 *Results for NACA 0015 N5 for 20° rudder deflection*

Rudder angle d [deg]	Angular velocity r [deg/min]	Elapsed time t [s]	Side rudder force Y_R [kN]	Elapsed time t [s]	Side rudder force Y_R [kN]	Elapsed time t [s]	Side rudder force Y_R [kN]
		h=1.3T		h=1.6T		h=2.5T	
δ_0=0°	r_0= 0	0.0	0.0	0.0	0.0	0.0	0.0
δ_1=20° PS	r_1= 20	53.4	12.2	16.6	14.0	21.1	16.4
δ_2=20° SB	r_2= 0	74.1	-28.2	42.8	-19.8	43.1	-24.5
δ_3=20° SB	r_3= -20	101.1	-19.2	62.4	-19.5	62.7	-21.4
δ_4=20° PS	r_4= 0	132,6	20,0	85,8	25,2	80,1	23,8

Table 4.2 *Results for NACA 0015 N5 for 45° rudder deflection*

Rudder angle d [deg]	Angular velocity r [deg/min]	Elapsed time t [s]	Side rudder force Y_R [kN]	Elapsed time t [s]	Side rudder force Y_R [kN]	Elapsed time t [s]	Side rudder force Y_R [kN]
		h=1.3T		h=1.6T		h=2.5T	
δ_4'=0°	r_4'= 0	0.0	0.0	0.0	0.0	0.0	0.0
δ_5=45° PS	r_5 = 0	26.4	45.2	13.9	54.6	12.1	65.8
δ_6=45° SB	r_6= 0	49.4	-64.3	39.0	-66.2	35.9	-71.1
δ_7=45° SB	r_7= 0	63.5	-51.4	54.3	-54.3	46.2	-57.6
δ_8=45° PS	r_8= 0	87.0	59.4	78.6	70.2	66.5	75.8

results obtained could be directly compared with manoeuvring standards providing instant information regarding the compliance with requirements. As far as the time required for tests performance and elaboration of the results is concerned, the proposed method was advantageous comparing to the captive methods (PMM). Usual source of inaccuracies caused by the environmental conditions were omitted due to performance the tests in the strictly controlled conditions of a towing tank (precisely controlled approach speed, constant water depth and calm wind conditions). The method can be successfully applied both in the case of comparative model tests and in order to determine the actual manoeuvring performance of the vessel with a given steering arrangement.

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The wave influence on wind pressure fluctuation of drifting rescue units

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Abstract

In the article the stochastic model of wave influence on wind loading fluctuation of drifting rescue units is presented. Wind speed is the single most important factor when trying to determine basic wind pressure. Wind motion is turbulent, and it is difficult to give a concise mathematical definition of turbulence. However, it is known that wind turbulence exists due to the lower viscosity of air in comparison with water. Any air motion faster than 4 km/h is turbulent; i.e., air particles move erratically in all directions. Basic wind pressure is affected by the uncertainty effect caused by the likelihood of the wind hitting the drifting rescue unit from any given direction. This parameter is known as the directionality effect.

The pressure exerted by strong winds on the life raft is a function of the dynamic part of Bernoulli's equation, known as basic pressure, which is modified by the following factors: wind direction according to a life raft axis system, wind speed, the life raft height, wave height, wave slope angle. Two random factors were considered. The first one is the drifting rescue unit heeling angle to the horizontal plane. The second one is connected with the position of drifting rescue unit on wave slope. The results obtained during laboratory tests in wind tunnel were used to model wind pressure on a life raft. The measurements of a life raft movement on waves obtained during sea experiments were used to estimate the distribution of pitch and roll angle. The position of drifting rescue unit on a wave slope has uniform distribution. The wind load coefficients for life rafts presented in this paper are derived from wind tunnel tests in uniform flow obtained at the Aviation Institute in Warsaw. Data of life raft movements on waves have been collected during full size experiments at sea. Data from wind tunnel test are the basis of knowledge of wind loads on drifting rescue units.

Keywords: *Drifting rescue units, wind pressure, wind pressure stochastic model*

INTRODUCTION

The power in the wind is a function of air density, the area intercepting the wind, and the instantaneous wind velocity [4]. Changing any one of these factors influence the power available from the wind.

In the case of variable wind the wind pressure Fw on a life raft should be treated as spatial - time stochastic process, stationary and ergodic with respect to time. Wind pressure depends on a moment speed of wind and it should be presented as amount of static load Fs and the random fluctuation of load dynamic Fd. For example a wind pressure on perpendicular surface in direction of undisturbed air flow is given by formula:

$$F_w = F_s + F_d \tag{1}$$

Wind intercepting area is a variable depending on the place on wave of a drifting rescue unit (DRU). In the case of random place of DRU the wind intercepting area should be treated as a realization of random function dependent on pitch angle, roll angle and location on a wave slope.

THE WIND FORCE

In the wind tunnel the apparent wind velocity Vw and angle are measured in the horizontal plane. The drive force and side force are measured in a horizontal plane, where the drive force is parallel to the centerline of the drifting rescue unit and the side force perpendicular to it, [7]. The vertical force is positive upwards.

The effect of a DRU heeling can be incorporated in the apparent wind angle to form an effective angle where the effective angle is the apparent angle in a plane normal to the z-axis.

The effective wind velocity (V_{eff}) is defined as the component of Vw in a plane normal to the z axis and calculated from

$$V_{eff} = V_w \cdot \cos(\phi) \cdot \cos(\psi) \tag{2}$$

where
ϕ - roll angle,
ψ - pitch angle.

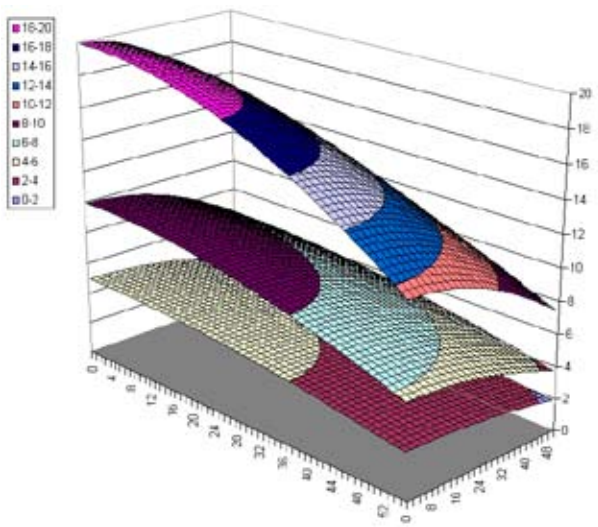


Figure 1 *Example of an effective wind velocity as a function of roll and pitch angles for wind speed 10, 20 and 40 knots.*

We will assume that the marginal distribution of the mean wind speed at 10 m can be described by the 2-parameter Weibull distribution:

$$F_w(x) = 1 - \exp\left\{-\left(\frac{x}{\beta}\right)^{\alpha}\right\} \tag{3}$$

where α and β are the shape and scale parameters, respectively.

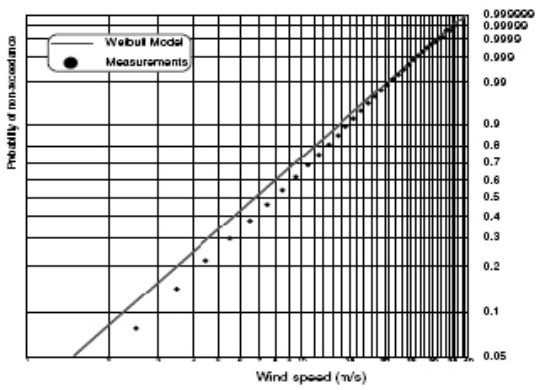


Figure 2 *Cumulative frequency distribution of 1-h mean wind speed for Northern North Sea, [1].*

The following equation is to be used to calculate the wind heeling force to be assumed acting on structure at a given height above the mean waterline:

$$F_w = \frac{0,5}{g} \cdot \rho_a \cdot A_d \cdot C_d \cdot \left(v_w^2 + v_w \cdot v(t)\right) \tag{4}$$

where:

F_w - is the wind force,
ρ - air density,
C_d - shape factor (drag coefficient),
A_d - the wind intercepting area,
v_w - average wind speed,
v(t) - random fluctuation of wind velocity.
g - is acceleration due to gravity.

The wave influence

The location of a drifting rescue unit on a wave (crest or slope) can cause changes in wind pressure affecting a DRU, significantly changing the wind intercepting area and wind's basic pressure. Other conditions, such as a DRU trim and a wave slope angle are very important too. The pressure exerted by strong winds on the DRU is a function of the dynamic part of Bernoulli's equation, [5], known as basic pressure, which is modified by the following factors: wind direction in relation to a DRU axis system, wind speed, the DRU height, wave height, wave slope angle. A trochoid is the locus of a point at a distance R from the centre of a circle of radius r rolling on a fixed line. A trochoid has parametric equations. One of the simple mathematical methods used to describe a sea wave motion is the trochoid formula, [3], [6]:

$$\begin{aligned} x &= R \cdot \Theta + r \cdot \sin\Theta \\ z &= R + r \cdot \cos\Theta \end{aligned} \tag{5}$$

where:

R - distance from the centre ,
r - radius of the inner circle, $2 \cdot r = h_w$ - wave height.
Θ - parameter of the position.

Approximating the sea waves with trochoid allows to show influence of the wave height on wind forces. If the reference plane „0" is a wave though then the formula for DRU vertical position on a wave is:

$$z = r - r \cdot \cos\Theta \tag{6}$$

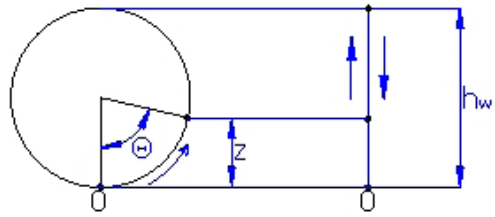


Figure 4 *Position of the search object on the trochoid, [9].*

Let's assume that random variable Θ has a continuous uniform distribution from 0 to 2π, which is described by the density function:

$$f(\theta) = \begin{cases} \frac{1}{2\pi} & \text{for} \quad \theta \in \langle 0, 2\pi) \\ 0 & \text{for} \quad \theta \notin \langle 0, 2\pi) \end{cases} \tag{7}$$

Accordingly, the cdf is

$$F(x) = \begin{cases} 0 & \text{for} \quad \theta \le 0 \\ \frac{x}{2\pi} & \text{for} \quad 0 < \theta \le 2\pi \\ 1 & \text{for} \quad \theta > 2\pi \end{cases} \tag{8}$$

The expectation of this distribution is

$$E(\theta) = \pi \tag{9}$$

According to (5) and [1] we can assume that random variable r has a Weibull distribution, with parameters dependent on sea region, which is described by the density function:

$$f_X(x) = \frac{c}{b}\left(\frac{x}{b}\right)^{c-1} e^{-\left(\frac{x}{b}\right)^c} \qquad x \ge 0, c > 0, b > 0 \tag{10}$$

where

b- scale parameter,
c- shape parameter.

Nondimensional parameter C_{Ap} describing the proportion of a DRU wind intercepting area is given by formula

$$C_{Ap} = \left(1 - \frac{h_w(1 + \cos\Theta)}{2h_{SO}}\right) \qquad \text{for } h_w \le h_{SO} \tag{11}$$

where:

h_{SO} - height of drifting rescue unit, [m];
hw - height of wave, [m].

In this case equation describing the wind heeling force acting on DRU at a given position on a wave is given by formula:

$$F_w = \frac{0,5}{g} \cdot \rho_a \cdot C_{Ap} \cdot A_d \cdot C_d \cdot \left(v_{eff}^2 + v_{eff} \cdot v(t)\right) \qquad (12)$$

where:

C_{Ap} - is the random variable;

Assuming that the h_{SO} is constant, the random variable C_{Ap} has the distribution function which is described by the density function:

$$\Pr\left(C_{Ap} < z\right) = \Pr\left(1 - \frac{h_w(1+\cos\Theta)}{2h_{SO}} < z\right) = \Pr\left(1 - z < \frac{h_w(1+\cos\Theta)}{2h_{SO}}\right) =$$
$$= \Pr\left((1-z)\cdot 2h_{SO} < h_w(1+\cos\Theta)\right) = 1 - \Pr\left(h_w(1+\cos\Theta) \le (1-z)\cdot 2h_{SO}\right) \qquad (13)$$

$$f_{C_{Ap}}(z) = -\frac{\partial \Pr\left(h_w(1+\cos\Theta) \le (1-z)\cdot 2h_{SO}\right)}{\partial z} =$$
$$\int_0^\infty \frac{\beta x^{\beta-1}}{\theta^\beta} \exp\left(\frac{x}{\theta}\right)^\beta \cdot f_{1+\cos\Theta}\left(\frac{(1-z)}{x}\cdot 2h_{SO}\right) \cdot \frac{2h_{SO}}{x} dx \qquad (14)$$

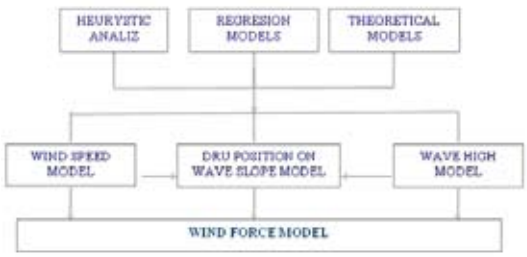


Figure 5. Wind force model diagram.

Application

Aerodynamic experiments of inflatable life rafts were performed in the Laboratory of Low Velocities in the Institute of Aviation, [7]. The aim of laboratory experiments was to determine the wind forces acting at a life raft. The research was carried out in the aerodynamic tunnel. The research concerned the range of speeds in the measurement space of the tunnel from 20 to 64 knots, Vw = 10-34 m/s. The results obtained from laboratory experiments allow to estimate life raft's real aerodynamic drag. This statement follows from lack of wind speed influence on flow character around raft.

Laboratory data were analyzed by the statistical program Statgraf. Regression models of relation between wind velocity and measured forces and moments were obtained.

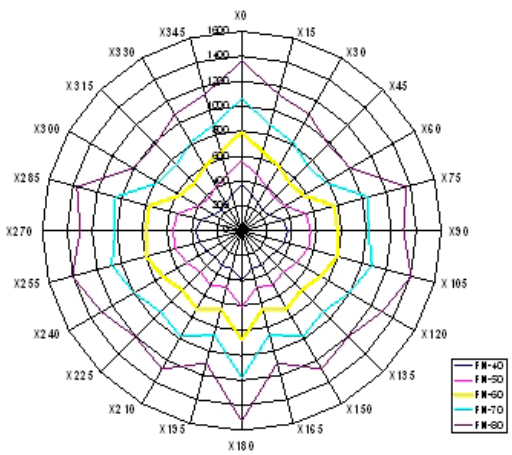


Figure 6. The space distribution of wind heeling force, steady conditions- 40, 50, 60, 70, 80 kn wind speed, results from wind test tunnel for a ten-person life raft, [7].

$Y_\theta(\omega) = \frac{2\cdot\theta_a}{H_w}$ - amplitude characteristic of pitching;

H_w - wave height, [m];

θ_α - pitching amplitude, [o]

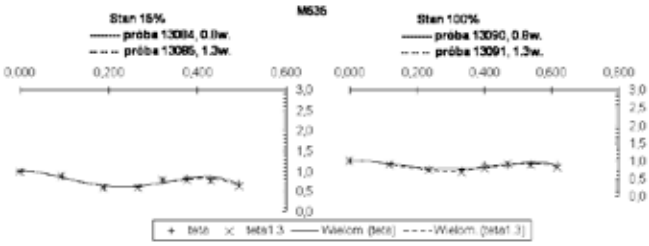
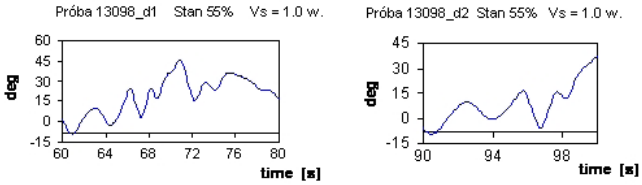


Figure 7. Examples of pitching amplitude characteristic for the life raft.



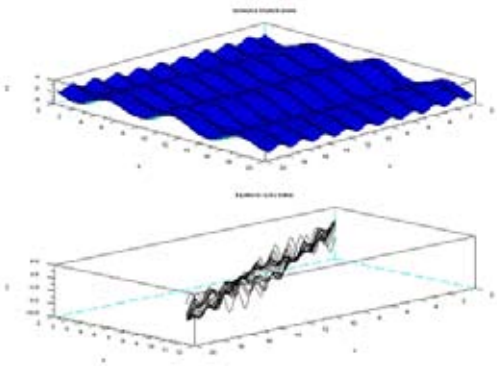


Figure 9. Examples of drifting trajectory for the life raft obtained by the Monte Carlo method.

Figure 10. Checking the roll time for the life raft.

Table 1 Summary Statistics for roll and pitch

Parameter	Roll	Pitch
Count	16383	16383
Average	-3,62876	-0,555882
Median	-3,65343	-0,55036
Variance	0,0214192	0,00721558
Standard deviation	0,146353	0,0849446
Minimum	-3,96105	-0,786566
Maximum	-3,13158	-0,270209
Range	0,829468	0,516357
Std. skewness	44,712	9,7818
Std. kurtosis	26,7091	4,51402

The table shows examples of summary statistics, measured for a 10-person life raft at sea tests. It includes measures of central tendency, measures of variability, and measures of shape. Of particular interest here are the standardized skewness and standardized kurtosis, which can be used to determine whether the sample comes from a normal distribution. Values of these statistics outside the range of -2 to +2 indicate significant departures from normality. The standardized skewness value is not within the range expected for data from a normal distribution. The standardized kurtosis value is not within the range expected for data from a normal distribution.

During tests the life raft had a trim according to the worst case of loading, asymmetry of 30% loading and drift velocity.

Conclusion

The excitation forces and moments in the DRU system are generated by wind and waves. Trim will play an important part in the stability of a DRU which is influenced by the wind, [8].

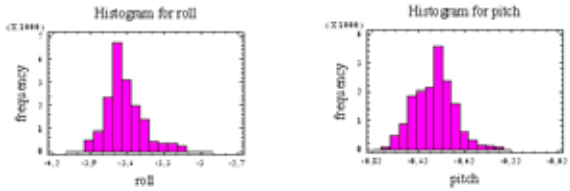


Figure 11 *Histogram for roll and pitch*

The mathematical model should be based on stochastic model and data from laboratory experiments.

Wind will play an important part in the response of any DRU

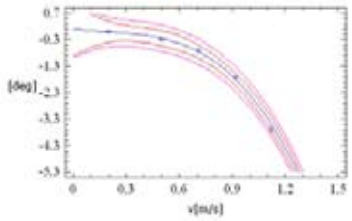


Figure 12 *The trim as a function of a life raft drift velocity, [1].*

that has a significant height above the waterline; the motions of DRU are influenced by the direction and characteristics of the wind. Application of wind forces and moments, estimated in the laboratory experiments for a particular drifting rescue unit type, will allow for more correct estimation of a DRU wind heeling arm and its stability. Dynamic models should be used to represent, or generate trends and patterns over time. They also could show averages per period, moving averages and comparative analysis. The dynamic wind force heeling model will be useful in estimation of a DRU safety.

Acknowledgement

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People, research work, publications and symposia

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Keywords: *research work, symposia, publications, Ilawa*

INTRODUCTION

The aim of this paper is to remember and to fix in the memory some events of the activities of the Experimental Centre in Ilawa. The idea and initiative of setting up in 1956 the Experimental Centre of the Gdansk University of Technology Chair of the Theory of Ships came from prof. Lech Kobylinski. No such research centre to support the developing shipbuilding industry was then available in Poland. Fifty years ago the beginnings of the Centre in Ilawa were modest, but within a short time, 10 to 15 years, it became an important centre of the ship hydromechanics in Poland. Apart from the head of the Chair, many people contributed, in a greater or less degree, to the development of the Centre. Some of them have been mentioned in the description of investigations performed. I would like to mention now some non-typical tests and their participants, but first of all those workers of the Centre who passed away. It should also be remembered that Ilawa is the cradle of Polish ship hydromechanics as here the hydromechanical scientific symposia were started. Since then they have been continued as international symposia with worldwide participation and organized in turn by several Polish institutions.

People

Many persons marked their presence in Ilawa with their activity in the course of time. We wish we could see here today the former workers of the Chair of Theory of Ships, later renamed to Division of Ship Hydromechanics in the Shipbuilding Institute, but not only them as many persons worked here who were not employees of the Gdansk University of Technology. The attendance of so many people tells about the ties with the Ilawa Centre. Therefore, let's take this opportunity and try to summarize the professional and scientific achievements brought about by the Ilawa Centre activities.

This is also an opportunity to remember all those who took part in the research work and contributed to the development of the Centre. It is difficult to mention all of them by name, but I will call those who have died. Fifty years is a long period in a human life. If the list of living former workers is still long, it is only because they were young or very young when they began to work here, some of them even 50 years ago. Some of those who passed away did not even reach the retirement age.

In the initial period of the Centre development Zbigniew Gryglewski (1954-1958, +1992, years of work with the Chair and the year of death) contributed a lot, then technical manager of the Division of the Theory of Ships, later director of the Gdansk Ship Repair Yard and worker of the United Polish Ship Repair Yards head office. Tadeusz Nasiłowski (1958-+1981), the next technical manager, supervised construction of the first brick building in the Centre. Our modellers built in Gdansk ship models for Ilawa, repaired them in Ilawa after collisions, made all the woodwork in the Centre and also constructed a small house on the Lipowa island. They were: Stanisław Kułak (1973-1986, +1988), Wacław Piechowiak (1963-1984, +2002), Antoni Staszak (1959-1974, +1998), and Bolesław Szymanek (1958-1979, +1999). The mechanicians working in Ilawa were: Jan Berendt* (1954-1979), the first K-1 hydrofoil boat foil maker, Walerian Gampe (1957-1970), also a supply van driver, Wiktor Strawski (1958-1965), Jan Wardak (1975-1991, +2002), Tadeusz Wiśniewski (1961-+1989) and Włodzimierz Wojtera (1964-1983, +1989). The measurement apparatus engineers spent a lot of time in Ilawa: Edmund Adelman (1957-+1966) and Romuald Snarski (1957-+1991). Tadeusz Racki* (1963-1972, +2002), the workshop manager, later worked with the CTO towing tank; Witold Krenicki (1958-+1978) took part in the fast ship tests; Andrzej Fiedziuszko (1952-1991, +2000) although did not come to Ilawa for tests, prepared documentation in Gdansk of models built for Ilawa. Designers: Lucjan Dębski (1955-1959, +1985), later employee of the PROREM design office i Jerzy Połubiński* (1959-1962, +1988), later in the then Central Ship Design Office and in the Gdansk Shipyard. Aleksandra Kempińska (1981-1987, +1989) draftswoman in the Divisions. Mikołaj Kusznir (1971-1989), the Centre housekeeper and Anna Kusznir (1956-1971, +1983), cleaner.

The mentioned persons, employees of the Chair of the Theory of Ships or the Division of Ship Hydromechanics, worked for the benefit of the Ilawa Centre. Some of them, e.g. those marked with (*), were formally, at least for a part of that period of time, employees of the Institute of the Fluid Flow Machines, Polish Academy of Sciences.

Non-typical tests

Apart from investigations that may be considered routine, very diversified tests, depending on the needs, were also carried out. They are worth reminding here. Some of the results were implemented in designs, other investigations did not go beyond laboratory tests or the results were used only in publications. Some of those non-typical tasks are described here.

Gas-stream propeller

In the years 1961-1965, on Jeziorak Lake in Ilawa, tests of a gas-stream propeller were carried out on large self-propelled models, to an order of the Maritime Institute in Gdansk. The main structural element was a straight inclined propulsion channel, an integral part of the hull.

Compressed air was supplied to the propulsion channel through a special conduit and then mixed with water in the preliminary mixing chamber. The mixture flowed freely along the propulsion channel. Horizontal component of the normal force was the propeller thrust force. The investigations were led by Tadeusz Witalewski from the Maritime Institute side and by Wiktor Maksymiuk from the Chair of the Theory of Ships side. The aim of the tests was to confirm the theoretical principles of such propeller, developed in the Maritime Institute, and also to obtain additional information necessary for the design of floating units with such propulsion system. It was assumed that such propellers without moving parts would have some advantage over the screw propellers mainly in the shallow, overgrown and fouled waters. The tests allowed to develop a propulsion channel design method for specific operating conditions. In view of the strong hovercraft development at that time, units with such propulsion system did not arouse much interest. The outcome of the investigations were publications, two patent applications and a doctor dissertation accomplished in 1968.

Damping of the ship rolling

In the years 1961 – 1964 all the large models in the Experimental Centre, used earlier for the resistance and propulsion tests, took part in the damped rolling tests on calm water in order to determine the rolling damping characteristics. The tests were performed as own research work. The models were tested in different loading conditions, with or without the bilge keels, tugs and fish cutters with bar keels. From those measurements an approximate method of damping calculations for different hull shapes was formulated and then used for the analysis of ship behaviour in waves.

In 1969, to an order of the Maritime Institute, a series of measurements were performed of the damping effectiveness with different shapes of the bilge keels. Selected bilge keels were installed on one of the "Koga" fishing company cutters. In the same year, during stormy weather on the Gulf of Gdansk waters, a Division of Ship Hydromechanics team carried out measurements of two B25s cutters, one with bilge keels, the other without. Results of those investigations were later a subject of several patent applications submitted by a Maritime Institute employee.

Landing craft

From 1961 comprehensive model tests of the landing craft were carried out as those ships were intended not only for modernization of the Polish Navy but also as an attractive export article. Those ships were built in different variants but on the same hull by the Northern Shipyard and Naval Shipyard. Apart from the resistance-propulsion and manoeuvring tests, also the beach landing tests were performed with the measurements of hull pressures and withdrawal from beach tests. Model landed on the beach with various speeds without the use of own propulsion and helmsman. In that test, the model was towed by a plummet falling from a high tower. Also landing tests of a self-propelled model with helmsman and withdrawal from beach tests by the astern operation of propellers were performed. As observers of the Warsaw Pact manoeuvres would tell, those ships had a strong instinct of self-preservation, as they would easily withdraw from the beach, whereas landing craft built in the USSR and GDR had considerable difficulties with the withdrawal.

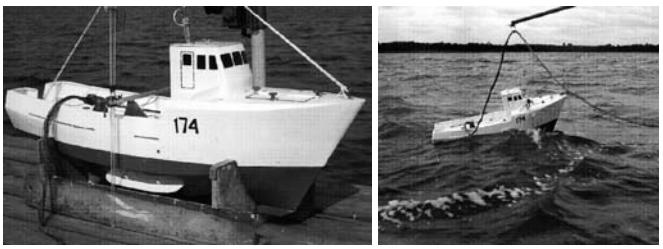

Fig. 1. Investigations of the bilge keel effectiveness

The Naval Shipyard in Gdynia built altogether 17 medium size landing craft, including 4 ships for India in 1974-1976 and additional 4 in 1984-1986; 4 ships for Iraq in 1976-1979 and 4 for Libya in 1977-1979, and 1 for Yemen in 2002. During the commissioning of ships in Gdynia, the Iraqi officers ordered commemorating medals with a Gdansk medallist. There is a medal for the first ship (ATIKA 1976), for the second ship (JENADA 1977) and for the fourth ship (NOAH 1979). No medal was ordered for the third ship GANDA in 1978. The ships received consecutive side numbers from 82 to 85. When a Shipyard delegation was in Iraq in 1989 to discuss the conditions of repair of those ships, the Iraqi fleet had only three ships and the last, NOAH, had number 84. It turned out that the third ship, GANDA, the one without the commemorating medal, had been destroyed by mistake by own air force. The medals were a good talisman for the ships. But in August 1990 the invasion on Kuwait took place and five months later the "Desert Storm" operation began. A rocket attack of British helicopters on ships stationed in the Umm Qasr harbour completed the destruction. Repairs were no longer needed.

Fig. 2. Landing craft investigations

In the water area near the Lipowa island and Siemiany village a system of the Gdansk Northern Port piers and jetties was reconstructed. A model of the then largest Polish tanker ZAWRAT was used for the handling tests. Before the real ship entered the port, self-propelled model tests were carried out and also with auxiliary floating units simulating the tugs, with measurements of forces in the tow-ropes. Tests were carried out in 1975 and 1976, with the participation of Jacek Nowicki

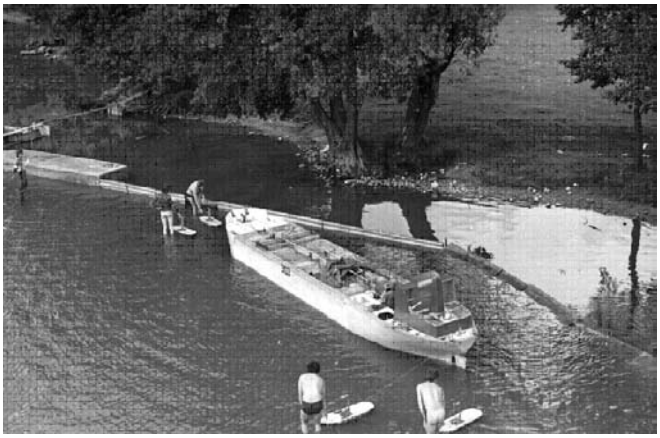

Fig. 3. Model tests of handling a large ship in the Gdansk Northern Port

(leader), Anicet Niedźwiecki, Wiesław Kopylec, Anna Kokoszka and students of the Shipbuilding Institute.

Trawl nets

In the 1970s, Polish shipbuilding industry was a world power in building seagoing fishing vessels. The Sea Fishing Institute (MIR) in Gdynia worked on the improvements in fishing tools and processes as well as on the optimisation of the ship - trawl system. In order to obtain information on the water flow speed distribution in the trawl during hauling and on forces in the individual trawl system elements, a series of tests were performed in Ilawa in 1971, in cooperation with MIR, on several trawl models hauled by catamaran with different speeds. The trawls had different net mesh size and string thickness. The speed distribution in trawl was measured with a set of MIR-designed logs. The test results allowed to develop improved trawls preventing fish escaping from the trawl system and thus improving the fishing effectiveness. The tests in Ilawa reduced the scale of later real tests at sea. From the MIR side the investigations were led by Zbigniew Ziembo.

In 1978 tests of the pelagic trawl models were performed. The models were delivered by MIR and the trawls were to be used on the B418 type factory trawlers. For different hauling speeds, tests were carried out of the trawl warp angle, trawl horizontal and vertical opening, trawl mean draught and forces in the trawl warps. Measurements were performed with one trawl as well as with a set of two or three trawls. For determination of the scale effect and tow rope power predictions, the test results of geometrically similar real trawls were used. Leader of the test team (a large team from MIR and from the GUT Division of Hydromechanics) was Andrzej Jarosz.

Kayaks and sportsboats

In 1975-1978 investigations were carried out, ordered by the PROMOR Ship Production Technology Centre in Gdansk, aimed at improving the performance of the Polish canoeists and oarsmen. The problem was coordinated by Bogdan Szanser from the RKS Stoczniowiec sports club and employee of PROMOR. The tests consisted in determining and improving the hydromechanical characteristics of the racing kayaks and canoes as well as designing the kayak rudders. The work included also the shape of oar blade for the racing canoe and blade shapes of other oar types. A conception was developed of an oar movement simulator and the oar driving mechanism together with the measurements of forces. Result of the work was patent application "Device for automatic measurement of the impulse and time of the force on an oar blade". The results were tested on a group of sportsmen and sportswomen. The work was led by Krzysztof Paul in cooperation with Ryszard Kaminski, Witold Blocki and Mikolaj Jagielka.

Determination of the maximum overloads of a dropped lifesaving capsule

Model tests, ordered by the GUT Division of Ship Production Technology, were carried out of a dropped lifesaving capsule, by means of an ejector. The capsule was intended for evacuation of people from a drilling platform or ship in emergency, first of all in the conditions of sea surface covered with burning oil. The aim of tests was to determine maximum overloads during such operation. In the real scale (model in 1:10 scale) the drop height was 10 to 30 m and the ejection distance 20 to 40 m. Maximum resultant accelerations could reach 10 g. Tests were carried out in December 1983, after ice had been removed from water at the jetty where the capsule was dropped to water. The tests were performed by Janusz Stasiak, Krzysztof Paul, Wieslaw Gozdur, Jerzy Seregiet and others.

Ship capsizing

In 1993 and 1994, the Foundation for Safety of Navigation and Environment Protection performed a series of measurements to show what are the conditions of a ship capsizing in waves. In view of a great number of different parameters influencing the behaviour of a ship in waves, the measurements were limited to wave recordings and determination of the effective wave height as well as the calm water righting lever of the tested model. The tests were performed on one self-propelled, remotely controlled model of a fishing trawler, with two different values of the hull depth. The model was tested with different stability characteristics, different speeds, different headings in relation to the waves near the wave recording probe, until the model capsized. Those results were used to describe a safe curve of righting levers as a function of the effective wave height and to verify the theoretical calculations. The tests were performed by the author of this paper with Ryszard Kaminski, Janusz Wolniak and Jan Bielanski.

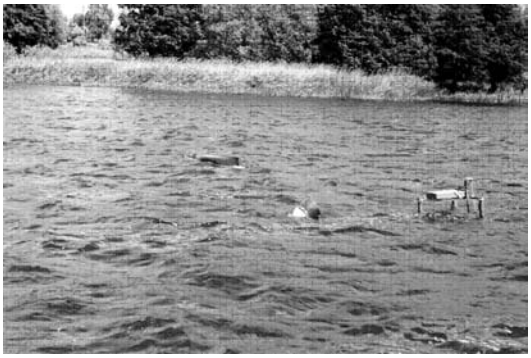

Fig. 4. *Tests of a ship capsizing in waves*

Cooperation with the Military Engineering Institute

From the end of 1980s to mid-1990s investigations were carried out for and in cooperation with the Military Engineering Institute in Wroclaw. The first tests consisted in the use of track chain drive as a floating tank propeller and were performed by the GUT Division of Ship Hydromechanics. The work on propellers for the armoured wheeled vehicles was carried out by the Foundation for Safety of Navigation and Environment Protection. All those tests were performed on Jeziorak Lake. An additional smaller model of an armoured vehicle was used for tests in the GUT Chair of the Theory of Ships towing tank, aimed at determining the scale effect in the wheeled vehicle resistance tests.

Publications and symposia

When the scope of investigations carried out in the Ilawa Centre was widened and the measurement techniques gradually improved, the Centre became a recognized performer of research work ordered by the ship design offices and ship owners. Also analyses were undertaken aimed at verification of the test results as well as scientific research work in the long-term R&D plans. That influenced greatly the number of reports issued and the number of papers published in the technical journals, domestic and foreign, by the Division of Ship Hydromechanics employees. In 1971, on the 15th anniversary of the Centre, prof. L. Kobylinski initiated organization of a symposium on the open water ship model tests. The symposium met with

a lot of interest in many ship hydromechanics research centres in the country. At that time the CTO Centre of Ship Hydromechanics in Oliwa did not exist yet. The symposium summarized the number of publications issued in connection with work carried out in Ilawa, comprising internal test reports, papers in technical journals, the International Maritime Organization (then IMCO) documents and patent applications. There were 174 such papers written by 29 persons. Three years later, in 1974, those numbers were 244 and 38, respectively. Among them were several accomplished doctor dissertations.

That first Symposium in Ilawa in 1971, organized together with the Polish Society of Mechanical Engineers (SIMP) (let's call it symposium number zero or initiating), where 10 papers of 13 authors were presented, started a permanent series of ship hydromechanics conferences in Poland. They have been organized until now and their list is given below.

Two years later, in 1973, the GUT Division of Ship Hydromechanics with the Ship Design and Research Centre (CTO) organized the next Symposium in Ilawa, which received number "1". There were more papers, including one author from abroad - Boris W. Mirokhin, assistant professor from the Leningrad Shipbuilding Institute, the then close cooperation partner. In view of large interest, it was declared at the end of that 1st Symposium that they would be organized every year. The next 2nd Symposium in 1974 was organized by the Ship Design and Research Centre (CTO) in Gdansk together with the GUT Shipbuilding Institute. In the conference proceedings the Shipbuilding Institute is named as an organizer, but in fact the organizer was always the SI Division of Ship Hydromechanics, and the role of Shipbuilding Institute was so underlined because the same person, prof. L. Kobylinski, was then head of the Division of Ship Hydromechanics and director of the Institute. In 1975 the Department of Ship Propellers of the Institute of

Fig. 5. *Scientific session on the 15th anniversary of the Ilawa Centre*

Fluid Flow Machines, Polish Academy of Sciences, joined the organizers of Ship Hydromechanics Symposia as a third permanent partner. It was then decided, however, that symposia would be held every two years organized in turn by one of the three organizers with support from the other two, which has been regularly happening. In 1989 the Faculty of Mechanical Engineering of the Technical University of Wroclaw joined the organizing group and it was then decided that in view of the increasing number of foreign participants the symposia would have an international character. In 1991 the conference papers were published in English and the symposium acronym HYDRONAV was adopted. From the 11th Symposium in 1995 the language of conference is English and all papers are published in English.

Apart from the Ship Hydromechanics, in connection with the development of the "School of Captains", first on the Jeziorak Lake and later on the nearby Silm Lake, as well as with the research work conducted there, scientific conferences devoted exclusively to ship manoeuvring were increasingly needed. The birthplace of those conferences, international from the start, was Ilawa. As it had been with HYDRONAV, they started modestly as a Ship Manoeuvring Workshop – Manoeuvring Qualities in Ship Design, on 4–7 October 1993, organized by the Division of Hydromechanics, Faculty of Ocean Engineering and Ship Technology, Gdansk University of Technology with cooperation of the Foundation for Safety of Navigation and Environment Protection, with 12 papers prepared by 14 authors. Two years later the Foundation for Safety of Navigation and Environment Protection organized in Ilawa, on 16-19 October 1995, the first International Symposium on Manoeuvrability of Ships at Slow Speed, with 23 papers prepared by 41 authors. It was then decided that those conferences would be held every five years. The consecutive ship manoeuvrability conferences were organized in 1999 and 2005 but as joint symposia with HYDRONAV. Those combined conferences received an own acronym - HYDMAN.

Fig. 6. *2nd Symposium on Ship Hydromechanics*

List of the symposia on ship hydromechanics

Model tests in open waters
Ilawa 17 – 18.09.1971. Organizer: GUT Shipbuilding Institute with the Polish Society of Mechanical Engineers. Chairman of the Organizing Committee– assist. prof. Wiktor Maksymiuk, secretary – Witold Krenicki, papers: 10, authors: 13.

1st Symposium on Ship Hydromechanics
Ilawa 20-21.09.1973. Organizer: GUT Shipbuilding Institute with CTO and the Polish Society of Mechanical Engineers. Chairman of the Organizing Committee – prof. Lech Kobylinski, secretary – Jacek Pawlowski, papers: 14, authors: 14 including one from abroad.

2nd Symposium on Ship Hydromechanics - Model tests in ship design
Gdansk 28 –30.10.1974. Organizer: Ship Design and Research Centre (CTO) Model Testing Centre with the GUT Shipbuilding Institute. Chairman – Kazimierz Szponar, secretaries – Marian Banacki and Andrzej Bujnicki, papers: 18, authors: 21, including three papers prepared by five authors from abroad.

3rd Symposium on Ship Hydromechanics - Hydrodynamic problems of ship propulsion
Gdansk 20 – 22.11.1975. Organizer: Institute of Fluid Flow Machines, Polish Academy of Sciences with GUT SI, and CTO. Chairman – prof. Henryk Jarzyna, secretaries – Tadeusz Koronowicz and Ryszard Kozubowski, papers: 19, authors: 20, including three authors from abroad.

4th Symposium on Ship Hydromechanics – Ship dynamics
Gdansk 26 – 27.05.1977. Organizer: GUT Shipbuilding Institute

with IFFM PAS and CTO. Chairman – assist. prof. Wieslaw Welnicki, secretary – Anicet Niedzwiecki, papers: 15, authors: 17.

5th Symposium on Ship Hydromechanics - Design and research problems of ship propellers
Gdansk 20 – 21.09.1979. Organizer: Ship Design and Research Centre with GUT SI and IFFM PAS. Chairman – Kazimierz Szponar, secretaries – Marian Banacki and Andrzej Bujnicki, papers: 17, authors: 17.

6th Symposium on Ship Hydromechanics - Hydromechanics in the design and economic operation of ships
Gdansk 9 - 11.10.1985. Organizer: Ship Design and Research Centre with GUT SI and IFFM PAS. Chairman – Marian Banacki, secretaries – Jan Dudziak and Antoni Bednarek, papers: 36, authors: 42.

7th Symposium on Ship Hydromechanics - Numerical methods in ship hydromechanics.
Gdansk 11 – 13.11.1987. Organizer: IFFM PAS with GUT IS and CTO. Chairman – prof. Henryk Jarzyna, secretaries – Jan Szantyr and Jacek Centkowski, papers: 29, authors: 31.

International Symposium on Ship Hydromechanics "Hydromechanics '89"
Wroclaw 20 – 22.11.1989. Organizer: Faculty of Mechanical Engineering, Technical University of Wroclaw. Chairman – prof. Waclaw Kollek, secretary – Jozef Samolyk, papers: 42, authors: 65.

Ninth International Symposium on Ship Hydromechanics HYDRONAV '91
Sarnowek 17 – 19.09.1991. Organized by: Division of Ship Hydromechanics, Faculty of Ocean Engineering and Ship Technology, Gdansk University of Technology. Chairman of the Organizing Committee – prof. Lech Kobylinski, secretary– Janusz Stasiak, papers: 30; authors: 46.

10th Symposium on Ship Hydromechanics - The role of hydromechanics in the design and operation of ships
Gdansk 2 – 3.12.1993. Organizer: Ship Design and Research Centre. Chairman - Ryszard Lech, secretary - Stefan Jaworski, papers: 27, authors: 36.

11 th International Conference on Problems of Marine Propulsion HYDRONAV'95
Gdansk 22 – 24.11.1995. Organized by: Department of Ship Propellers, Institute of Fluid Flow Machines of the Polish Academy of Sciences. Chairman – prof. Jan Szantyr, secretary – Leszek Wilczynski, papers: 22, authors: 31.

Twelfth International Conference on Hydrodynamics in Ship Design HYDRONAV'97
Szklarska Poreba 17 – 19.09.1997. Organized by: Faculty of Mechanical Engineering, Technical University of Wroclaw. Chairman – prof. Jan Kulczyk, secretary - Tomasz Tabaczek, papers: 35, authors: 48.

Joint 13th International Conference on Hydrodynamics in Ship Design and 2nd International Symposium on Ship Manoeuvring, HYDRONAV'99 and MANOEUVRING'99 dedicated to professors of the Gdansk University of Technology Lech Kobylinski and Mieczyslaw Krezelewski on their Golden Jubilee.
Ostroda 22 – 24.09.1999. Organized by: Faculty of Ocean Engineering and Ship Technology, Gdansk University of Technology and Foundation for Safety of Navigation and Environment Protection. Chairman – prof. Jan Szantyr, secretary – Wojciech Misiag, papers: 46, authors: 59.

14th International Conference on Hydrodynamics in Ship Design
Miedzyzdroje 27 – 29.09.2001. Organized by: Technical University of Szczecin. Chairman – prof. Tadeusz Szelangiewicz, secretary - Tomasz Abramowski, papers: 32, authors: 60.

15th International Conference on Hydrodynamics in Ship Design – Safety and Operation, HYDRONAV'03
Gdansk 22 – 23.10.2003. Organized by: Ship Design and Research Centre. Chairman – Ryszard Lech, secretary - Leszek Wilczynski, papers: 28, authors: 50.

Joint 16th International Conference on Hydrodynamics in Ship Design and 3rd International Symposium on Ship Manoeuvring HYDMAN'05
Ostroda 7 – 10.09.2005. Organized by: Faculty of Ocean Engineering and Ship Technology, Gdansk University of Technology and Foundation for Safety of Navigation and Environment Protection. Chairman – prof. Lech Kobylinski, secretary – Milosz Frackowiak, papers: 56, authors: 94.

Summary

It can be seen from this overview that those two Centres, one of the Gdansk University of Technology in Ilawa and the other of the Foundation for Safety of Navigation and Environment Protection in Ilawa-Kamionka have greatly influenced the development of ship hydromechanics. All the conferences on these subjects were initiated here. In sixteen HYDRONAV and three MANOEUVRABILITY Symposia held in the 1971-2005 period, together with two preliminary symposia, 511 papers were presented by many Polish and foreign authors. Ilawa is well known on all the continents, also because of a great number of shipmasters trained in the Research and Training Centre for Ship Manoeuvrability. Apart from the symposia listed here, results of research work carried out in Ilawa were presented also in the Conferences on Fluid Mechanics, Scientific Conferences of Naval Architects and Marine Engineers and also in many conferences abroad. It may well be said that Ilawa is a cradle of the Polish ship hydromechanics.

It has to be underlined that the test conceptions and result interpretation had an individual character but test execution was always a team work carried out by teams assigned to each task.

Measurements on the lake caused some losses which always interfered with the course of tests. The lake would swallow up some tools, sometimes pieces of apparatus, it happened that a self-propelled model lost its propeller and once a model was sunk and in spite of its quite large size, was found in the muddy waters of Jeziorak only after a prolonged search.

Summing up today the professional, teaching and scientific achievements of the Ilawa centre for the shipbuilding and shipping industry, one may say that Ilawa is a lucky place. In fifty years of activities not a single serious accident occurred, although dramatic situations were plenty. May Ilawa remain such a lucky place for the years to come.