THE ARCHIVES OF TRANSPORT
Volume 33, Issue 1, 2015

ISSN (print): 0866-9546
e-ISSN (online): 2300-8830
DOI: 10.5604/08669546.1160928

MODEL-BASED INVESTIGATIONS ON DYNAMIC SHIP HEELS IN RELATION TO MARITIME TRANSPORT SAFETY

Waldemar Mironiuk

Naval Academy, Department of Navigation and Naval Weapons, Gdynia, Poland
e-mail: w.mironiuk@amw.gdynia.pl

Abstract: *The paper has been presented criteria of similarity between of liquid motion. Results of initial research on air flow's dynamic impact on a ship model of 888 project type are presented in the elaboration as well. The research has been executed at a test stand located in the Polish Naval Academy. The ship model of 888 project type has been an object of the tests. Results of executed measurements have been compared with theoretical calculations for an angle of dynamic heel. Input parameters for the tests and calculations have been defined in accordance with recommendations of Polish Register of Shipping (PRS) and IMO (IMO Instruments). Determination of a heeling moment by wind operation has been a key issue.*

Key words: *heeling moment arm, dynamic heel angle, righting lever, ship stability.*

1. Introduction

Increase in migration of people and in trade by sea have contributed to substantial increase in traffic on sea lanes and progress in technology has made it possible to build ships having big displacement. More than 80% of the world trade makes use of maritime transport, which has become one of the pillars of international trade (EMSA). Apart from many advantages, this has created several hazards to safety in maritime transport and to natural environment.

The present day indicates economic use of tonnage. Sizes of ships, tonnages are terminal objectives in themselves. Transport of large amounts of cargo, mining and exploiting natural mineral resources, carrying large number of passengers by sea are characterized by high risk, even if the latest technologies are employed. It is not a long time ago that thousands of people lost their lives in catastrophes of ships, off-shore oil rigs and other marine objects, e.g. the tragedy of RMS Titanic in which over 1500 people lost their lives, the ferry Estonia, the Ro-Ro ferry Herald of Free Enterprise, Costa Concordia, the catastrophe of the tanker Prestige, and numerous other disasters. The tragedy of our train-car ferry Jan Heweliusz, which sank on 14 January, 1993 during her cruise from Świnoujście to Ystad, must be mentioned here. She was overcome by forces of nature and sank off the coast of the island of Rugia in the Baltic Sea with 55 people on board. The greatest maritime catastrophe was that of Wilhelm Gustloff , carrying refugees, torpedoed by a Soviet submarine S-13 in which about 9.5 thousand people died. Hazards posed by Mobile Off-shore Driling Units (MODU) cannot be neglected. There have been a lot of catastrophes relating to their operations, e.g. the oil rig Piper Alpha in the North Sea during which 167 people lost their lives within a few hours and the rig burnt down, Deepwater Horizon in the Gulf of Mexico where 11 people died in an explosion and Kolskaja, which sank while being towed off the coast the island of Sakhalin in the North Pacific Ocean.

Many people suffered injuries and lost relatives or friends at sea. Each of these catastrophes was different. A question arises, whether most of them could have been avoided. The answer is not simple as it is associated with people's continuous efforts to satisfy their needs, sometimes well beyond their capabilities (… may be I will manage, … may be I will manage before the storm hits, … may be this device will be strong enough, …. nothing like this can happen to such an experienced person as me) and that is perhaps one of the problems, in fact, impossible to solve or eliminate from life of seafarers. This and several other questions cannot be answered unequivocally at the moment but asking them will, for sure, contribute to attracting attention to safety in marine navigation. According to some authors it is estimated that around 80% of accidents at sea are caused by human and organizational errors (HOE) (EMSA). A special case of such errors is making wrong decisions by persons keeping watch on the bridge, especially during difficult navigational and weather conditions. Accidents can also be caused by a faulty performance of propulsion systems, steering devices and other mechanisms and appliances used in navigation or for propulsion as well as a lack of skills necessary for crews to fast repair them or use spare devices because of insufficient training or absence of appropriate tools. Therefore, it is important that the highest standards should be observed in training seafarers.

Special role, having impact on maritime safety, is played by naval ships. Due to the nature of missions they carry out they are exposed to damage, fires and even sinking. A naval ship is a complex technical system whose combat capability depends on her reliability. The analysis of literature and maritime practice shows that even the best organized naval fleets suffer from accidents and ship malfunctions. They can be hazardous to lives and health of a ship crew or result in the ship's total loss.

In order to gain knowledge of phenomena that occur during a ship operation at the Naval Academy in Gdynia a decision was made to design and build a test site for carrying out model-based investigations of ships, including in situations of hazard to buoyancy.

The model-based investigations are used as the basic and universal method for forecasting ship dynamic properties, especially at a ship design stage. They also have enormous significance relating to acquiring knowledge and carrying out scientific studies as an autonomic method for acquiring knowledge and as a method used to verify the theory.

2. The idea of model-based investigations

The main idea of the model-based investigations is to use model-based measurement results to infer how a real vessel will perform. In this connection, a basic phenomenon or a real life phenomenon as well as a model-related phenomenon are distinguished as an image of a basic phenomenon (Dudziak, 2008; Jacyna, Wasiak et al, 2014) In order to relate measurement results to a phenomenon existing in reality, a model phenomenon must meet similarity of phenomena conditions, which include similarity criteria and algorithms for converting measurement results from models to reality (Charchalis, 2001; Dudziak, 2008; Jacyna and Merkisz, 2014).

There exist the following kinds of similarities:
- geometric,
- kinematic,
- dynamic.

A geometric similarity occurs when the relation of any, corresponding to each other, measurements in reality and in a model is constant, regardless of the adopted variant. This relation is referred to as a geometric scale (Charchalis, 2001; Dudziak, 2008)

$$\lambda = \frac{L_o}{L_m} = \frac{B_o}{B_m} = \frac{T_o}{T_m} = const \tag{2.1}$$

where: index „o” designates a dimension of an object in reality, index „m” designates a dimension of a model.

In modeling unsteady phenomena, including ship rolling, a geometric similarity as a consequence of dynamic similarity, extends across a distribution of masses in a ship, i.e. it contains such magnitudes as axes and radiuses of mass gravity and coordinates of the center of mass (Dudziak, 2008; Mironiuk and Pawlędzio, 2011).

A kinematic similarity occurs when velocity magnitudes relating to a real object and a model at points and time corresponding to each other are parallel to each other and a relation between their modules is constant (kinematic scale) and independent of the selection of points (Dudziak, 2008; Jacyna and Merkisz, 2014):

$$\lambda_V = \frac{V_o}{V_m} = \frac{\omega_o R_o}{\omega_m R_m} = const \tag{2.2}$$

Time scale λT as a relation of the time in real life phenomena to the time corresponding to it in a model-related phenomenon is expressed by the dependence:

$$\lambda_T = \frac{t_o}{t_m} \tag{2.3}$$

Thus a kinematic scale can be presented by means of a geometric scale and time scale:

$$\lambda_V = \frac{\lambda}{\lambda_T} \tag{2.4}$$

Relations concerned with other kinematic magnitudes also follow this, such as: an angle speed, an angle acceleration and a linear acceleration. A dynamic similarity occurs when forces in reality and in a model acting on elements and time corresponding to each other are parallel to each other, and the relation of their modules (dynamic scale) is constant and independent of the selected elements (Dudziak, 2008):

$$\lambda_F = \frac{F_o}{F_m} = const \tag{2.5}$$

In order to transfer measurement results from a model phenomenon to a real life phenomenon geometric, kinematic and dynamic scales derived from the similarity criteria must be known

3. The model-based investigations on a seagoing ship

The aim of investigations focused on maritime properties is developing mathematical methods, useful from a technological point of view, for forecasting performance of a floating vessel on rough sea. The main role played by model-based investigations and measurements made using real life objects is verification of these methods. Both types of experiment are also a source of inspiration for developing new modified mathematical models and calculation methods based on them.

Due to a lack of or weaknesses of theories some phenomena can be investigated effectively mainly by means of experiments. Such phenomena include e.g. issues relating to co-operation in a hull-propulsion system, ship safety under stormy or damage conditions. Model-based investigations offer much broader possibilities than investigations based on real objects as they allow for investigating a model in all conditions, even in conditions of bad stability, which can lead to capsizing of a model (Dudziak, 2008).

Model-based investigations on seagoing properties of a ship and their results must be carried out and interpreted in accordance with probability requirements. A geometric similarity includes a bottom part of ship, her above water line part to her upper deck. If investigated are phenomena relating water action on a deck and elements placed on the deck then additional geometric similarity is required with regard to the deck, bulwark, and lower parts of superstructures, etc.

In model-based investigations of seagoing properties of ships Strouchal and Froude numbers are retained, as in the case of ship rolling the main forces which decide about the course of the phenomena are body forces: gravitational and inertial (generated by an unsteady movement of the vessel). Assuming that a ship and a model sail in water having the same density the scale of time, speed and force magnitudes depend on the geometric scale (Dudziak, 2008):

$$\lambda_V = \frac{V_o}{V_m} = \sqrt{\frac{L_o}{L_m}} = \lambda^{\frac{1}{2}} \tag{3.1}$$

$$\lambda_T = \frac{\lambda}{\lambda_V} = \lambda^{\frac{1}{2}} \tag{3.2}$$

$$\lambda_F = \frac{V_o^2 A_o}{V_m^2 A_m} = \lambda^3 \tag{3.3}$$

3.1. The model-based investigations on a seagoing ship

While considering forces, moments and a liquid flow around a body generated in the course of ship motion it is important to know hydrodynamic characteristics of the bodies and streams of liquid and their interdependence in the function of specific dimensions of bodies, speed and properties of the liquid (Charchalis, 2001; Dudziak, 2008).

Two flows are considered similar when the fields of all magnitudes characterizing the flow (field of pressure, density, temperatures, viscosity, etc) are similar in relation to each other. Due to impossibility of satisfying all the conditions concerned with the model-related flow, with a limited number of parameters selected at random by a researcher, the total similarity of flows is a phenomenon difficult to achieve (Dudziak, 2008). Usually there occur a partial similarity of flow, which includes magnitudes having the dominant significance for an investigated case.

In order to insure a total similarity of flow the following conditions should be met (Jacyna and Merkisz, 2014):

- equations describing flows must be identical,
- boundary surfaces must be geometrically similar.

Criteria of similarity between particular phenomena of liquid motion can be found using a dimensional analysis or a differential equation of motion. The motion of incomprehensible liquids are described using Navier-Stokes (N-S) equations (Charchalis, 2001; Dudziak, 2008). The equation N-S for the model-related flow is expressed as follows (Dudziak, 2008):

$$\frac{\partial v_1}{\partial t_1} + v_1 \frac{\partial v_1}{\partial x_1} = F_1 - \frac{1}{\rho_1}\frac{\partial p_1}{\partial x_1} + \nu_1 \frac{\partial^2 v_1}{\partial x_1^2} \tag{3.4}$$

The spatial coordinate was designated as x. For the basic flow the equation N-S will assume the form:

$$\frac{\partial v_2}{\partial t_2} + v_2 \frac{\partial v_2}{\partial x_2} = F_2 - \frac{1}{\rho_2}\frac{\partial p_2}{\partial x_2} + \nu_2 \frac{\partial^2 v_2}{\partial x_2^2} \tag{3.5}$$

Using the general formula of scale of any λ_w:

$$\lambda_w = \frac{W_2}{W_1} \tag{3.6}$$

where:
λ_w – size scale, W_1 – model size W_2 – real size.

Equation (3.5) is transformer into the form (Dudziak, 2008):

$$\frac{\lambda_v}{\lambda_t}\frac{\partial v_1}{\partial t_1} + \frac{\lambda_v^2}{\lambda_l} v_1 \frac{\lambda v_1}{\lambda x_1} = \lambda_F F_1 - \frac{\lambda_p}{\lambda_\rho \lambda_l}\frac{1}{\rho_1}\frac{\partial p_1}{\partial x_1} + \frac{\lambda_\nu \lambda_v}{\lambda_l^2} \nu_1 \frac{\partial^2 v_1}{\partial x_1^2} \tag{3.7}$$

where:
λ_v – speed scale, λ_p – pressure scale, λ_ρ – density scale, λ_t – time scale, λ_F – scale of body forces, λ_l – geometric scale, λ_ν – viscosity scale.

The identity of equations required for similarity of flows (3.4) and (3.7) is obtained on condition that scale factors preceding the equation terms (3.7) are equal to the same constant, different from zero. This way the Newton flow similarity conditions (Dudziak, 2008; Prosnak, 2006) are obtained, as follows:

$$\frac{\lambda_v}{\lambda_t} = \frac{\lambda_v^2}{\lambda_l} = \lambda_F = \frac{\lambda_p}{\lambda_\rho \lambda_l} = \frac{\lambda_\nu \lambda_v}{\lambda_l^2} = const \tag{3.8}$$

3.2. The partial similarity criteria

Combining particular pairs of the equation terms with each other (3.8) the partial similarity criteria and criterion numbers directly linked to them are obtained (Dudziak, 2008). The obtained four dimensionless groups of variables constitute the hydrodynamic similarity criteria. The numerical identity of any of them for two different flows produces its probability, so (Charchalis, 2001; Prosnak, 2006):

- $\frac{lv}{\nu} = Re$ – Reynolds number determining the relationship between inertia forces and internal friction,
- $\frac{v^2}{gl} = Fr$ – Froude number characterizes weight forces (number having no importance for gases),
- $\frac{l}{vt} = Sh$ – Strouhal number characterizes unsteady charter of flow,
- $\frac{p}{\rho v^2} = Eu$ – Euler number characterizes pressure forces in flow.

3.3. The Similarity criteria of pressure forces in liquids – Euler number

Taking into account the partial similarity condition, which results from the second and fourth terms of the equation (3.8) (Dudziak, 2008; Charchalis, 2001; Prosnak, 2006),

$$\frac{\lambda_v^2}{\lambda_l} = \frac{\lambda_p}{\lambda_\rho \lambda_l} \text{ or } \frac{\lambda_p}{\lambda_\rho \lambda_v^2} = 1 \tag{3.9}$$

from this it follows:

$$\frac{p_1}{\rho_1 v_1^2} = \frac{p_2}{\rho_2 v_2^2} \text{ or } Eu_1 = Eu_2 \tag{3.10}$$

where: $Eu = \frac{p}{\rho v^2}$ – Euler number

The Euler number represents the relation of pressure forces to inertia forces, however, only in the case of incompressible flow, as pressure and density are treated here as independent parameters. The practice

indicates that using Euler number air flow can be modeled for an assumed constant density.
According to Dudziak (2008) the size of an object has the essentials effect on a change in air density acting on a ship. The smaller the ship is, the lower resistance to air is produced, and consequently changes in air density are lower. This has an essential effect on the accuracy of results in calculations of heeling moment due to wind action M_W, as while calculating the moment M_W in accordance with IMO and PRS regulations it is assumed that the wind acting on the model exerts pressure on the whole lateral plane. In this project, while calculating M_W it was assumed that the wind acting on the model produces constant pressure. This assumption introduces a negligibly low error to the calculations.
With regard to similarity of pressure force fields in any two liquid flows, necessary and sufficient are (Dudziak, 2008, Prosnak, 2006) :
- geometric similarity of boundary surfaces,
- equality of Euler numbers.

In order to retain appropriate scale, in the investigations carried out in an investigation site, the dependence (3.10) was used.
Additionally, within the framework of the project mentioned above, the magnitudes of wind stream speed were calculated in the model site using dependencies (Polski Rejestr Statków, 2008):

$$M_w = 2 \cdot 10^{-5} F_W z_W v_W^2 \cos^2 \varphi \tag{3.11}$$

where:
F_W – lateral plane $\left[m^2\right]$, z_W – distance from the center of the lateral area at height T/2 above the basic plane in a given load condition $\left[m\right]$, φ – heel angle $\left[°\right]$, v_W – wind speed at the height of the geometric center of the lateral area calculated with the (Polski Rejestr Statków, 2008):

$$v_W = v_{10}\left(\frac{z_W}{10}\right) \tag{3.12}$$

where:
v_{10} – wind speed at the height of 10 meters above the waterline, for objects capable of sailing in any region, is assumed as $v_{10} = 80$ knots

Failing to fulfill all the hydrodynamic similarity requirements during model-based investigations on seagoing properties of a ship leads to the occurrence of the *scale effect* and errors associated with it. The magnitude of errors mainly depends on the kind of investigated phenomena, vessel shape as well as on the size of the model (geometric scale): the larger the model (lower scale) is, the lower the errors resulted from the scale effect are . The biggest errors occur during model-based investigations on heave roll, where water viscosity and surface tension may have a large effect on the damping moment.

4. The structure and equipment in the test site for investigating stability and water-tightness of ship models

A test site for model-based investigations on mobility and water-tightness of naval ships was designed and built at the Naval Academy in Gdynia with the aim of improving their safety at sea. The main elements of the site are two models of the Polish Navy ships: type 888 and 666. The model of the ship type 888 was used for the investigations presented in this article. The basic technical particulars of the model are as follows:
- overall length L_{Cm} = 1,444 m,
- length between perpendiculars L_{ppm} = 1,284 m,
- breadth B_m = 0,2332 m,
- displacement of model D_m = 13,15 kg.

In order to maintain geometric similarity of the model, having an effect on the quality of the investigations, theoretical line in scale were used to make the hull, whereas the elements of superstructures and deck equipment were appropriately simplified. All elements, whose size have an effect on the lateral area used in stability calculations, were placed aboard the models.
The ship model 888 used as the main investigation object was equipped with specialized instrumentation for simulating hull damage, fixing position and analyzing model’s performance in various operation conditions hazardous to ship safety. The array of the main elements of the model measuring system is presented in fig. 1. Single compartments PIII, PV, PVII, which have the largest volume and whose flooding has significant effect on stability and water-tightness, were selected for the investigations. The process of flooding the compartments to the level of the overboard water is realized after remotely controlled bottom valves

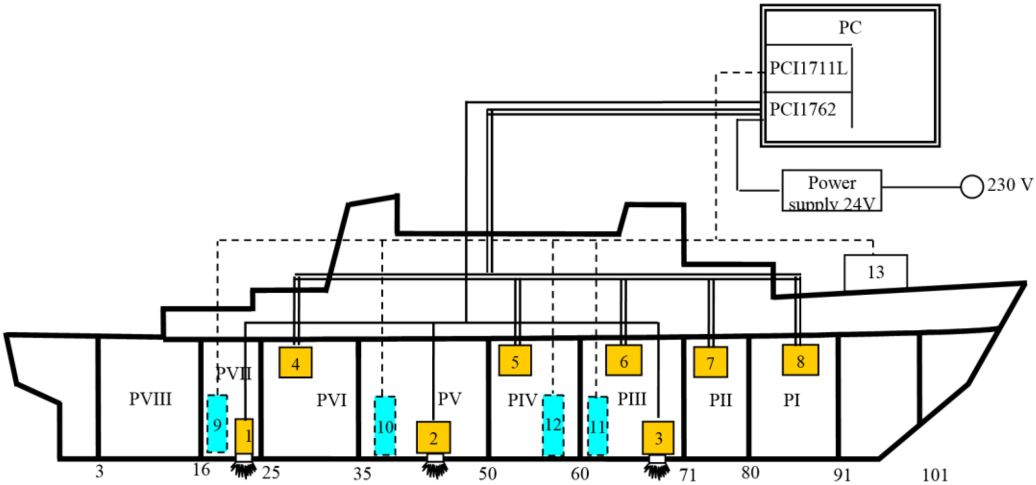

Fig.1. The array of sub-assemblies in the model of ship type 888

marked with numbers 1, 2 ,3 are opened. The other group of valves is designed to flood the compartments used in a refloating process or righting a ship in cases of asymmetric damage. The ship model is also equipped with a water installation and sensors used e.g. for measuring the water level in compartments. These valves, fitted in compartments PIII, PV, PVII, measure the water level using hydrostatic pressure measurements. A heal indicator, fitted in the fore of the model, was used in order to measure the heal and trim of the model.

Signals received from the sensors, are transmitted, in the wireless manner, to a computer fitted with two analogue-digital cards, and then are read from a display in the form of ready-made results.

1. Valve for simulating penetration of compartment VII; 2. Valve for simulating penetration of compartment V; 3. Valve for simulating penetration of compartment III; 4. Valve for flooding compartment VI; 5. Valve for flooding compartment IV; 6. Valve for flooding compartment III; 7. Valve for flooding compartment II; 8. Valve for flooding compartment I; 9. Sensor of water level in compartment VII; 10. Sensor of water level in compartment V; 11. Sensor of water level in compartment III; 12. Sensor of ship draught; 13. Heel indicator.

The measuring instruments and execution elements fitted in the model are connected to the computer by means of cables having low unitary mass. The computer is used for reading measurement data shown on the display. Using the computer software it is possible to flood selected compartments in the model and to drain them. To carry out these operations a software package was developed in the Delphi environment. The image on the display is presented in fig. 2 (Mironiuk and Pawłędzio, 2011; Mironiuk, 2012).

The amount of water in the compartment seen in the upper part of the window on the display of the computer software is given in per cent. The data relating to the model’s position such as heel angle, trim angle, forward draught in the perpendicular, after draught in the perpendicular are displayed in real time. The test site equipped and prepared this way was employed to investigate initial stability parameters having impact on operation safety of ships.

A strong wind and wave pose a large hazard to maritime transport safety in everyday operation of floating vessels and a frequent cause of accidents at sea. In order to take into account the effect of the natural environment on safety of floating vessels in the investigations it was necessary to add a set of ventilators simulating air movement to the described test site. Two type of ventilators with variable adjustment were fitted. They worked in the range from 0 to 2775 rpm – ventilators type HRB/2-250-AN and from 0 to 2685 rpm – ventilators type

HRB/2-200BN. The ventilators generating air movement can be started in three configurations:
- low power generators,
- high power generators,
- combined work of high power and low power generators.

The maximum air velocity recorded during the work of all the ventilators was 9 m/s. Due to safety reasons the ventilators were placed in a casing protected with a net. Such a solution makes it impossible for any objects to access the area of rotating ventilator blades. A general view of the set of ventilators is presented in fig. 2.

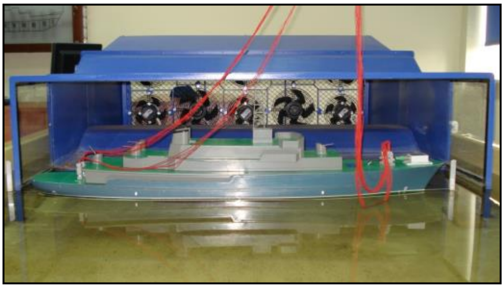

Fig. 2. The view of the set of ventilators installed in the laboratory site

Another investigation problem was to determine the axis of model rotation during wind action. The position of the axis of model rotation is important to calculate the heeling moment caused by wind action. In these investigations, the height of the center of the height of the lateral area measurement in relation to the floating water plane was assumed in accordance with the regulations of the Polish Registration of Ships. The draft corresponding to this water plane was marked with a white line. At this height seats were installed on the ship hull. Rods which make it possible to rotate the hull are placed in the seats. The way the model is fitted in the rods is shown in fig. 3. The solution presented in fig. 4 also allows for free vertical movement of the model owing to the rod ways in which the rods move.
In order to obtain the appropriate velocity of air flow the structure of the ventilator casing was reduced to a aerodynamic tunnel. Air velocity measurements were made using a portable measuring device type CTV 100, in which magnitudes are measured in the range from 0 to 30 m/s. In order to make air velocity measurements at different points of the cross-section of the control aerodynamic tunnel a holder was designed and built for fitting the measuring device in the air flow velocity sensor. It is presented in fig. 4. Owing to this structure it is possible to measure air velocity at various ranges from the aerodynamic tunnel and any height above water surface. This fitting method and the way of changing the position of the air flow sensor are presented in fig. 4 and 5.

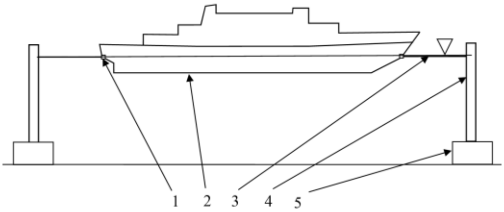

Fig. 3. The design of the rotation axis of the ship model; 1 – road seat; 2 – ship model; 3 – rotary rod; 4 – rod way; 5 – mount

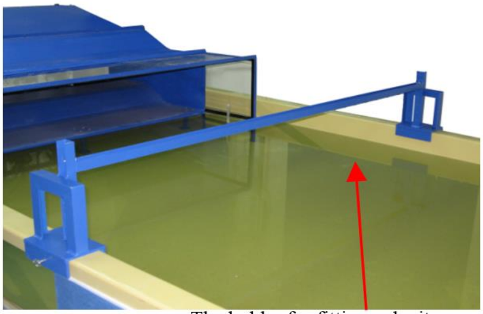

Fig. 4. The view of the model basin with the fitted hold

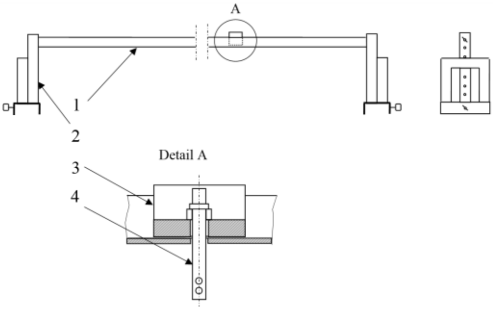

Fig. 5. The holder for fitting the wind velocity measuring device; 1- arm ; 2- way; 3- holder; 4 – wind velocity measuring device

The preliminary investigations on the air velocity showed that a position of the wind velocity measuring device in relation to the direction of air flow has substantial effect on the measurement accuracy. In order to avoid measurement errors the device had to be fitted at the right angle to the direction of air flow so that it could not rotate during measurements.

5. The model-based investigations on the ship type 888

5.1. The aim and conduct of experimental investigations

The main aim the investigations was to determine the dynamic heeling moment for the ship type 888, taking into account the IMO (International Maritime Organization) weather criterion as the main marine safety criterion. The investigations were carried out at the site for investigating stability and water-tightness of ship models, described above.

Before the main stage of the investigations several preliminary steps were made. Among others, the following were made at the investigation site:

a) it was made sure devices for measuring the heel angle, trim angle and wind speed showed correct indications,

b) bilge keel surface was measured,

c) deck flooding angle φ z was measured from the model of ship 888,

d) ship speed distribution was measured at the exit of the ventilators' casings

e) heel angle relating to wind action φd was measured.

While carrying out the model-based investigations it was necessary to solve the problem of scale, i.e. adjusting the wind speed and pressure acting the model, taking into account the weather criterion, which is one of the most important factors affecting stability safety of a ship. In order to carry out the investigations in the proper manner the scale of geometric similarity and Euler criterion determining similarity of pressure and force fields and were retained. It was assumed that changes in air pressure and density were negligibly small, and therefore, employing Euler criterion would not lead to significant errors.

The magnitude of pressure acting dynamically on a real object, i.e. a ship was adopted in accordance with IMO and PRS regulations (Dudziak, 2008; IMO, 2008; Szozda, 2004).

In the case of ships capable of sailing in any region, wind acting statically is 504 Pa. For the wind acting dynamically the magnitude used is 1.5 higher, i.e. 756 Pa. This pressure magnitude corresponds to the wind speed, which can be determined in different ways . One of them is using dependence on a dynamic pressure:

$$p = \frac{\rho v^2}{2} \tag{5.1}$$

For the magnitude p=756 Pa the air speed having density 1,293 kg/m^3 is 34 m/s. It is impossible to generate such a high pressure in a model site. Applying wind of such pressure to a model made in the scale 1:50 would cause it to capsize immediately. Therefore the wind speed calculated for the ship must be converted to the speed for the model. Two methods were adopted for solving the problem of determining the wind stream pressure acting on the model. First Euler similarity criterion was employed, described in chapter 2.3. The geometric similarity of the earlier calculated magnitudes of the righting arm curves for the model and for the ship were used for this purpose. It means that the relation of the maximum magnitude of the righting arm to the magnitude of the heeling moment should be the same for the model and for the ship:

$$\frac{GZ_{\max o}}{l_{wo}} = \frac{GZ_{\max m}}{l_{wm}} = const \tag{5.2}$$

where:

index „o" relates to the ship, whereas index „m" to the model.

Graphic representation of the dependence (5.2) is presented in fig. 6.

The equation (5.2) presents a relation of the magnitude of the maximum righting lever GZ to the magnitude of the heeling moment arm *l* calculated for the model and for the ship. Knowing the magnitude of the ship heeling arm l_{wo} calculated from the formula:

$$l_{wo} = \frac{q_v F_w Z_v}{1000\, g\, D} [m] \tag{5.3}$$

where:

q_v = 504 Pa – wind pressure; F_w- lateral area [m^2]; Z_v- the distance of the lateral area, measured in the vertical plane, from the center of the bottom projected on the symmetry plane, approximately to ship half draught [m]; *D* – ship displacement, [t]; *g* – 9.81 m/s2;

and the model scale the magnitude of the model heeling arm l_{wm}, could be calculated and then, following the transformation of the formula:

$$l_{wm} = \frac{q_{vm} F_{wm} Z_{vm}}{1000\, g\, D_m}[m] \qquad (5.4)$$

the wind pressure, which had to be generated in the model site, was calculated equal to q_{vm} = 15,12 Pa.

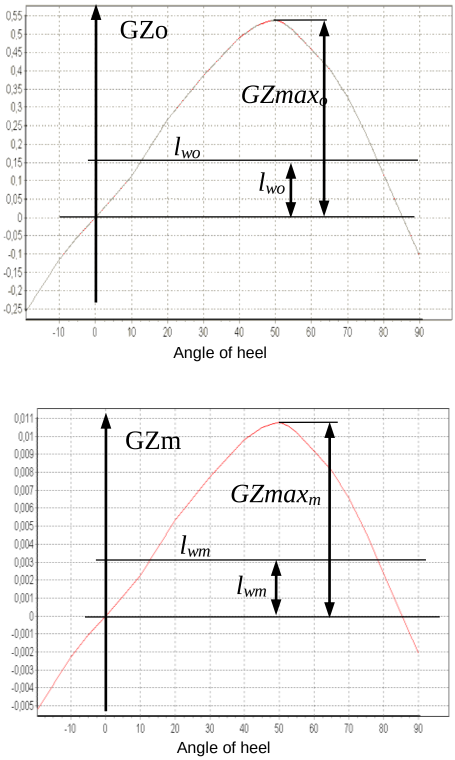

Fig. 6. The magnitude of the heeling moment arm due to the wind action calculated for the model

Employing the Euler assumption of the criterion number equality for the ship and the model (3.10) the required wind stream pressure vm, which has to be generated in the model site, was calculated:

$$Eu_o = Eu_m \text{ or } \frac{q_o}{\rho_o v_o^2} = \frac{q_m}{\rho_m v_m^2} \qquad (5.5)$$

From this dependence the wind speed for the model equal to v_m = 4,52 m/s was derived. The other method was using the formula for calculating a heeling moment due to wind thrust determined in accordance with the PRS regulations for naval ships (Szozda, 2004):

$$M_w = 2 \cdot 10^{-5} \cdot F_w \cdot z_w \cdot v_w^2 \cdot \cos^2\phi \qquad (5.6)$$

where:
F_w – lateral plane [m^2], z_w – distance from the center of the lateral area to the waterline located at the height T/2 above the base plane in a given load condition [m], φ – heel angle, v_w – wind speed at the height of the geometric center of the lateral plane calculated following the formula [6]:

$$v_w = v_{10}\left(\frac{z_w}{10}\right)[\text{knots}] \qquad (5.7)$$

where:
v_{10} – wind speed at the height of 10 meters above the waterline, for ships capable of sailing in any region is adopted as v_{10}=80 knots.

Knowing the magnitude M_{wo} the heeling moment arm due to the wind action on the ship l_{wo} was calculated, and then using the dependence (5.2) the heeling moment arm due to the wind acting on the model l_{wm} was determined. In the next step of the equation (5.4) the pressure acting on the model q_{vm} was determined. Based on the Euler criterion number equality (3.10) the required wind speed was calculated for the ship model v_m = 4,51 m/s. The ship wind action on the model was calculated v=4,52 m/s after the weather criterion determined for the ship and the model scale effect were taken into account. The presented solution to the problem of the scale dynamic similarity produced closely similar results relating to the wind stream speed. Thus it can be expected that the magnitudes of the wind speed were calculated in the correct manner. In the next step the wind speed was measured in an aerodynamic tunnel cross-section at three height levels above the water

surface in the model basin. At each level six measurements were made at points selected earlier.
The speed was measured at the following level:
- highest – 0.355 m above water level,
- middle – 0.0185 m above water level,
- lowest – 0.085 m above water level.

Owing to such an array of the measuring points an accurate distribution of the wind stream speed generated by the set of ventilators at the exit of the aerodynamic tunnel was obtained and the measurement results are presented in table 1.

Table 1. The results of measuring the wind stream speed

Measurement height level	Place of measurement and speed magnitude [m/s]						Mean magnitude [m/s]
	1	2	3	4	5	6	
35.5 cm	4.57	4.68	4.69	4.16	4,10	4.53	4.46
18.5 cm	4.67	4.86	4.77	4.53	4,16	4.65	4.61
8.5 cm	4.33	4.63	4.60	4.65	4,65	4.10	4.49
							4.52

Based on the obtained results the mean wind speed acting on the model equal to v=4,52 m/s was calculated.
The model-based the site described above was employed in the investigations, using ventilators to simulate wind blows. Strong wind acting on a ship can lead to substantial heels which in turn can result in ship capsizing and affect navigation safety. In order to measure the model heel angle in the laboratory site the rolling amplitude was taken into account. This required inclining the ship to windward side to the heel magnitude of 15°, 18°. The magnitudes of these angles are derived from the calculations of the weather criteria made for the ship model in accordance with IMO regulations.
When the heal angle was being measured the ventilators were working at the constant rotary speed, which corresponds to the constant characteristics of the heeling moment. Examples of the measurement results of the ship heel angle are presented in the graphic form in fig. 7.

5.2. The theoretical calculations of the ship heel angle

The next step was to calculate the ship heel angle for the heeling moment determined in accordance with the IMO recommendations.
The arm of the dynamically acting heeling moment was determined for the assumption that the distance of the center of the lateral plane was measured from the half draught. The arm sought for was calculated using the dependence as follows (Dudziak, 2008; Polski Rejestr Statków, 2008; Szozda, 2004; Więckiewicz, 2006):

$$l_w = 1{,}5 \frac{q_v F_w Z_v}{1000\, g\, D} [m] \tag{5.8}$$

where:
q_v = 504 Pa – wind pressure; F_w - lateral plane [m^2]; Z_v - the distance of the lateral area, measured in the vertical plane, from the center of the bottom projected on the symetry plane, approximately to ship half draugt [m]; D – ship displacement, [t]; g – 9.81 m/s^2.

After completing the calculations the magnitude of the heeling arm due to the wind action equal to 0.111 was obtained. Afterwards the ship heal angle was derived from the earlier made diagram of the curve of dynamic stability arms, presented in fig. 8. The magnitudes of heel angles obtained from the model-based investigations and the magnitudes calculated for the real object, taking into account roll amplitude of 6, 15, 18, degrees are presented in table 2.

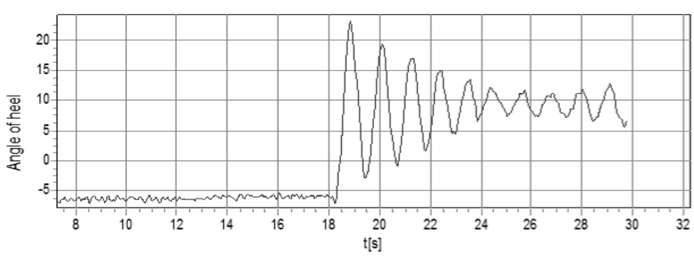

Fig. 7. The measurement of the dynamic heel angle after inclining the model to windward side to the angle of 6°

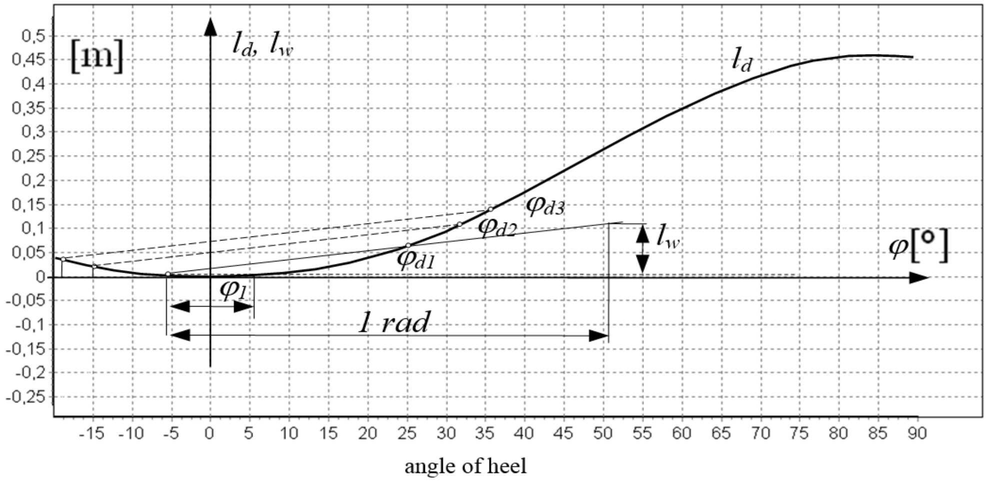

Fig.8. Determining the dynamic heel angle for a ship; lw – heeling moment arm due to the wind action; ld – dynamic stability arm

Table 2. The magnitudes of dynamic heel angles

No.	1	2	3
Angle of heel to windward side [o]	-6	-15	-18
Dynamic heel angle derived from figure 5 [o]	25	32	36
Dynamic heel angle measured in the site	23	29	31

Differences in the results obtained in the experimental tests and analytical calculations do not exceed 16%. High conformity of the investigation results may testify to the good workmanship quality of the test site.

6. Conclusions

The carried out preliminary investigations concerned with determining a ship heel angle due to action of a heeling moment caused by wind show high conformity of the theoretical calculations with the investigation results.

It follows from the analysis of the results of the experimental investigations and the theoretical calculations that in the investigated cases the calculated dynamic heel angles are higher than the angles measured in the model site. Thus these results allow for a claim that the assumptions made by classification organizations contain a certain margin of safety. In an everyday operation of a ship there can occur atypical situations, in which, apart from stormy weather, several other circumstances may occur negatively affecting stability of a floating vessel.

Making use of the developed investigation methodology it is possible to carry out , in the described site, experiments concerned with determining heeling moments caused by a wind blowing with a constant speed endangering navigation safety in various of ship operation conditions.

The described investigations are a preliminary stage leading to a broader analysis of phenomena of ship-related hydromechanics, stability, water-tightness and navigation safety. The presented measurement results can be, in the future, used for verifying computer software employing numerical methods.

References

[1] CHARCHALIS, A., 2001. *Opory okrętów wojennych i pędniki okrętowe.* Gdynia: AMW.

[2] DERETT, D., 1999. *Ship stability for Masters and Mates.* Oxford: Butterworth-Heinemann.

[3] DUDZIAK, J., 2008. *Teoria okrętu.* Gdańsk: Fundacja Promocji Przemysłu Okrętowego i Gospodarki Morskiej.

[4] EMSA, , European Maritime Safety Agency. Available: www.emsa.europa.eu.

[5] IMO, 2008. *International Code on Intact Stability.* London: IMO.

[6] JACYNA M., WASIAK, M., LEWCZUK, K. and KŁODAWSKI, M., 2014. Simulation model of transport system of Poland as a tool for developing sustainable transport. *Archives of Transport*, 31(3), pp. 23-35.
[7] JACYNA, M. and MERKISZ, J., 2014. Proecological approach to modelling traffic organization in national transport system. *Archives of Transport*, 30(2), pp. 31-41.
[8] MIRONIUK, W. and PAWLĘDZIO, A., 2011. Determination of Ship's Angle of Dynamic Heel Based on Model Tests. In: A. WEINTRIT and T. NEUMANN, eds, *Miscellaneous Problems in Maritime Navigation, Transport and Shipping - Marine Navigation and Safety of Sea Transportation.* CRC Press, pp. 101-105.
[9] MIRONIUK, W., 2012. The Model Research on the Flooding Time of the Warship Damaged Compartment. *Journal of Shipping and Ocean Engineering*, 2(4), pp. 217-223.
[10] POLSKI REJESTR STATKÓW, 2008. *PRZEPISY KLASYFIKACJI I BUDOWY OKRĘTÓW WOJENNYCH. CZĘŚĆ IV: STATECZNOŚĆ I NIEZATAPIALNOŚĆ.* Gdańsk.
[11] PROSNAK, W.J., 2006. *Równania klasycznej mechaniki płynów.* Warszawa: Wydawnictwo Naukowe PWN.
[12] SZOZDA, Z., 2004. *Stateczność statku morskiego.* Szczecin: Akademia Morska.
[13] WIĘCKIEWICZ, W., 2006. *Podstawy pływalności i stateczności statków handlowych.* Gdynia: Akademia Morska w Gdyni.