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A research model of a ship's angle of heel

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Abstract

According to some authors it is estimated that around 80% of accidents at sea are caused by human and organizational errors (HOE). In order to gain knowledge of phenomena that occur during ship operations, 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. The results of initial research on the dynamic impact of air flow on an 888 project type ship model are presented in the elaboration. The research has been executed at a test stand located in the Polish Naval Academy. The experimental results have been compared with theoretical calculations for angle of dynamic heel. Input parameters for the tests and calculations have been defined in accordance with recommendations of the Polish Register of Shipping (PRS) and International Maritime Organization (IMO) (IMO Instruments).

Introduction

Both increase in migration of people and sea transportation have contributed to the substantial increase in traffic at sea and progress in technology. This progress has made it possible to build ships of big displacement. More than 80% of world trade is carried out using maritime transport, which has become one of the pillars of international trade (EMSA, 2016). Alongside many advantages, this has created several hazards to safety in maritime transport and to the natural environment.

The present day demands the economic use of tonnage. The main dimensions of ships and their tonnage are key objectives. The transport of large amounts of cargo, mining and exploiting natural mineral resources, and carrying large numbers of passengers at sea are characterized by high risk, even if the latest technologies are implemented. In recent history, thousands of people have lost their lives in catastrophes of ships, off-shore oil rigs, and other marine objects, e.g. the tragedy of RMS Titanic when over 1500 people lost their lives, the tragedy of the Estonia passenger ferry, the tragedy of Costa Concordia, and other numerous disasters. The tragedy of our cargo-passenger ferry Jan Heweliusz, which sank on 14 January 1993 during her cruise from Świnoujście to Ystad, must be mentioned here. She was overcome by the forces of nature and sank off the coast of the Rugia island in the Baltic Sea with 55 people on board. The greatest maritime catastrophe in the Baltic Sea was that of the Wilhelm Gustloff, torpedoed by the S-13 Soviet submarine during which about 9500 refugees died. Many people have suffered injuries and lost relatives or friends at sea. Each of these catastrophes was different.

The question arises, whether most of them could have been avoided. The answer is not simple as it is associated with the people's continuous efforts to satisfy their needs, sometimes well beyond their capabilities. (A few examples: "maybe I will manage to…", "maybe I will manage to … before the storm hits", "maybe this device will be strong enough", "nothing like this can happen to such an experienced person as me".) This is perhaps a problem that is impossible to solve or eliminate from the life of seafarers. This and several other questions cannot be answered unequivocally at the moment, but asking them will certainly contribute to attracting attention to the safety of marine navigation. According to some authors it is estimated that about 80% of all accidents at sea are caused by human and organizational errors (HOE) (EMSA, 2016). A special case of such errors is wrong decisions made by a crew keeping watch on the bridge, especially during difficult navigational and weather conditions.

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

Model-based investigations are used as the basic and universal method for forecasting ship dynamic properties (dynamic angle of heel, ship rolling). 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 theory.

The structure and equipment in the test site for investigating the 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 four models of Polish Navy (PN) and cargo ships. The model of the PN ship type 888 was used for the investigations presented in this article. The basic technical particulars of the model are as follows:

a) overall length L_{Cm} = 1.444 m;
b) length between perpendiculars Lpp_m = 1.284 m;
c) breadth B_m = 0.2332 m;
d) displacement D_m = 13.15 kg.

In order to maintain the geometric similarity of the model, having an effect on the quality of the investigations, body lines at scale were used to make the hull, whereas elements of superstructures and deck equipment were appropriately simplified. All elements whose size has an effect on the lateral area used during the stability calculations were placed aboard the models.

The PN ship model 888 used as the main investigation object was equipped with specialized instrumentation for simulating hull damage, fixing position, and analyzing the model's performance in various operation conditions hazardous to ship safety. The main elements of the model measuring system are presented in Figure 1 (Mironiuk, 2012; Mironiuk & Pawlędzio, 2013).

The signals received from the sensors are transmitted wirelessly to a computer fitted with two analog-digital cards, and are then read from a display in the form of preprocessed results.

The measuring instruments and execution elements fitted in the model are connected to the

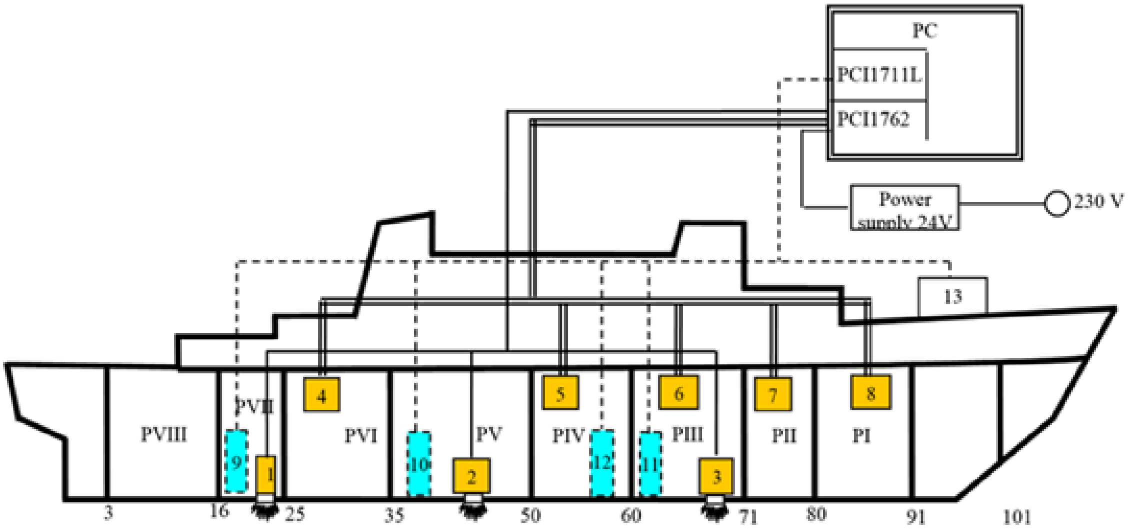

Figure 1. The array of sub-assemblies in the model of the PN ship type 888; 1 – Valve for simulating penetration of compartment VII, 2 – Valve for simulating penetration of compartment V, 3 – Valve for simulating penetration of compartment III, 4 – Valve for flooding compartment VI, 5 – Valve for flooding 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

computer by means of cables having a low unitary mass. A computer is used for reading the measurement data shown on the display. Using computer software it is possible to flood selected compartments in the model and to drain them. A software package was developed in the Delphi environment to carry out these operations.

The data relating to the model's position such as the heel angle, trim angle, fore and aft draughts in the perpendiculars are displayed in real time. The test site equipped and prepared this way was employed to investigate the initial stability parameters having an impact on the operational safety of ships.

Strong winds and waves pose a great hazard to maritime transport safety in everyday operation of floating vessels and are a frequent cause of the accidents at sea. In order to take into account the effect of the natural environment on the safety of floating vessels in the investigations it was necessary to add a unit of fans simulating air movement to the described test site. Two types of fans with variable adjustment were fitted. They worked in the range from 0 to 2775 rpm – fans type HRB/2-250-AN and from 0 to 2685 rpm – fans type HRB/2-200BN.

The maximum air velocity recorded during the work of all the fans was 9 m/s. Due to the 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 fans blades. A general view of the set of ventilators is presented in Figure 2 (Mironiuk & Pawlędzio, 2011).

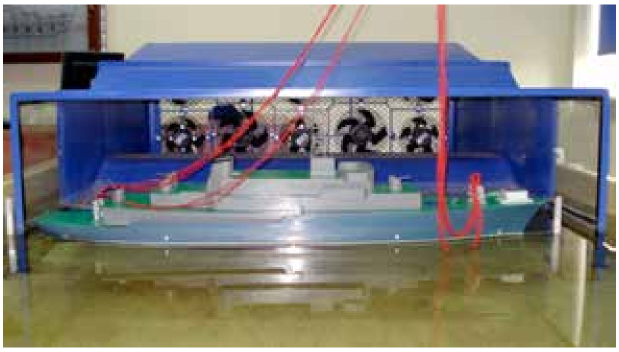

Figure 2. View of the set of ventilators installed in the laboratory site

In order to obtain the appropriate velocity of the air flow, the structure of the fan casing was reduced to an aerodynamic tunnel. Air velocity measurements were made using a portable measuring device type CTV100, in which the 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. Due to this structure, it is possible to measure the air velocity at various distances from the aerodynamic tunnel and any height above water surface.

The aim and conduct of experimental investigations

The main aim of the investigations was to determine the dynamic heeling moment for the PN ship type 888, taking into account the International Maritime Organization (IMO) weather criterion as the main marine safety criterion. The investigations were carried out at the site for investigating the 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 done at the investigation site:

a) bilge keel surface was measured;
b) it was made sure that the devices for measuring the heel angle, trim angle, and wind speed showed the correct indications;
c) deck flooding angle φz was measured from the model of PN ship 888;
d) heel angle relating to the wind action φd was measured;
e) ship speed distribution was measured at the exit of the fans' casings.

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 on the model, taking into account the weather criterion, which is one of the most important factors affecting the stability of a ship. In order to carry out the investigations in the proper manner, the geometric similarity at scale and Euler criterion determining the similarity of pressure and force fields were preserved. It was assumed that the changes in the air pressure and density were negligibly small, and therefore employing the Euler criterion would not lead to significant errors.

The magnitude of the pressure acting dynamically on a real object, i.e. a ship, was adopted in accordance with the IMO and Polish Register of Shipping (PRS) regulations (Dudziak, 2008; Szozda, 2004; IMO, 2008). In the case of ships capable of sailing in any region, a pressure of 504 Pa is used for the wind acting statically. For the wind acting dynamically the magnitude used is 1.5 higher, i.e. 756 Pa.

For the magnitude p = 756 Pa, and taking air density as 1.293 kg/m^3 density, the speed is 34 m/s.

It is impossible to generate such a high pressure in a model site. Applying wind of such pressure against a model made in the scale 1:50 it would cause the model to capsize immediately. Therefore the wind speed calculated for the ship must be converted to the speed for the model. To resolve this problem the Euler similarity criterion was employed.

The geometric similarity of the earlier calculated magnitudes of the righting lever curves for both the model and ship were used for this purpose. This means that the relation of the maximum magnitude of the righting lever to the magnitude of the heeling moment should be the same for the model and ship:

$$\frac{\mathrm{GZ}_{\max o}}{l_{wo}} = \frac{\mathrm{GZ}_{\max m}}{l_{wm}} = \mathrm{const} \qquad (1)$$

where: index "*o*" relates to the ship, index "*m*" to the model.

The equation (1) presents a relationship of the magnitude of the maximum righting lever GZ to the magnitude of the heeling moment arm l calculated for both the model and ship. Knowing the model scale, and the magnitude of the ship heeling arm l_{wo} calculated from the formula (Dudziak, 2008):

$$l_{wo} = \frac{q_v\, F_w\, Z_v}{1000 g\, D}\ [m] \qquad (2)$$

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 half the ship draught [m];

D – ship displacement [t];

$g = 9.81$ m/s^2;

the magnitude of the model heeling arm l_{wm}, could be calculated according to the formula (1) and then, following transformation of the formula (2) the wind pressure which had to be generated in the model site was calculated equal to $q_{vm} = 15.12$ Pa.

Employing the Euler assumption of the criterion number equality for the ship and model (3) the required wind stream pressure v_m, which has to be generated in the model site, was calculated (Dudziak, 2008):

$$Eu_o = Eu_m \quad \text{or} \quad \frac{q_o}{\rho_o v_o^2} = \frac{q_m}{\rho_m v_m^2} \qquad (3)$$

From this dependence the wind speed for the model was derived as equal to $v_m = 4.52$ m/s.

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 levels:

- 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 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 (Mironiuk & Pawlędzio, 2011).

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	4.56	4.69	4.69	4.17	4.11	4.52	4.46
18.5 cm	4.65	4.86	4.79	4.50	4.19	4.65	4.61
8.5 cm	4.35	4.60	4.62	4.63	4.64	4.11	4.49
							4.52

According to the obtained results the mean wind speed acting on the model was calculated as equal to $v = 4.52$ m/s.

The model-based site described above was employed during the investigations, using the ventilators to simulate blowing wind. Strong wind acting on a ship can lead to substantial heels, which in turn can result in a ship capsizing and affect the safety of navigation. In order to measure the model heel angle in the laboratory site, rolling amplitude was taken into account. This required inclining the ship to the windward side to a heel magnitude of 15º and 18º. The magnitudes of these angles are derived from the calculations of the weather criteria made for the ship model in accordance with the IMO regulations.

When the heel angle was measured, the fans were working at constant rotary speed, which corresponds

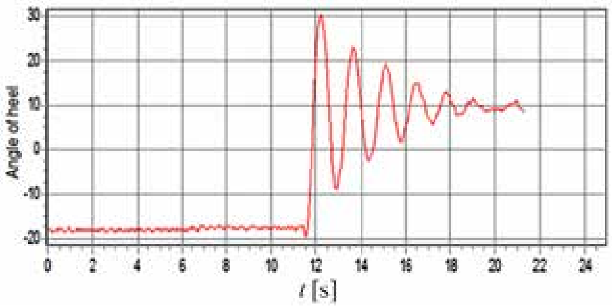

Figure 3. The measurement of the dynamic heel angle after inclining the model to the windward side at an angle of 18º

to the constant characteristics of the heeling moment. Examples of the measurement results of ship heel angle are presented in graphic form in Figure 3.

Theoretical calculations of the ship heel angle

The next step was to calculate 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 dependency as follows (Dudziak, 2008; Derret, 1999; IMO, 2008):

$$l_w = 1.5\frac{q_v F_w Z_v}{1000 g D} \text{ [m]} \tag{4}$$

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 symmetry plane, approximately half the ship draught [m];

D – ship displacement [t];

$g = 9.81$ m/s^2.

After completing the calculations, 0.111 was obtained for the magnitude of the heeling arm due to the wind action. Afterwards the ship heel angle was derived from the earlier diagram of the curve of dynamic stability arms, presented in Figure 4. The magnitudes of the heel angles obtained from the model-based investigations and magnitudes calculated for the real object, taking into account the roll amplitude of 6, 15, and 18 degrees are presented in Table 2.

Table 2. The magnitudes of dynamic heel angles

No.	1	2	3
Angle of heel to windward side [°]	–6	–15	–18
Dynamic heel angle derived from Figure 4 [deg]	25	32	36
Dynamic heel angle measured in the site [deg]	23	29	31

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

Conclusions

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

Making use of the investigation methodology developed herein, along with the test facility described, it is possible to carry out experiments to determine the heeling moments caused by a wind blowing with constant speed, which could potentially endanger navigation safety in various ship operational conditions.

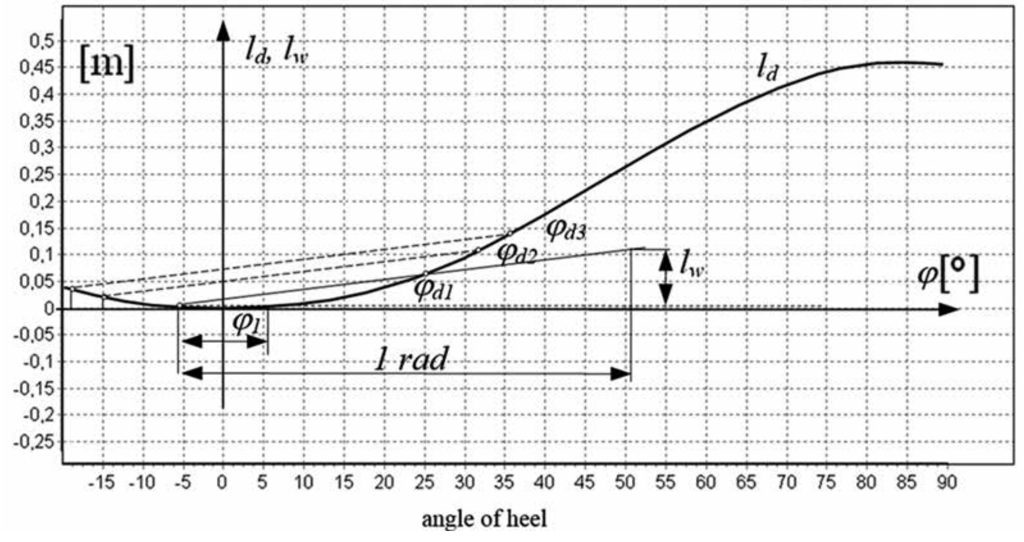

Figure 4. Determining the dynamic heel angle for a ship; l_w – heeling moment arm due to the wind action, l_d – dynamic stability arm

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

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