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VIRTUAL SHIP'S ROLL DECAY TEST WITH THE USE OF CFD TECHNIQUE

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Abstract

Since safety of navigation is related to the stability performance of a ship, the transverse stability is routinely calculated and measured. One of the crucial experimental approach is a roll decay test. Although, an obtained result of the roll decay test carried out on the full-scale ship needs to be compared to a benchmark enabling an estimation of the relevant stability. Nowadays such a benchmark is just based on the simplified GM-based IMO-recommended formula. This research aims at the more sophisticated method of ship's natural period of roll estimation and thus her stability assessment. The CFD (computational fluid dynamics) technique is applied and the result of the free roll simulation is compared to the solution of a roll equation. The one degree-of-freedom roll equation is applied with regard to the nonlinear ship righting moment and the nonlinear damping moment obtained according to Ikeda's method. The six degrees-of-freedom simulation of ship's roll decay test was carried out by the use of FlowVision code utilizing the Reynolds-averaged Navier–Stokes equation with regard to the turbulent flows based on the eddy viscosity concept. The semi-empirical k-ε turbulence model was applied. Thereby, the CFD-based approach allows to get rid of any assumptions regarding the value of the damping coefficient, which is an advantage over the roll equation based approach.

Keywords: *sea transport, ship stability, roll simulation, roll decay test, computational fluid dynamics*

1. Introduction

One of the most critical features of seagoing ships related to their safety is the stability influencing ship's overall sea-keeping performance. The loading condition of a ship causing the insufficient stability may lead to her capsizing or generally the stability accident which is commonly defined as exceeding the amplitude of rolling or an angle of heel at which operating or handling of a ship is impossible [6]. Generally, such an approach focusing on the excessive heel avoidance is valid both in a port during cargo operations [8] and in rough sea when underway [7].

Contemporary approach towards stability incidents avoidance is mainly based on an assessment procedure with the use of a set of rules and criteria known as the International Code on Intact Stability [4] issued by the International Maritime Organization. To assess ship stability a number of calculations are routinely carried out, however the data taken into account are based on declarations regarding cargo weight, which are not always precise and even sometimes intentionally forged. Thus, an experimental check of the transverse stability of a ship ought to be performed as an element of a good seamanship practice.

One of the typical methods for an experimental assessment of ship stability is a roll decay test, which consists in arousing ship's rolling and measuring the natural period of roll. The notion of the natural period of roll is used in many research works, IMO documents, manuals for masters etc. The simple method for calculation of the rolling period τ is given by the IMO in the International Code on Intact Stability and it is recommended for use in absence of sufficient information [4]:

$$\tau = \frac{2 \cdot c \cdot B}{\sqrt{GM_0}}, \tag{1}$$

with the value of c coefficient:

$$c = 0.373 + 0.023\frac{B}{T} - 0.00043L, \tag{2}$$

where:

c – coefficient describing ships transverse gyration radius r_x (the radius of gyration equals $r_x = c \cdot B$),
B – ship's breadth,
GM_0 – initial transverse metacentric height,
L – ship's length at waterline,
T – mean ship's draft.

Typically, the IMO formula is utilized in majority of issues related to ship rolling including scientific papers, although the formula is based on the initial metacentric height of a ship. It contains numerous significant simplifications as well. Thus, the modern and sophisticated approach is applied in this paper to perform the virtual roll decay test with the use of Computational Fluid Dynamics technique. Additionally, the numerical simulation based on the roll equation is carried out to compare the obtained results. In the course of the research, the universal methods are considered and applied to one ship in one loading condition as a case study.

2. Mathematical model of ship rolling

The main parameters of the rolling equation are inertia, damping, stiffness and excitation. Each of them more or less reveals significant nonlinearity and its proper application has an impact on the obtained results. Therefore, the nonlinear effects are key issues related to the complex motion of a ship. The mathematical model of ship's rolling utilized in the course of this research is given in the following notation:

$$\ddot{\phi} + 2\mu\dot{\phi} + \frac{g}{r_x^2}GZ(\phi) = 0, \tag{3}$$

where:

ϕ – angle of ship heel,
μ – damping coefficient,
g – gravity acceleration,
r_x – gyration radius of a ship and added masses,
GZ – righting arm.

The rolling equation given by the formula (3) contains the righting arm $GZ(\phi)$, so modelling of the ship stiffness related to her transverse stability is required. The most straightforward approach would be using a calculation of the righting arm based on the actual shape of the underwater part of the ship's hull, obtained consecutively in every time step of a rolling simulation. However, such a solution is too excessively time consuming for practical use. To address this problem we apply and test various approximations of the GZ curve. Many authors use the fifth to ninth order polynomials [2, 9] and a limited number of authors apply even the higher order polynomials [1]. In numerous contemporary ship roll simulations which results are presented in the literature, the ninth order polynomial power series is applied to approximate the value of the righting arm. Therefore, the ninth order polynomial power series is utilized in this study to trace the actual shape of the righting arm curve with its essential nonlinearities [10].

Another significant parameter of the equation (3) is roll damping. To evaluate this item the Ikeda's method is applied. This method for damping estimation comprises the contribution of numerous components like friction, lift, eddy making, wave and bilge keels damping [5]. The resultant damping coefficient of the considered ship is shown in Fig. 1.

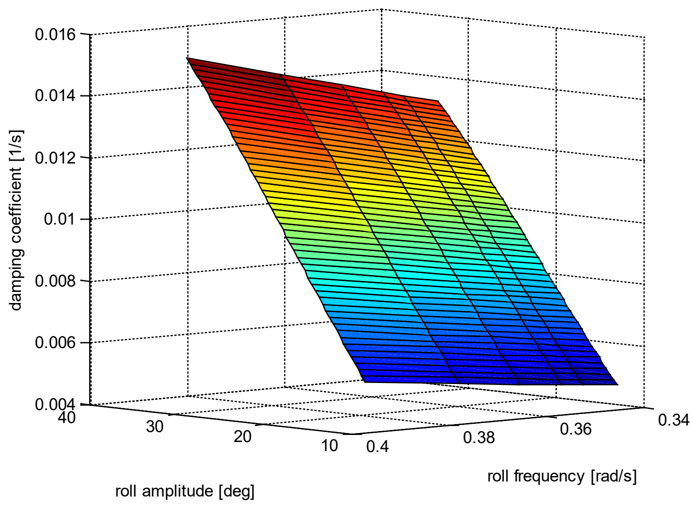


Fig. 1. Roll damping coefficient for B-354 ship according to Ikeda's method

The plot in Fig. 1 presents the damping coefficient versus the roll amplitude and the roll frequency. This is due to the sensitivity of the damping moment to both listed roll characteristics.

3. Application of the computational fluid dynamics technique

The entirely different approach than the ship roll equation utilization is an application of the Computational Fluid Dynamics (CFD) technique. The object e.g. the ship in considered case is no longer perceived as a whole body floating in water. Instead of that, the space surrounding the ship is divided into relatively small cells and the Navier-Stokes equation is solved in each cell. Actually, the Reynolds-averaged Navier–Stokes (RANS) is applied giving approximate time-averaged solutions to the Navier–Stokes equations.

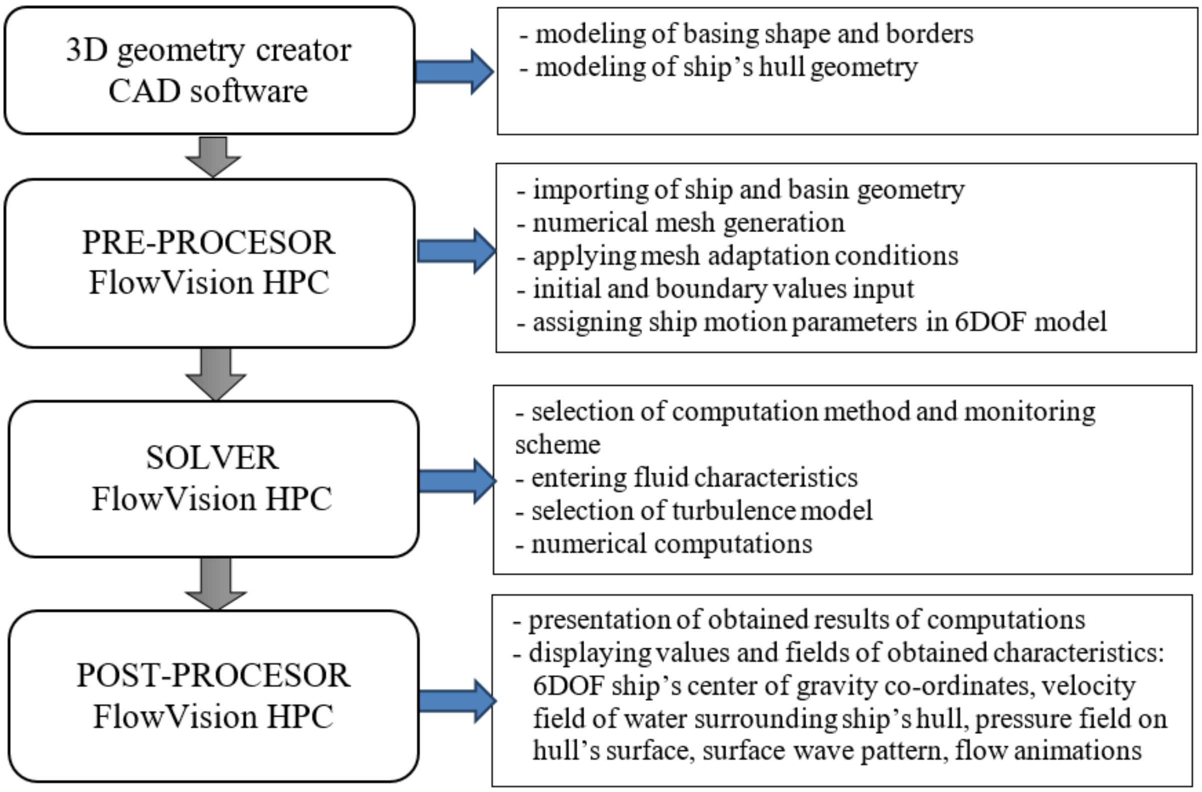


Fig. 2. Scheme of Flow Vision HPC software application

The CFD software utilized in the course of this research is called Flow Vision HPC. The code is based on the finite volume method (FVM) and is used the VOF method for free surface problems [3]. High accuracy of computation is achieved by solving the governing equations in the 'free surface' cells (the cells partly filled with liquid) [3]. The conducted simulations of turbulent flows are based on the eddy viscosity concept. The semi-empirical *k-ε* model turbulence model is applied.

The practical application of the Flow Vision software requires a number of consecutive steps to be performed. They are related to the geometry identification and modelling, pre-processing, equations solving and post-processing which is shown in Fig. 2.

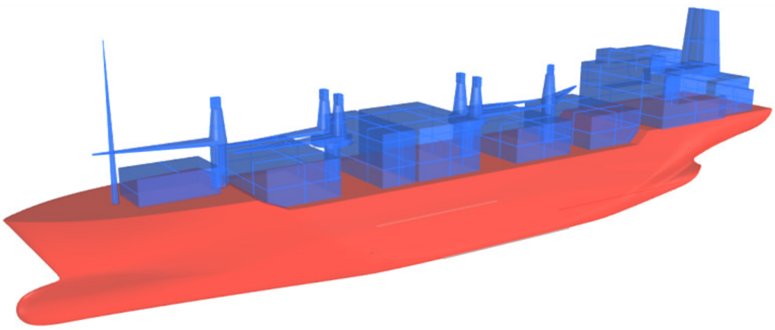
4. Ship geometry and space meshing for the purpose of CFD simulation

The ship taken into account in the course of the research is medium-size Polish general cargo vessel project B-354, 140 m long, 22 m wide with the draft 6 m reflecting partly loaded cargo holds. The particulars of the ship essential from the roll computation point of view are presented in Tab. 1.

Tab. 1. Considered ship B-354 particulars

Length between perpendiculars	*Lpp*	[m]	140.00
Length overall	*L*	[m]	149.15
Moulded breadth	*B*	[m]	22
Draft aft	$Tr_{1,000}$	[m]	6
Draft forward	$Td_{1,000}$	[m]	6
Longitudinal centre of gravity	*Xg*	[m]	69.69
Transverse centre of gravity	*Yg*	[m]	0
Vertical centre of gravity	*Zg*	[m]	7.04
Displacement	*D*	[t]	$1.273 \cdot 10^4$
Initial transverse metacentric height	*GM*	[m]	1.00
Moment of inertia about X axis	*Ixx*	[kg·m^2]	$9.71 \cdot 10^8$
Moment of inertia about Y axis	*Iyy*	[kg·m^2]	$1.55 \cdot 10^{10}$
Moment of inertia about Z axis	*Izz*	[kg·m^2]	$1.55 \cdot 10^{10}$

The three-dimensional numerical model of this ship is worked out to import it to the Flow Vision HPC. The general view of the numerical model and the body plan is shown in Fig. 3.



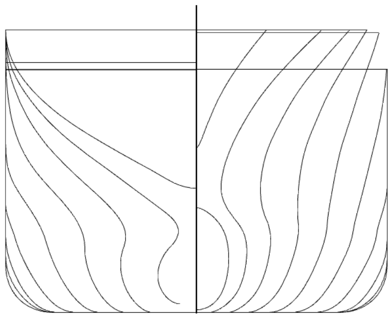


Fig. 3. Ship project B-354 - 3D numerical model (left) and her body plan (right)

The numerical model of the analysed ship is then surrounded by the computational domain. Besides the obvious need for the domain size establishing, numerous conditions are set up to ensure the steady volume of water and the proper distribution of pressure. The computational domain is shown in Fig. 4.

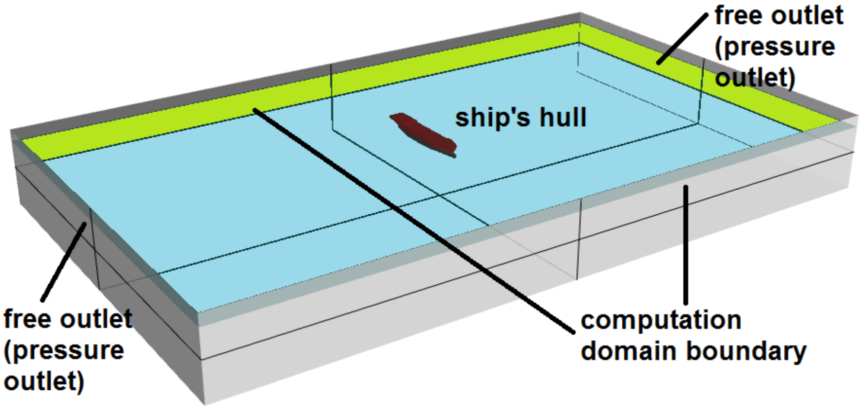


Fig. 4. Computation domain with set up conditions

The domain containing the considered ship is divided into cells due to the discretization process. The generated mesh is shown in Fig. 5. To achieve satisfactory level of accuracy the Sub-Grid Geometry Resolution (SGGR) is applied where the triangulated surfaces naturally cut Cartesian cells and reconstructs the free surface [3]. This idea is shown in Fig. 5.

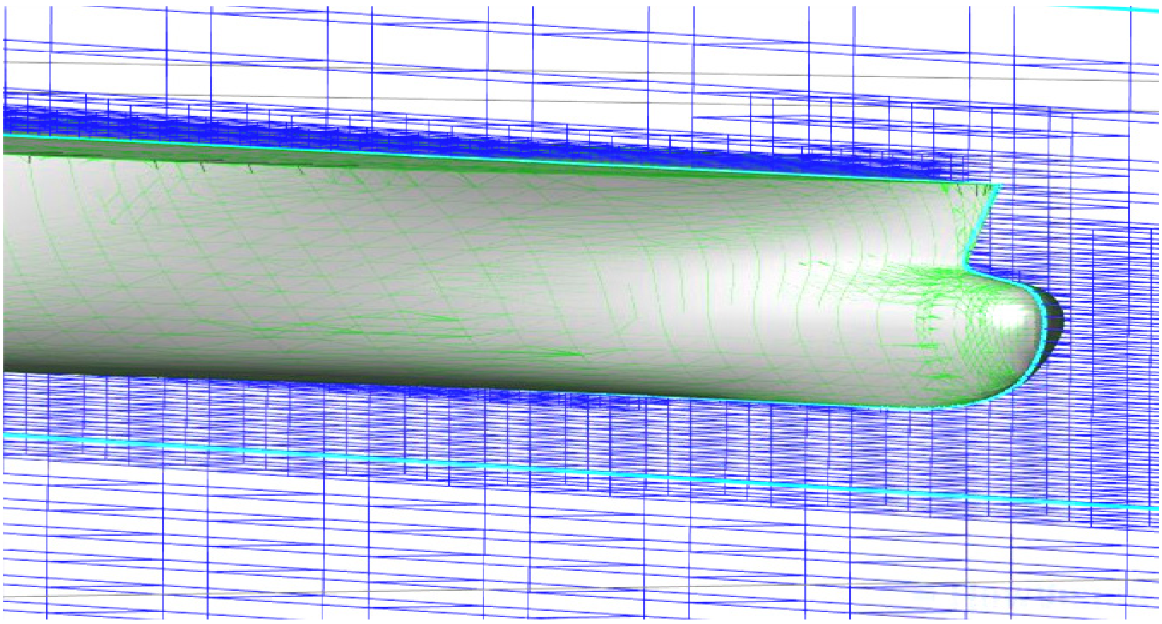


Fig. 5. Hexahedral structural mesh and moving object (e.g. ship) and identification according to SGGR method

The SGGR method is intended for an approximation of curvilinear boundaries on a hexahedral mesh. The method consists in natural splitting of the boundary cells by the triangulated boundaries. The number of the obtained child cells depends on the geometry peculiarities. The child cells are arbitrary polyhedrons. The equations of a given mathematical model are approximated on the polyhedrons without simplifications. The approach enables accurate calculations in a complex domain on a reasonably coarse mesh [3].

5. Results of computations

The final result of the simulation obtained after the post-processing comprises the general flow pattern, the velocity and pressure fields and the resultant motion of the ship, which is the most important element of the conducted study. The visualization of a sample velocity field recorded in one time step of computation is shown in Fig. 6.

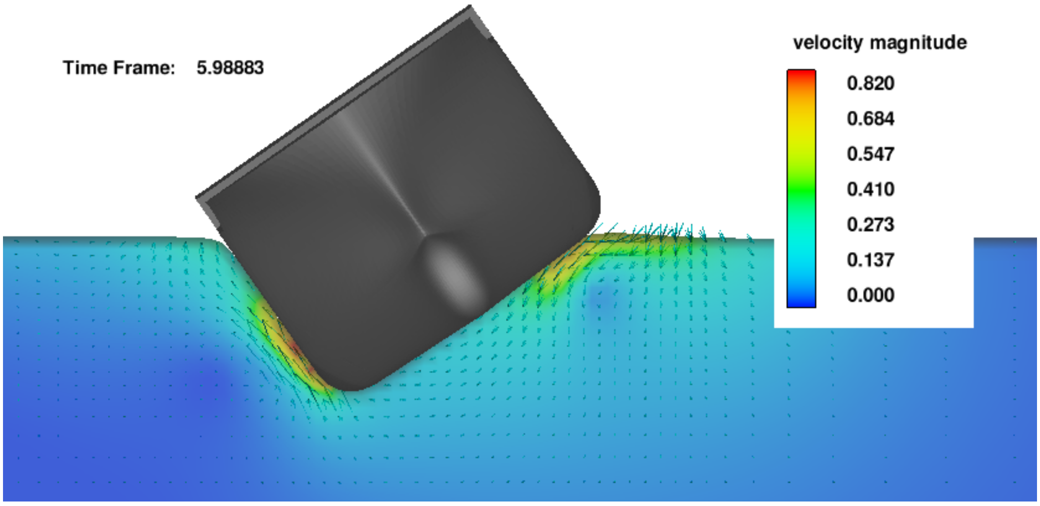


Fig. 6. Sample velocity field (freeze frame of ship roll animation)

The crucial issue considered in this research is virtual roll decay test performed for the exemplary cargo ship. Thus, the history of roll motion due to the initial inclining by a given angle of heel is obtained which is exposed in Fig. 7.

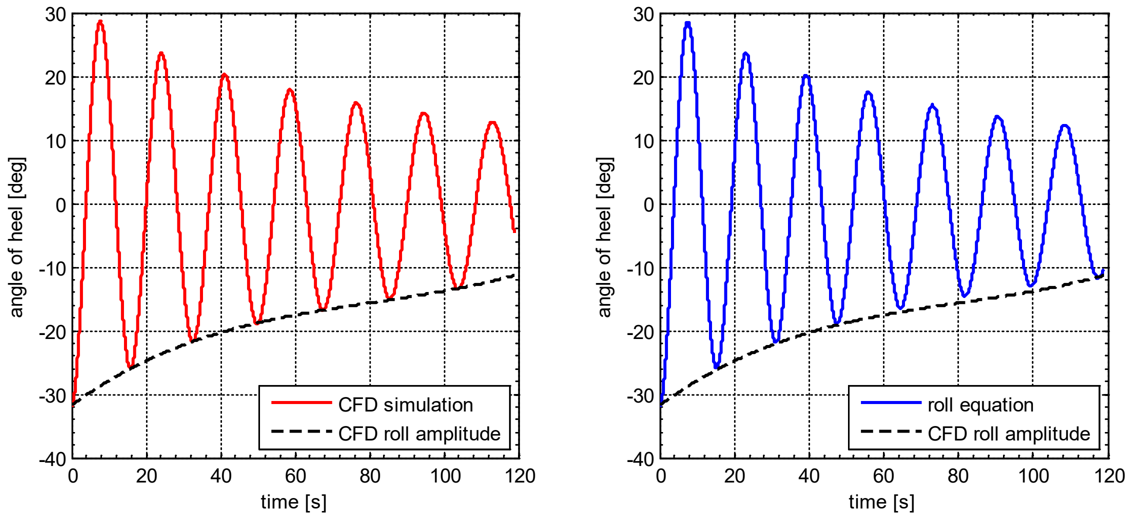


Fig. 7. Comparison of obtained free rolling history according to CFD simulations (left) and roll equation (right)

The plots shown in Fig. 7 present the history of ship's free rolling obtained with the use of CFD technique (on the left side) and on the basis of the roll equation (on the right side) accordingly. Although, the dashed line plotted roll amplitude envelope is given in both cases the same, actually taken from the CFD simulations. This facilitates the comparison of the roll amplitude decay pace.

The presented history of roll (Fig. 7) reveals that the pace of amplitude decay is equal in both applied approaches, e.g. in case of CFD application and the roll equation based simulation. Thus, the logarithmic decrement, which is usually used to find the damping ratio of an oscillating damped system in the time domain, should be equal. The logarithmic decrement is the natural log of the ratio of the amplitudes of any two successive peaks. However, in case of the conducted research the logarithmic decrement is not steady due to the nonlinearity of the damping coefficient. The decreasing amplitude of roll causes the decrease in damping. Nevertheless, the convergence of the roll amplitude decay when comparing the CFD's results and the roll equation based simulation's results is evident.

Besides the roll decay pace's compliance also the natural period of ship roll needs to be assessed. Three following values can be compared in this research:

- the natural period of roll according to the IMO-recommended formula (1) which equals 19.2 s,
- the natural period of roll obtained as the mean time difference between following maxima according to the roll equation (3) based simulation which equals 16.4 s,
- the natural period of ship's roll found as the mean time difference between following maxima according to the CFD simulation, which equals 17.6 s.

Actually, the only reasonable way to evaluate the accuracy of these methods is an experiment. Although, the natural period of roll obtained in the course of both simulation seems to be closer to each other while the formula (1) based prediction is a bit farther apart.

6. Conclusions

The main purpose of the research is to assess the feasibility of application of the virtual roll decay test and to compare the CFD's results with other available methods. The conducted study revealed the practical feasibility of utilizing of the CFD technique, which is the cost-effective approach comparing to model tests or full-scale experiments. Anyway, the experimental verification in some selected cases is required to assess the accuracy of the virtual roll decay test.

The main advantage of the studied approach based on the Computational Fluid Dynamics is its independence on the damping coefficient approximation since the CFD method deals with the dynamics of fluid in every cell of the computational domain and all essential forces are determined in each cell separately. In addition, the geometry of the ship's hull is automatically integrated in the computation scheme therefore; there is no need for the righting arm curve approximation. Taking into account the crucial merits of the CFD approach, this method can be assessed as the most convenient to perform the virtual roll decay test of seagoing ships.

References

[1] Bulian, G., *Nonlinear parametric rolling in regular waves – a general procedure for the analytical approximation of the GZ curve and its use in time domain simulation*, Ocean Eng., Vol. 32, pp. 309-330, 2005.

[2] Contento, G., Fracescutto, A., Piciullo, M., *On the effectiveness of constant coefficients roll motion equation,* Ocean Eng., Vol. 23, pp. 597-618, 1996.

[3] FlowVision HPC Manual, Capvidia, Belgium 2010.

[4] IMO, International Code on Intact Stability (2009 Ed.), 2008.

[5] Kawahara, Y., Maekawa, K., Ikeda, Y., *A simple prediction formula of roll damping of conventional cargo ships on the basis of Ikeda's method and its limitation*, Journal of Shipping and Ocean Engineering, Vol. 2, pp. 201-210, 2012.

[6] Kobyliński, L., Kastner, S., *Stability and Safety of Ships, Vol. 1: Regulation and Operation*, Elsevier Ocean Engineering Books, Vol. 9, 2003.

[7] Krata, P., Szłapczynska, J., *Weather hazard avoidance in modelling safety of motor-driven ship for multicriteria weather routing*, International Journal on Marine Navigation and Safety of Sea Transportation, Vol. 6 No. 1, 2012.

[8] Krata, P., Szpytko, J., Weintrit, A., *Modelling of ship's heeling and rolling for the purpose of gantry control improvement in the course of cargo handling operations in sea ports*, Solid State Phenomena, Vol. 198, pp. 539-546, 2013.

[9] Tylan, M., *The effect of nonlinear damping and restoring in ship rolling*, Ocean Eng., Vol. 27, pp. 921-932, 2000.

[10] Wawrzyński, W., Krata, P., *Method for ship's rolling period prediction with regard to non-linearity of GZ curve*, Journal of Theoretical and Applied Mechanics (JTAM) – in press.