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STUDY OF SEAKEEPING PERFORMANCE OF FISHING VESSELS WITH THE HELP OF CFD METHODS

ДОСЛІДЖЕННЯ МОРЕХІДНОСТІ РИБАЛЬСЬКИХ СУДЕН ЗА ДОПОМОГОЮ CFD МЕТОДІВ

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ABSTRACT

Seakeeping performance is quite important for certain ship types. Fishing vessels often operate in areas with frequent storms, and sometimes it is necessary to continue fishing despite the worsening sea state. The development of hull forms providing good seakeeping performance of fishing vessels is the problem of current interest in ship design. The conventional approach to seakeeping studies is testing models in ship model basins. However, it is time-consuming and expensive, especially when many hull form variants are studied. For this reason, computer calculations based on the theory of ship motions and strip theory were developed and introduced. Today the more advanced methods of computational fluid dynamics (CFD) can be applied to the problem. The study of ship motions with the help of Reynolds-averaged Navier-Stokes (RANS) CFD method is considered in this paper. A suggested numerical model implies the generation of waves through initial and boundary conditions, which express fully developed waves with preset parameters. An object of research is the seagoing trawler with an overall length of 44.6 m. Three versions of hull form are used in simulations. All versions have similar transom afterbodies, but different forebodies: one similar to Axe Bow, a bulbous bow and one similar to X-bow. Ship movement with headings 180° and 150° at speed of 3.5 knots was studied to reveal differences in added resistance and ship motions. While added resistance and characteristics of heaving and pitching have shown no clear advantages among the considered shapes of forebodies, the version similar to X-bow has demonstrated a significant decrease in rolling at heading 150°. The results of the study have shown that the suggested numerical setup in combination with the CFD methods described can be used for quite realistic simulations of ship behaviour in rough seas.

Keywords: seakeeping simulations, seakeeping of fishing vessels, CFD for ship design, improved seakeeping performance, simulation of ship motions.

РЕФЕРАТ

Мореxідність має особливе значення для певних типів суден. Рибальські судна часто оперують у районах з постійними штормами, і іноді вимушені продовжувати промисел незважаючи на плоху погоду. Розробка форми корпусу, що забезпечує рибальським суднам добрі морехідні якості, є актуальною проблемою проектування. Традиційний підхід до дослідження морехідності полягає у модельних випробуваннях. Однак, він потребує значних затрат часу та коштів, особливо коли розглядається багато варіантів корпусу. З цієї причини свого часу були запроваджені обчислення на основі теорії хитавиці та гіпотези плоских перерізів. Сьогодні до проблеми можуть бути застосовані більш досконалі методи CFD. Дослідження хитавиці судна за допомогою методу RANS CFD розглядається у даній статі. Запропонована чисельна модель передбачає генерацію хвиль через початкові та граничні умови, що описують повністю розвинуті хвилі зі заданими параметрами. Об'єктом дослідження є морський траулер найбільшою довжиною 44.6 м. У моделюванні були *використані три варіанти форми корпусу. Усі вони мали подібну транцеву кормову частину, але різні носові частини: подібну до Axe Bow, бульбову та подібну до X-bow. Для виявлення відмінностей у додатковому опорі та параметрах хитавиці було досліджено рух судна з курсовими кутами 180° та 150° при швидкості 3,5 вузла. Додатковий опір та параметри вертикальної і кільової хитавиці не виявили чіткої переваги однієї з розглянутих носових частин, проте варіант, подібний до X-bow, продемонстрував значне зниження бортової хитавиці. Результати дослідження показали, що запропонована чисельна постановка у комбінації з описаними методами CFD можуть використовуватися для досить реалістичного моделювання поведінки суден на морському хвилюванні.*

Ключові слова: моделювання мореxідності, мореxідність рибальських суден, CFD для проектування суден.

Defining the general matter and its connection to important scientific or practical objectives

Theoretically, seakeeping is considered one of the qualities of seaworthiness, namely, the capability of ships to keep all other qualities in conditions of rough seas and stormy wind. In practice, it comprises a number of various criteria, which describe one or the other negative effect restricting normal operation. Such negative effects (e.g. swift rolling, slamming, deck wetness, etc.) may impact either ship structures or crew and mechanisms. Some ship types need certain seakeeping performance more than others. In particular, fishing vessels have to continue fishing as long as possible despite the worsening sea state. It is not so easy to provide this simple requirement due to such factors as relatively small sizes of fishing ships and operational areas with frequent storms. In this way, the problem of seakeeping occupies an important place in the design of fishing vessels.

While individual characteristics can be improved by special technical devices (e.g. rolling can be moderated through applying stabilizers), complex improvement of the seakeeping performance can be achieved with the help of appropriate hull form only. Thus, the development and improvement of hull forms providing good seakeeping performance is an important scientific and practical problem. The author has been considering this problem in connection with the research work "Research of seaworthiness and effectiveness of modern transport ships" of the department "Theory and structure of ships" (NU "Odessa Maritime Academy").

Previous researches analysis and definition of new trends in problem solution

Design studies of seakeeping are normally based on experimental or mathematical modelling of ship motions on sea waves. As a result, kinematic and dynamic parameters of motions, including displacements, velocities and accelerations along coordinate axes, added resistance, etc. can be evaluated. Their correlation with features of hull forms is the focus of the studies.

Experimental simulations or model tests are primarily conducted in towing tanks equipped with wavemakers (e.g. the towing tank of Odessa national maritime university [12]). The advantages and disadvantages of the seakeeping model tests are well-known [3]. They can provide a full set of high-quality results in specialized ship model basins only. Such experimental facilities are rather rare. As well as other model tests for ship design, the seakeeping tests are time-consuming and expensive, especially when many variants of a hull form are considered. The latter feature is caused mainly by the high production costs of hull models. As compared with propulsion model tests, the seakeeping tests require more runs to cover a full range of headings and parameters of waves. For this reason, it is difficult to widely involve the seakeeping tests in the design of merchant ships.

Mathematical modelling has been developing from calculations based on strip theory [4, 6, 13] to CFD (computational fluid dynamics) simulations with the help of potential and RANS (Reynolds-averaged Navier-Stokes) solvers. Strip theory implies the representation of a hull form as a set of cross-sections. Corresponding calculations are quite prompt and physically adequate. Due to these features, they can be used for mass serial calculations [11]. Their disadvantage is the formal approach to the local effects of interaction between waves and hulls. Such phenomena like slamming, wiping, wetness and propeller racing are not simulated directly, only their probability can be estimated taking into account relative positions, velocities or accelerations of water surface and certain hull points. More realistic simulations can be performed with the help of modern CFD methods based on solving the equations of the fluid mechanic, particularly, the Reynolds-averaged Navier-Stokes equations (RANS). Despite certain difficulties of numerical setup, these methods are successfully applied to the seakeeping problems [14].

The research objective

An objective of the represented study is an assessment of the seakeeping performance provided by different forebody shapes of a fishing trawler based on CFD methods.

Presenting the main material of research with a full grounding of received scientific results

1. Object of research

An object of research is the seagoing trawler with an overall length of 44.6 m and a design speed of about 12 knots. Three versions of hull form were considered to investigate its influence on propulsion and seakeeping. Principal characteristics of the ship with the considered hull forms are submitted in Table 1, and fragments of corresponding lines planes are shown in Fig. 1. As it can be observed from Table 1, the versions have certain differences in mass displacement, which can be explained by the complex influence of hull form on design characteristics based on preliminary versions of general arrangement.

The considered hull forms have more or less similar shapes of afterbodies, namely, a transom stern with central gondola, but drastically different shapes of forebodies. Version I has a normal bow with an almost vertical stem resembling the well-known Axe Bow [9]. Version II has a bulbous bow, which is the most conventional type from standpoint of ship design. Version III has an inverted bow similar to the well-known X-bow [8].

Table 1. Principal characteristics of the ship with the considered hull forms

No.	Denomination	Symbol, unit	Version of hull form		
			I	II	III
1	Length on waterline	L_{WL}, m	44.300	43.252	40.574
2	Breadth	B, m	12.600	12.600	12.710
3	Draught amidships	d, m	3.500	3.500	4.144
4	Displacement mass	Δ, t	1194.5	1143.6	1257.2
5	Vertical center of gravity	z_{CG}, m	4.294	4.407	5.044
6	Area of wetted surface	S, m^2	685.5	659.5	625.8
7	Longitudinal center of buoyancy	L_{CB}, %	0.23	−0.63	−7.81
8	Block coefficient	C_B	0.585	0.597	0.574
9	Waterplane area coefficient	C_{WP}	0.810	0.809	0.815
10	Midship section coefficient	C_M	0.943	0.948	0.927

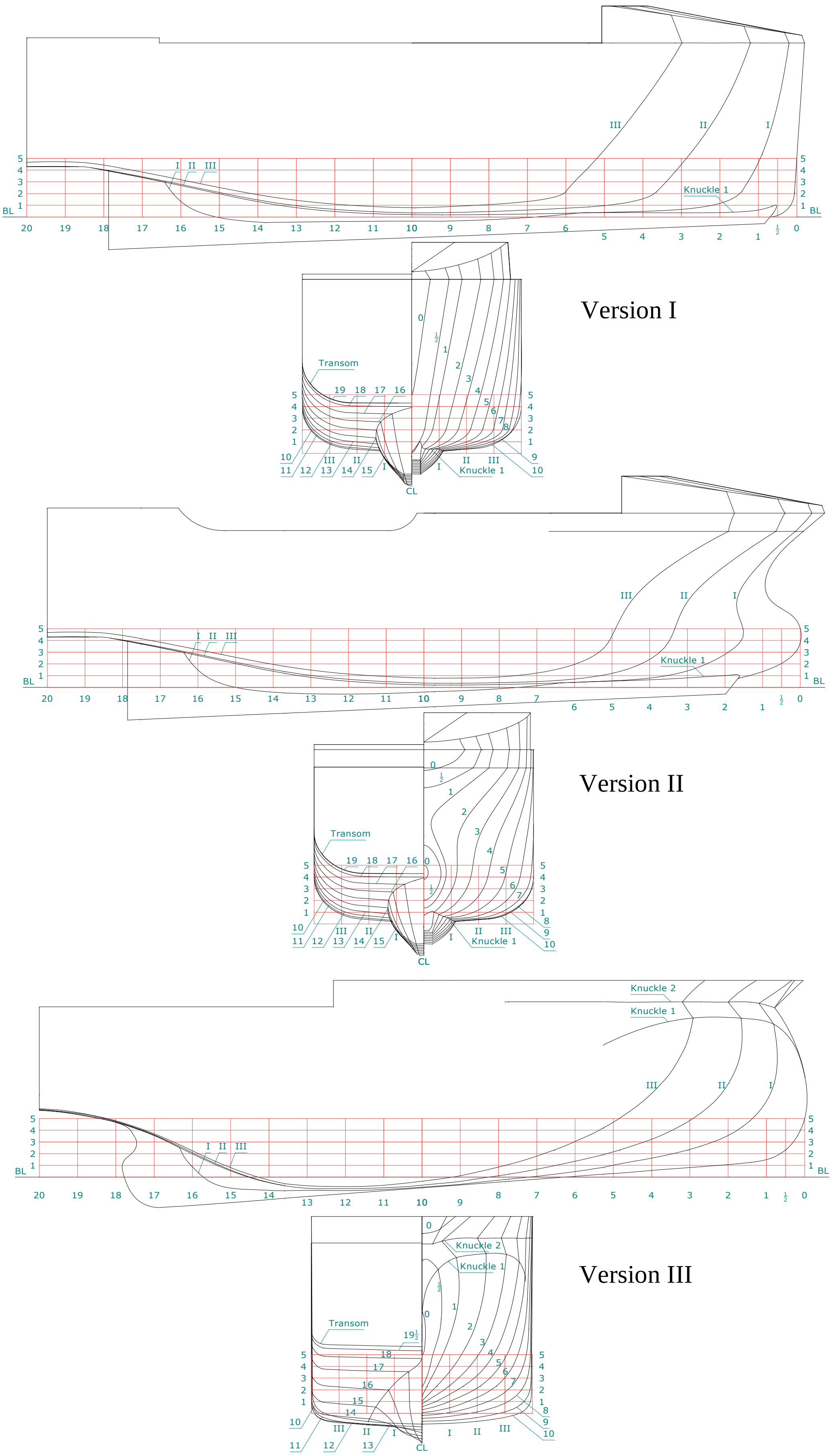

Fig. 1. Lines plans of the considered hull forms

2. The used CFD methods

2.1. Mathematical model

A mathematical model is based on the model of incompressible fluid according to RANS approach. The model includes RANS and continuity equations (mathematical form is based on [15, p. 430]):

$$\begin{cases} \frac{\partial u_i}{\partial t} + \sum_{j=1}^{3} u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\left(\mu + \mu_t\right)\Delta u_i, \ i = 1, 2, 3; \\ \sum_{j=1}^{3} \frac{\partial u_j}{\partial x_j} = 0, \end{cases} \quad (1)$$

where u_i – components of velocity vector;

t – time, s;

p – pressure, Pa;

ρ – density of water;

μ – molecular viscosity, kg/ms;

μ_t – turbulent viscosity, kg/ms.

A keystone of the RANS approach is a notion of turbulent viscosity μ_t and the method of its determination. The mathematical model of this study included the standard k-e turbulence model [10], where:

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}. \quad (2)$$

where $C_\mu = 0.09$ – empirical parameter;

k – turbulent kinetic energy, m^2/s^2;

ε – dissipation of the turbulent kinetic energy, m^2/s^3.

Generation and distribution of k and ε throughout a flow are subdued to the system of differential equations.

Simulation of free surfaces is provided by the modified method ‘volume of fluid’ (VOF) [7]. According to this method, the transfer of fluid is described by piecewise-continuous fill function F. Fully filled cells have $F = 1$; empty cells have $F = 0$ and there are partially filled cells, where an interface occurs. Free surfaces correspond to isosurfaces $F = 0.5$. Transfer of F is subdued to the equation:

$$\frac{\partial F}{\partial t} + \mathbf{v} \cdot \nabla F = 0. \quad (3)$$

2.2. Numerical solver

The equations of the submitted above mathematical model were numerically resolved by the finite-volume method implemented in the commercial CFD code FlowVision. The software and computational resources are courtesy of Digital Marine Technology LTD.

The numerical solver uses computational grids based on non-uniform Cartesian initial grids. The geometry of the computational domain and moving bodies are represented as faceted surfaces.

A computational grid is formed by cutting an initial grid with the faceted surfaces, on which inner edges boundary conditions are set. The main grid is built by using the subgrid geometry resolution method [1], the essence of which is Boolean subtraction of volumes, cut by closed surfaces, from the initial Cartesian grid. The cells crossed by a freeform surface are converted into complex polyhedrals, where the solved equations of the mathematical model are approximated with high-order schemes. This approach to grid formation significantly simplifies preprocessing and also allows dynamic rebuilding of computational grids, e.g. during the movement of objects with respect to them. The latter feature is used for the simulation of ship motions.

2.3. Numerical setup

A numerical setup of ship movement in waves has certain difficulties. Application of the finite-volume approach implies resolution of a simulated flow with some number of three-dimensional cells of the computational grid. The number of cells is important since it determines the needed computational efforts. For this reason, a rational numerical setup of linear movement (e.g. towing of ships) is based on inverted flow (a water tunnel scheme), where a flow moves through a motionless grid [2]. Thus, only a limited volume of the flow is simulated, and this volume doesn't depend on movement speed.

However, unlike the numerical setup of movement in still water, which can more or less directly copy model tests in water tunnels, movement in waves cannot be easily simulated by this method. The point is that movement of a ship with respect to motionless water and vice versa are equal in the case of steady movement only. Since flows with waves include accelerated motions, they are quite different in normal and inverted coordinate systems. That's why the seakeeping tests are never conducted in water tunnels. On the other hand, a numerical setup similar to towing tanks leads to excessively high grid numbers. Another related problem is a method of wave generation providing the necessary parameters of waves. Towing tanks are equipped with wavemakers based on flaps driven by hydraulic cylinders. But such a wavemaker would block an oncoming flow in water tunnels.

Taking into account the aforementioned circumstances, the following numerical setup has been suggested. The inverted flow is simulated, but the waves are generated analytically through initial and boundary conditions. Corresponding equations of the waves for flow velocities and coordinates of the free surface are drawn up accounting constant velocity of oncoming flow. For the initial moment of time, fully developed waves are preset throughout the computational domain, and then the waves are supported by synchronous inlet boundary conditions. The geometry of the computational domain is a rectangular prism in which edges serve as boundary conditions – Fig. 2.

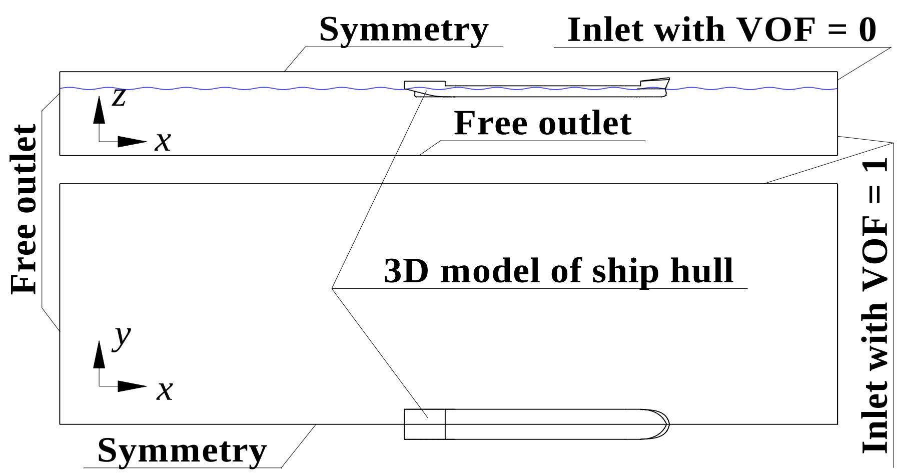

Fig. 2. Computational domain and boundary conditions

The initial conditions and inlet boundary conditions are based on the equations of regular waves of finite amplitude suggested by G.G. Stokes [5]:

$$\eta = \frac{H}{2}\cos(kx - \sigma t) + \frac{H^2 k}{16}\frac{\cosh kh}{\sinh^3 kh}\left(2 + \cosh 2kh\right)\cos 2(kx - \sigma t); \qquad (4)$$

$$u = \frac{H}{2}\frac{gk}{\sigma}\frac{\cosh k\left(h+z\right)}{\cosh kh}\cos\left(kx - \sigma t\right) + \frac{3}{16}\frac{H^2 \sigma k \cosh 2k\left(h+z\right)}{\sinh^4 kh}\cos 2\left(kx - \sigma t\right); \qquad (5)$$

$$w = \frac{H}{2}\frac{gk}{\sigma}\frac{\sinh k\left(h+z\right)}{\cosh kh}\sin\left(kx - \sigma t\right) + \frac{3}{16}\frac{H^2 \sigma k \sinh 2k\left(h+z\right)}{\sinh^4 kh}\sin 2\left(kx - \sigma t\right), \qquad (6)$$

where η – vertical coordinate of the wave profile, m;
k – wavenumber, rad/m;
σ – frequency, rad/s;
H – wave height, m;
h – water depth, m.

3. Initial data

The ship is considered moving in head seas with a constant velocity of 3.5 knots. Since in numerical simulations heading 180° completely excludes rolling, heading 150° is considered as well. Parameters of waves (Table 2) have been chosen close to the pitching resonance.

Table 2. Parameters of waves

Denomination, symbol and unit	Value
Wave height H, m	3
Wave period T, s	6
Wave length λ_W, m	60
Wave steepness H/λ_W	1/20
Corresponding wind speed V_W, m/s	10.288

4. Main results

The main results of the simulations are submitted in Tables 3, 4. They include total resistance in waves R_T and amplitudes of ship motions. Values of ship motions versus periods of waves calculated accounting the ship speed and heading are also shown in Fig. 3-5 for heading 150°. Heave and pitch at heading 180° have a similar pattern, but slightly higher values.

As can be observed from the tables and figures, resistance in waves as well as characteristics of heaving and pitching indicate no clear advantages among the considered versions of the forebody. However, the version III similar to X-bow has a significantly lower rolling at heading 150°. The character of rolling is nonsymmetric, with higher amplitude towards oncoming waves. The dependency of roll versus time (Fig. 5) is chaotic. Curiously enough that the version III has a notably higher vertical center of gravity (see Table 1), which can be explained by features of general arrangement inherent to many ships with inverted bows. But this difference has a limited impact on stability and doesn't explain the observed character of rolling in terms of natural period.

Thus, according to the performed study, the most obvious advantage of hull forms with inverted bows is significantly lower rolling, while added resistance and characteristics of heaving and pitching are quite comparable to those of other bow shapes.

Table 3. The main results of simulations for heading 180°

Version	R_T, [kN]	θ_{max}, [deg.]	θ_{min}, [deg.]	z_{Gmax}, [m]	z_{Gmin}, [m]
I	341.6	10.00	-8.87	1.872	-1.406
II	316.9	9.43	-8.50	1.678	-1.512
III	343.0	10.87	-8.00	1.727	-1.272

Table 4. The main results of simulations for heading 150°

Version	R_T, [kN]	θ_{max}, [deg.]	θ_{min}, [deg.]	z_{Gmax}, [m]	z_{Gmin}, [m]	ϕ_{max}, [deg.]	ϕ_{min}, [deg.]
I	220.2	8.85	-8.37	1.774	-1.763	1.46	-3.35
II	262.7	8.27	-7.19	2.052	-2.032	1.88	-3.22
III	269.6	10.72	-8.62	1.704	-1.452	-0.34	-2.19

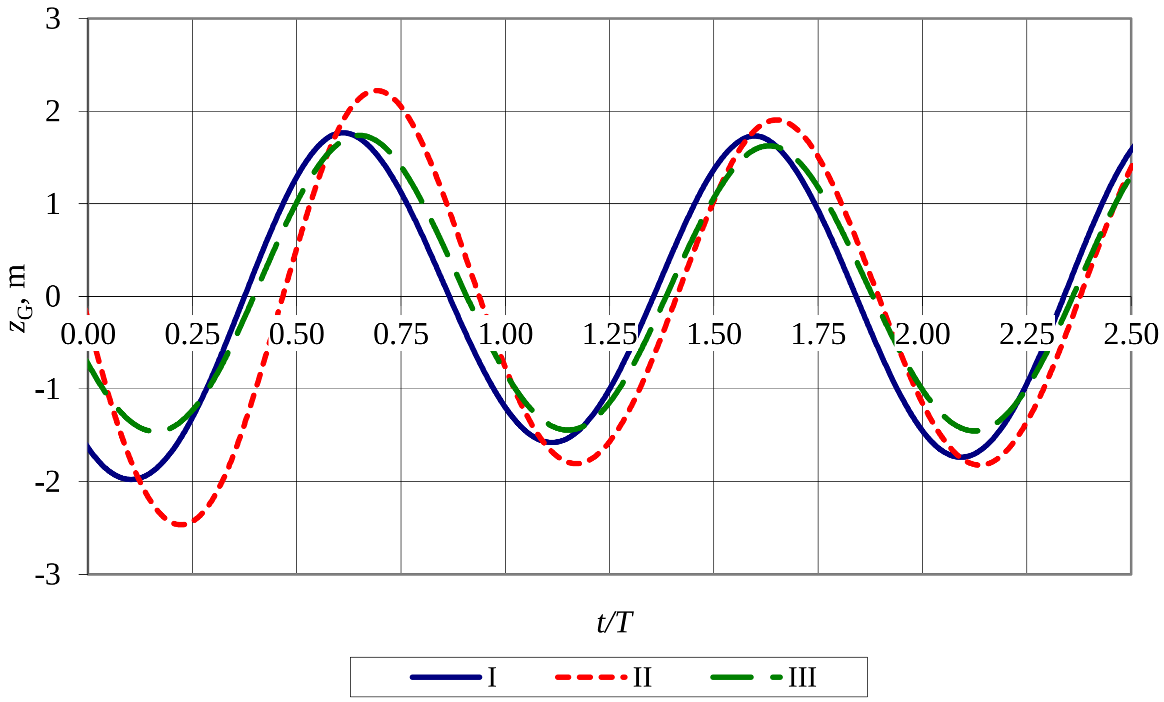

Fig. 3. Heave in the CG versus periods of waves, heading 150°

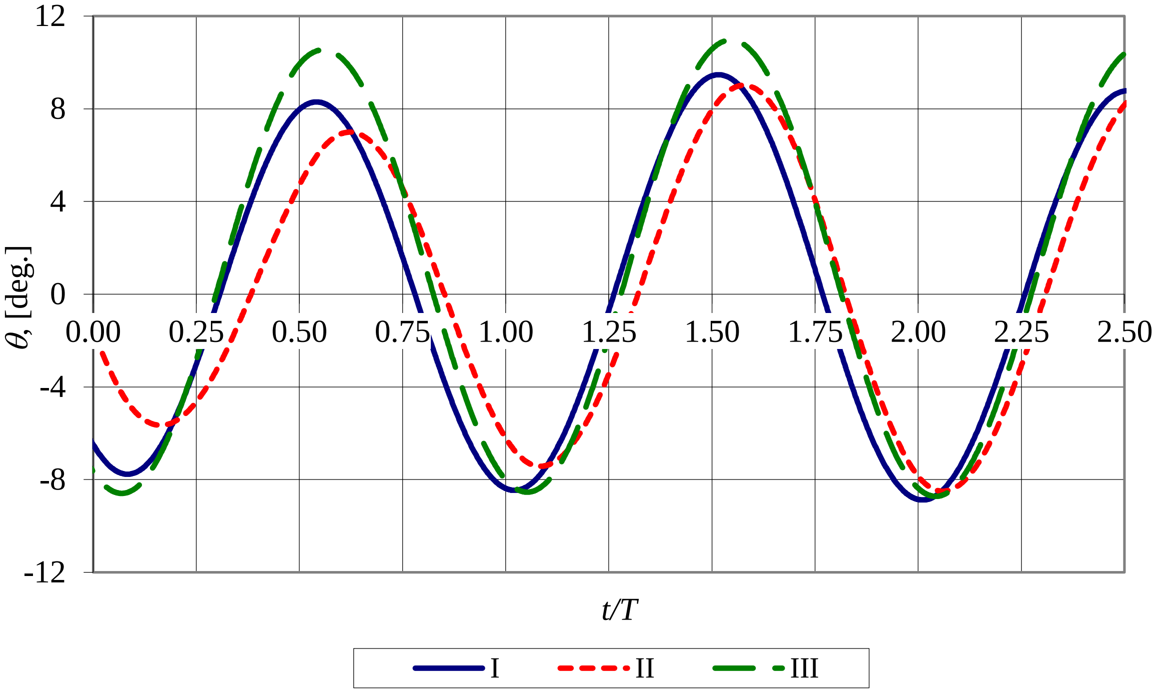

Fig. 4. Pitch versus periods of waves, heading 150°

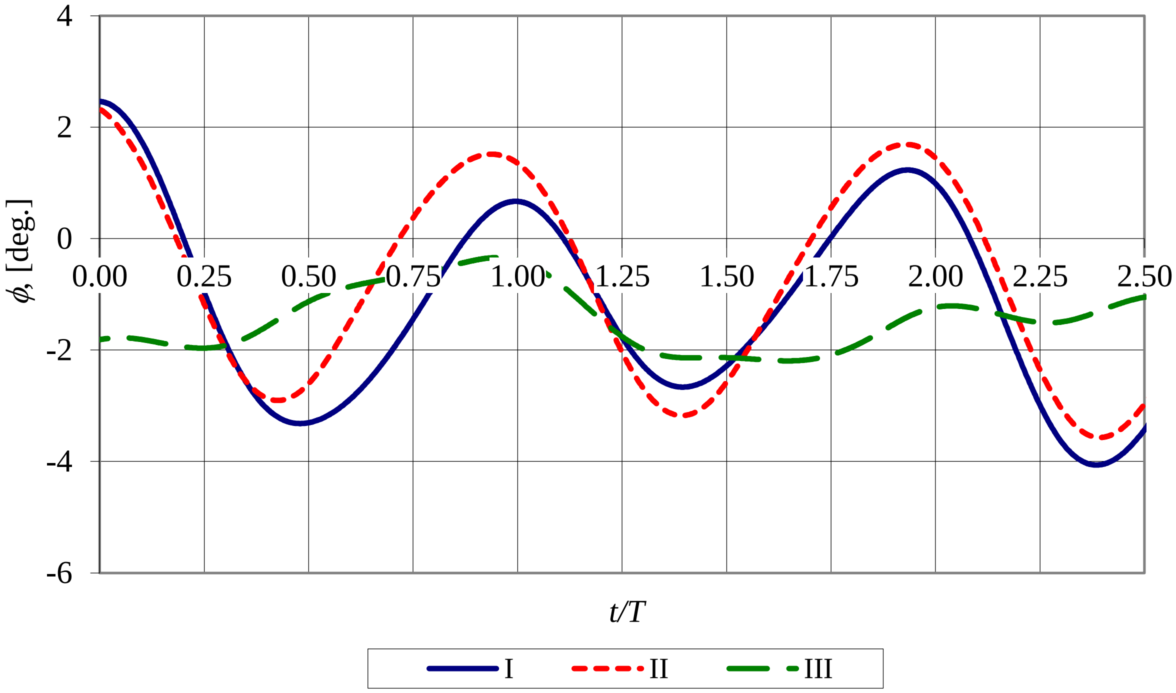

Fig. 5. Roll versus periods of waves, heading 150°

Conclusions and further research prospects

The seakeeping tendencies provided by different forebody shapes of the fishing trawler have been carried out based on the RANS CFD method.

The numerical setup based on inverted flow has been suggested. The waves are generated analytically through initial and boundary conditions containing equations for flow velocities and coordinates of the free surface. For the initial moment of time, fully developed waves are preset throughout the computational domain, and then the waves are supported by synchronous inlet boundary conditions. The parameters of regular waves were set close to the pitching resonance.

Three versions of hull form have been studied with headings 180° and 150° at speed of 3.5 knots to reveal differences in added resistance and ship motions. While added resistance and characteristics of heaving and pitching have shown no clear advantages among the considered shapes of forebodies, the version similar to X-bow has demonstrated a significant decrease in rolling at heading 150°. The results of the study have shown that the suggested numerical setup in combination with the CFD methods described can be used for quite realistic simulations of ship behaviour in rough seas.

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