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Computational model for simulation of lifeboat motions during its launching from ship in rough seas

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ABSTRACT

This paper presents a computational model which describes motion of an object of six degrees of freedom (DoF), intended for simulation of spatial motion of one- or two- rope-sling lifeboat or rescue boat during its launching from ship in rough sea. This is a complex model which accounts for sea conditions as well as elasticity and damping properties of davit's elements and mechanisms, rope and boat hull. Also, are presented results of example calculations for an assumed set of technical parameters of davit and boat as well as sea conditions.

Key words: ship in rough seas; life saving appliances (LSA); lifeboat launching; lifeboat motions; lifeboat launching simulation

INTRODUCTION

Human life protection and rescue is one of the most important problems which must be faced by designers of objects doing duty for man, especially sea-going passenger ships.

Life saving appliances (LSA) systems which make it possible to evacuate persons especially from large passenger ships, have evaluated beginning from the simplest open lifeboats and rafts thrown off into water and ending to unsinkable sheltered boats of high strength and fire resistance, lowered with the use of more and more advanced side davits.

In Fig. 1 is presented a photo of an example contemporary davit together with suspended boat during launching it into water.

Operation of launching boats together with embarked persons into water is the most hazardous phase of process of rescuing persons from endangered ship in rough seas. Boat, during its launching from a significant height in the neighbourhood of rolling ship's side, often impacts against the side. In the case of large passenger ships the lowering height is significant and boat displaces close to ship side, that often leads to its bumping against the side. The bumps generate the relatively largest overloading which results from a change of motion of the boat and affects persons inside the boat. The overloads may lead to failures of boat and person injures and even casualties. For this reason many recognized research centres as well as leading producers of ship life saving and rescue appliances are searching for more and more exact methods for calculation of motion parameters of boat lowered from ship to water in rough seas conditions. When a reliable computational software is at disposal it is possible to perform investigations of LSA systems intended for rough seas conditions. This allows to improve the existing design solutions and test new ones of the devices in question.

Fig. 1. *View of the lifeboat and the luffing-jib davit during launching test*

The problem was included into the scope of the research program realized, in the period of 2004-2009, within the frame of the European project SAFECRAFTS (Safe Abandoning of Ships - improvement of current Life Saving Appliances Systems) in which also the Faculty of Ocean Engineering and Ship Technology, Gdansk University of Technology, took part [2].

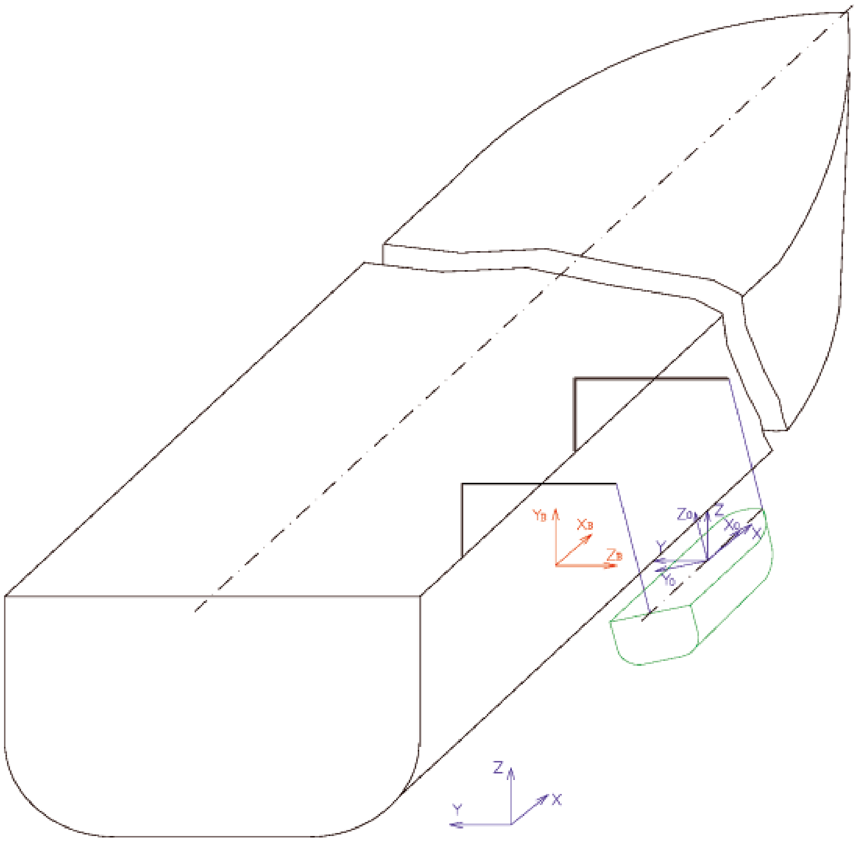

***Fig. 2.** Coordinate systems: **x, y, z** – absolute coordinate system, x_0, y_0, z_0 – local coordinate system of the boat, x_B, y_B, z_B – local coordinate system of the ship*

This paper presents results of one of the project's tasks realized by these authors, which concerns elaboration of a complex mathematical model and computational program, called RESBO, intended for simulation of lifeboat motion during its launching from ship in rough seas.

GENERAL DESCRIPTION OF RESBO PROGRAM

RESBO program serves to simulation of 3D motion of one- or two – suspension - point object during its launching from the ship in waves and its recovering as well. The program is prepared for simulation of the 1 - point lifeboat, 1- point fast rescue boat, 1- point davit for launching life raft and 2 - point lifeboat.

The RESBO was written in C++ language and compiled under Linux system.

Algorithm of the program takes into account:
- movement of the ship in waves
- operation of davit mechanisms
- elasticity and damping properties of davit parts
- elasticity and damping properties of object hull
- influence of wind
- lifeboat impact against ship's side
- lifeboat impact against water during launching
- movement of the lifeboats in waves during a short period after releasing the hooks.

THEORETICAL MODEL

Assumptions

The object (e.g. lifeboat) is modelled as a rigid body. However special flexible elements called "fenders" are attached to one side of the lifeboat hull. The object performs motions of 6 DoF. Elements and factors restricting (extorting) motion of the object are formulated as external forces dependent on
- relative position between the object and a restricting (extorting) element
- relative velocity
- time

Influence of the elasticity and damping properties of the object structure on its motion is formulated as a separate segment of the extorting forces function.

The elements and factors restricting (extorting) motion of the object are the following:
- suspension system and mechanisms: ropes, davit arm, absorber, brake, with regard to elasticity and damping properties of the hull construction in hook suspension point
- ship's side which restricts area range of the object's motions (possibility of the impact against ship's side)
- wind – aerodynamic reaction
- force of gravity
- water – hydrostatic and hydrodynamic reaction, including slamming
- functioning the hydrostatic locking device

The launching system includes: brake and the elements connected in series: davit arm, absorber, rope and catch. The elements transfer the same load, hence deformation of the system is a sum of their deformations.

The object's motion equations

The dynamic equations of free spatial motion of the solid are as follows [1]:

$$m\,\ddot{x}_c = \sum_{i=1}^{k} F_{xi} \quad m\,\ddot{y}_c = \sum_{i=1}^{k} F_{yi} \quad m\,\ddot{z}_c = \sum_{i=1}^{k} F_{zi}$$

$$J_{x_0}\ddot{\varphi}_{x_0} - \left(J_{x_0} - J_{z_0}\right)\dot{\varphi}_{y_0}\dot{\varphi}_{z_0} = \sum_{i=1}^{k} M_{x_0 i}$$

$$J_{y_0}\ddot{\varphi}_{y_0} - \left(J_{z_0} - J_{x_0}\right)\dot{\varphi}_{z_0}\dot{\varphi}_{x_0} = \sum_{i=1}^{k} M_{y_0 i}$$

$$J_{z_0}\ddot{\varphi}_{z_0} - \left(J_{x_0} - J_{y_0}\right)\dot{\varphi}_{x_0}\dot{\varphi}_{y_0} = \sum_{i=1}^{k} M_{z_0 i}$$

x_c, y_c, z_c – coordinates of the solid's mass centre
x_o, y_o, z_o – principal central axes of inertia (moving system)
$\dot{\varphi}_{x_o}, \dot{\varphi}_{y_o}, \dot{\varphi}_{z_o}$ – momentary angular velocities of the solid rotating around principal central axes of inertia
$J_{x_o}, J_{y_o}, J_{z_o}$ – principal central moments of inertia of the boat
F_{xo}, F_{yo}, F_{zo} – vectors of „i" force
$M_{x_o}, M_{y_o}, M_{z_o}$ – vectors of moment of „i" force relative to central axes of inertia

Forces

The forces which influence the object $\mathbf{F_i}$ depend on:

- the position of the gravity centre of the object, $\mathbf{x_c}$, and the vector of the angular position, $\boldsymbol{\varphi}$, (position of the object's local coordinate system determined by the principal central axes of inertia: $\mathbf{x_o}$, $\mathbf{y_o}$, $\mathbf{z_o}$)
- the vector of linear velocity, $\dot{\mathbf{x}}_c$, and angular velocity, $\dot{\boldsymbol{\varphi}}$
- the wind velocity and direction, $\mathbf{v_{wind}}$
- time t

$$\mathbf{F_i = F_i(x_c, \dot{x}_c, \boldsymbol{\varphi}, \dot{\boldsymbol{\varphi}}, v_{wind}, t)}$$

Detailed description of the forces function F_i follows from reaction of the elements on the object.

Characteristics of the system's elements

Davit

The davit is modelled as a linear springy element (without restriction of linear range). The stiffness of the davit, EI, is an input parameter of the algorithm.

Absorber

The absorber is modelled as a linear springy element with restrictions for the deformation: Δl_0 and Δl_1 As assumed, the absorber starts working when the force in the rope, Fr, reaches its nominal value Frn, and stops when it obtains the value of 1,5 Frn._The absorber has immanent friction – if velocity of the deformation is not zero, then the friction force Ta which inhibits progress of the process, appears. Module of the force has constant value, independent of the force transferred by the absorber. The absorber is defined by the following parameters: Δlo, Fr, Ta, ν_0.

The parameter ν_0 - velocity of friction waning (below this value of deformation velocity, friction linearly decreases to zero) is added only to obtain numerical solution. It does not follow from physical model of the system.

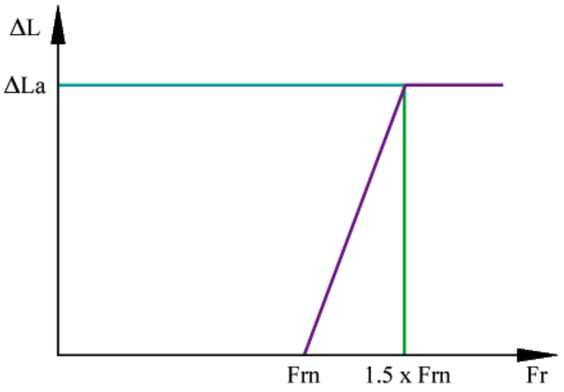

Fig. 3. *Assumed static characteristic of the absorber*

Steel rope

The rope is modelled as a linear springy element with the minimum restriction for the transferred force: $Q_0 = 0$. It means that the force in the rope cannot be negative, but process of the rope length reduction can be still in progress. The rope is defined by the following parameters: its length l, cross-section area A, Young modulus E.

"Catch" of the rope to the object

This is an imaginary element added for taking into account elasticity and damping properties of the object's hull structure. When we simulate a system without absorber, function of the catch can be especially noticeable. The catch is modelled as a linear springy element. Its damping is modelled as an immanent friction, linearly dependent of transferred force.

The catch characteristic is defined by the following parameters: its stiffness I, friction coefficient f, velocity of friction waning $\nu_{0.}$

Fender

The fender is modelled as a linear springy element with a minimum restriction for the transferred force. It cannot work on stretching. It starts working in the moment of contact with ship's side. Its damping properties are: immanent friction which is in opposite direction to the perpendicular vector of the fender velocity relative to ship side surface. Damping force depends linearly on fender pressure force. Tangent friction force of the fender on the ship side surface is modelled analogously.

The fender characteristic is defined by the following parameters: its stiffness I, perpendicular friction coefficient f_n, tangent friction coefficient f_t, velocity of friction waning ν_0.

Centrifugal brake

The centrifugal brake controls unreeling velocity of the ropes during launching the boat. The velocity is linearly dependent of force transferred by the rope. The brake's characteristic is presented in Fig. 4.

Hydrostatic locking device

The hydrostatic locking device is used for releasing the hook and disconnecting lifeboat's steel ropes during launching. The device is defined by its position level.

Aerodynamic reaction

Motion of the object in the air causes aerodynamic reaction. This force can be described as follows:

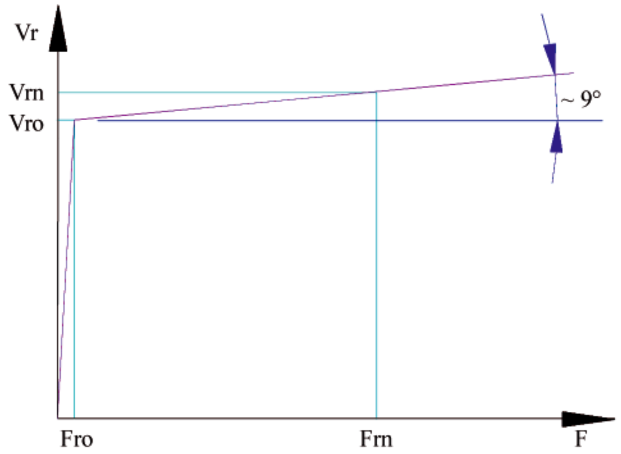

Fig. 4. Assumed characteristic of the centrifugal brake, where: ***Vro*** *– the minimum value of the velocity* ***Vr*** *of the ropes which triggers the centrifugal brake and begins to control of unreeling velocity of the ropes during launching the boat,* ***Fro****,* ***Frn*** *– the minimum and nominal values of the load in the ropes during controlled launching the boat*

$$R_A = C_A \frac{\rho |V_A| V_A S}{2}$$

where:

CA– air resistance coefficient

ρ – air density

VA– object's velocity relative to the air, including wind

S – windage area

Hydrostatic reaction

The hydrostatic reaction is connected with hydrostatic pressure exerted on lifeboat hull's wetted area. The reaction which acts on the area element dS in the direction determined by the unit vector n, is calculated as follows:

$$dF_{hs} = -\rho_w\, g\, h\, \mathbf{n}\, dS$$

where:

ρ_w – water density

g – gravitational acceleration

h – immersion depth of the area element dS

n – unit vector normal to the area element dS

The total hydrostatic reaction is calculated as follows:

$$F_{hs} = -\int_S \rho_w\, g\, h\, \mathbf{n}\, dS$$

Hydrodynamic reaction

Lifeboat movement in the water induces hydrodynamic reaction which is roughly equal to sum of frictional resistance and pressure resistance. The force vector of the frictional resistance is calculated as follows:

$$R_F = C_F{}'' \rho_w \int_S |\boldsymbol{\upsilon}_w| (\boldsymbol{\upsilon}_w \cdot e_t) \mathbf{t}\, dS$$

where:

C_F – frictional resistance coefficient

$\boldsymbol{\upsilon}_w$ – tangential component of the velocity vector of the area element dS, in relation to the water

t – unit vector tangent to the area element dS, defined as follows:

$$e_t = \frac{\boldsymbol{\upsilon}_w - (\boldsymbol{\upsilon}_w \cdot \mathbf{n})\mathbf{n}}{|\boldsymbol{\upsilon}_w - (\boldsymbol{\upsilon}_w \cdot \mathbf{n})\mathbf{n}|}$$

where:

n – unit vector normal to the area element dS.

The force vector of the pressure resistance is calculated as follows:

$$R_p = C_p{}'' \rho_w \int_S |\boldsymbol{\upsilon}_w \cdot \mathbf{n}| (\boldsymbol{\upsilon}_w \cdot \mathbf{n}) \mathbf{n}\, dS$$

where:

C_p – pressure resistance coefficient.

Free surface reaction (slamming)

The pressure caused by hull impact against free water surface is calculated by using the von Karman formula:

$$p_{slam} = \frac{\rho_w \boldsymbol{\upsilon}_0^2}{2} \frac{\pi ctg(\alpha)}{(1 + \frac{\rho_w g \pi x^2}{2W})}$$

where:

υ_o – first impact velocity [m/s]

α – angle of inclination of the lifeboat bottom surfaces [deg]

ρ_w – water density [kg/m³]

g – gravitational acceleration [m/s²]

x – breadth of the wetted part of the bottom [m]

W – weight of the body per unit length [N/m]

The total reaction of slamming is calculated by using the following integral:

$$R_{slam} = -\int_S p_{slam}\, \mathbf{n}\, dS$$

where:

n – unit vector normal to the area element dS

NUMERICAL MODEL

The applied calculation algorithm of the object motion is based on the Euler explicit method. Its essence can be described as follows:

0. START. Initiation of the constant values. Reading input data.
1. Number of updating: n = n+1
2. Calculation of current position of ship.
3. Calculation of forces in the elements according to positions of ship and object.
4. Summing the forces and reactions which influence the object:
   a. Gravity force
   b. Aerodynamic reaction
   c. Force in the rope
   d. Force in the fender
   e. Hydrostatic reaction
   f. Hydrodynamic reaction
   g. Force of the free water surface impact (slamming)
5. Calculation of a new position and velocity of the object, resulting from forces working in the time interval Δt.
6. Calculation of a new length of the rope
7. Updating the time: $t_{n+1} = t_n + \Delta t$.
8. If $t_{n+1} = t_{max,}$ then go to STOP; if not, go to 1.

RESBOVI PROGRAM

The RESBOVI program is the post-processor for the RESBO program. It serves to visualize (animate) the calculation results of the lifeboat (or rescue boat) motion during its launching (and recovering) from the ship in waves. The RESBOVI was written in C++ language and compiled under Linux system.

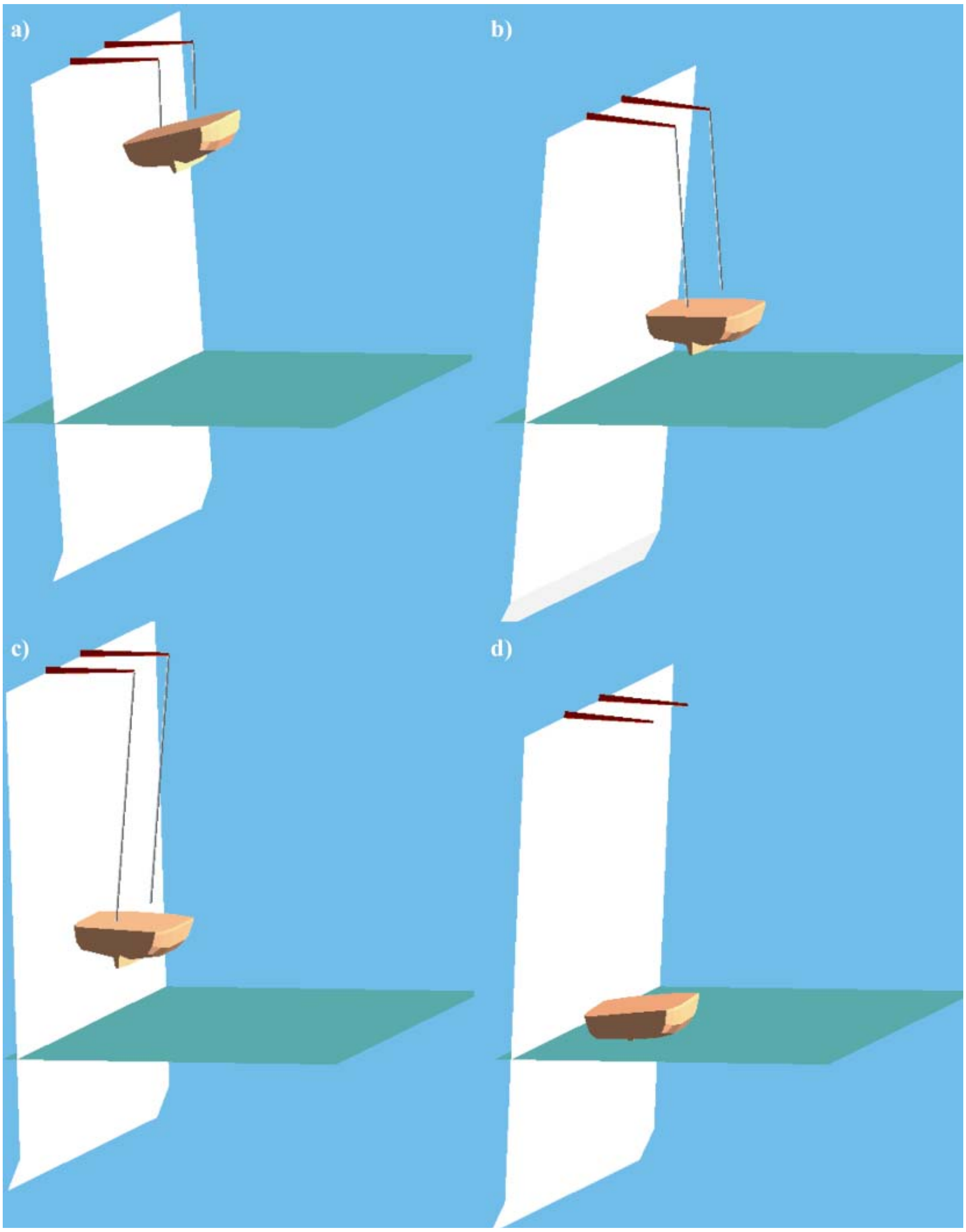

Fig. 5. *Lifeboat during launching. Freeze frames (dumps) taken from the RESBOVI animation*

In Fig. 5 are given 4 successive screen dumps of animation which presents calculation results based on the following example test data:_

- Heave and roll period of ship: T = 8 s
- Heave amplitude: $Z_A = 1.0$ m
- Drift amplitude: $Y_A = 0.8$ m
- Roll amplitude: $\Phi_A = 1.0$ m
- Distance between ship's side and its symmetry plane (PS): B/2 = 16.1 m
- Distance between boat's centre of gravity(CG) and ship's PS: bl = 20.1 m
- Distance between ropes suspending the boat: l = 8 m
- Initial position of the suspension point: h = 20 m
- Mass of the boat: m = 15550 kg
- Boat's moments of inertia: Jx, Jy, Jz = 36792, 80102, 80102 kg, respectively
- Steel rope diameter: d = 16 mm
- Nominal lay-out velocity of rope: $V_{r\,n} = 0.8$ m/s

CALCULATION CASES

The calculation cases concern the two- suspension- point lifeboat in 3D movement during launching (and recovering) from the ship in waves. Two cases are selected to compare their calculation results.

The first case applies to the system with elasticity and damping properties of the davit arm, rope, centrifugal brake and boat's hull. For comparison purposes, a small absorber is added to the system which is used for fast rescue boat davit. The second case, without any absorber, applies to the lifeboat davit system. Below in the sections 6.1 and 6.2 in the successive figures are presented calculation results for both the considered systems in the form of runs of the main parameters which describe motion of the life boat with embarked persons during its launching from ship to water in rough seas. The successive figures present the following:

- Fig. 6 and 11: Displacement (linear motion) of the boat's centre of gravity against the Earth (in the coordinate system x,y,z – acc. Fig. 2).
  G_X – displacements along x- axis – horizontal parallel to the ship's plane of symmetry (PS);
  G_Y – displacements along y- axis – horizontal perpendicular to the ship's plane of symmetry (PS);
  G_Z – displacements along z- axis – vertical.
- Fig. 7 and 12: Run of change in position of the local boat-fixed coordinate system in the global system:
  Exo_x, Exo_y, Exo_z – coordinates of the unit vector **Exo** which determines direction and sense of Xo – axis of the local boat-fixed coordinate system;
  Eyo_x, Eyo_y, Eyo_z – coordinates of the unit vector **Eyo** which determines direction and sense of Yo – axis of the local boat-fixed coordinate system;
  Ezo_x, Ezo_y, Ezo_z – coordinates of the unit vector **Ezo** which determines direction and sense of Zo – axis of the local boat-fixed coordinate system).
- Fig. 8 and 13: Displacement (linear motion) of the centre of gravity of boat and its oscillations (angular motions) against ship's side (the coordinate system X_B, Y_B, Z_B – acc. Fig. 2).
  G_{XB} – displacements along X_B - axis –parallel to the ship's plane of symmetry (PS);
  G_{YB} – displacements along Y_B - axis –parallel to the ship's plane of symmetry (PS);
  G_{ZB} – displacements along Z_B - axis –perpendicular to the ship's plane of symmetry (PS);
  Roll, pitch, yaw – angular displacements (motions) of the boat;
- Fig. 9 and 14: Linear and angular accelerations acting onto the boat.
  a_x, a_y, a_z– components of linear acceleration vector;
  ε_x, ε_y, ε_z – components of angular acceleration around the axis X,Y, Z, respectively;
- Fig. 10 and 15: Linear and angular velocities of the boat against the Earth.
  V_x, V_y, V_z – components of linear velocity vector;
  ω_x, ω_y, ω_z – components of angular velocity vector.

System with absorber and elasticity and damping properties
Diagrams

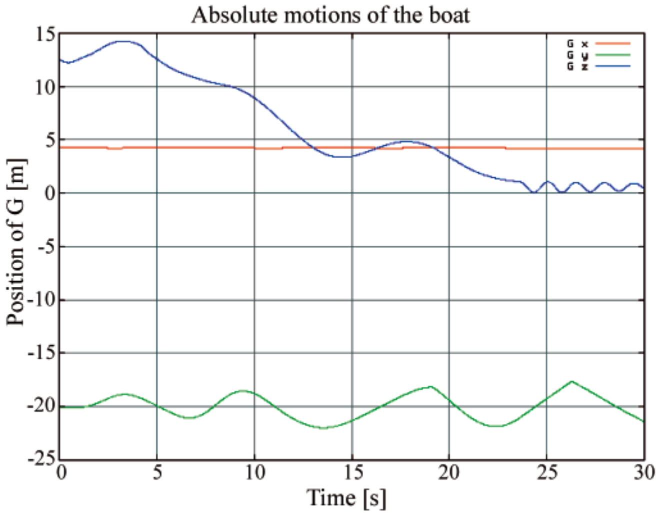

Fig. 6. *Linear and angular motions of the lifeboat. Absolute coordinate system. Diagram of the mass centre motions*

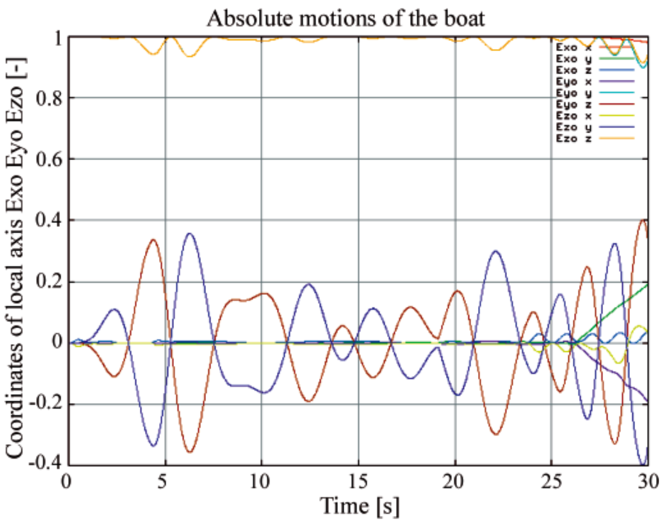

Fig. 7. *Angular motions of the lifeboat. Absolute coordinate system. Unit vectors of the boat's local coordinate system*

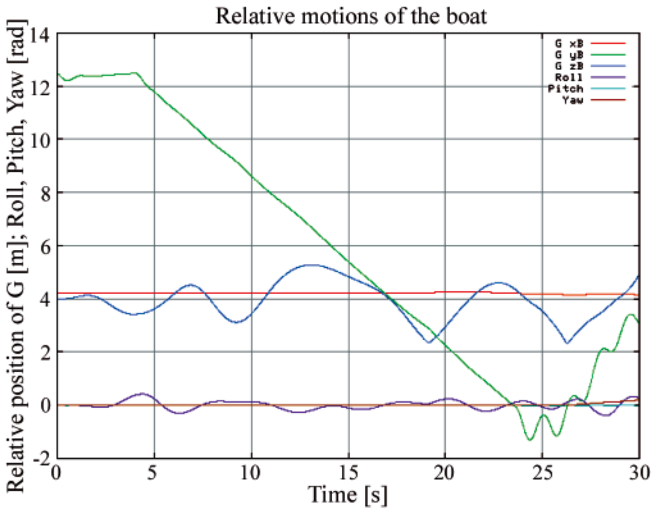

Fig. 8. *Linear and angular motions of the lifeboat. Ship side's coordinate system. Diagram of the relative motions of lifeboat's mass centre and the lifeboat rotations: roll, pitch, yaw*

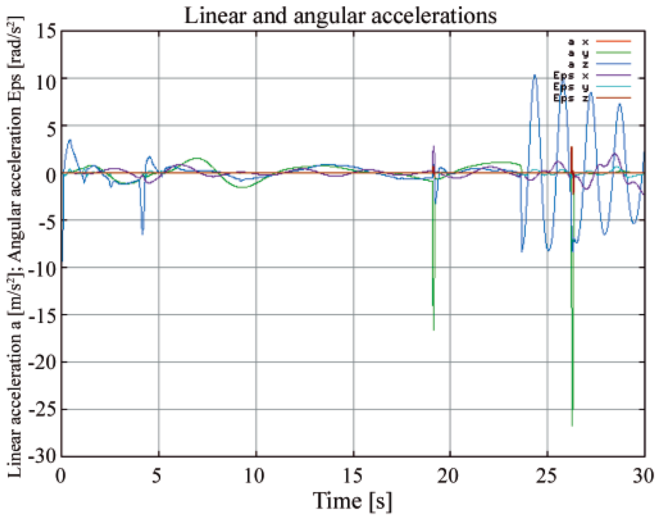

Fig. 9. *Linear and angular accelerations of the lifeboat*

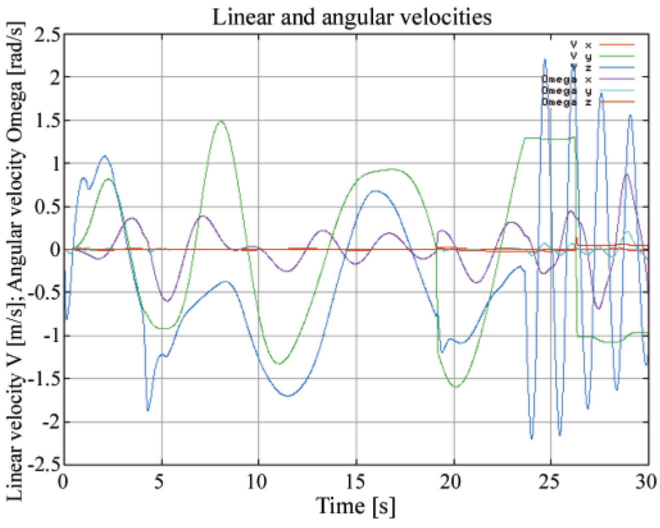

Fig. 10. Linear and angular velocities of the lifeboat

System without absorber Diagrams

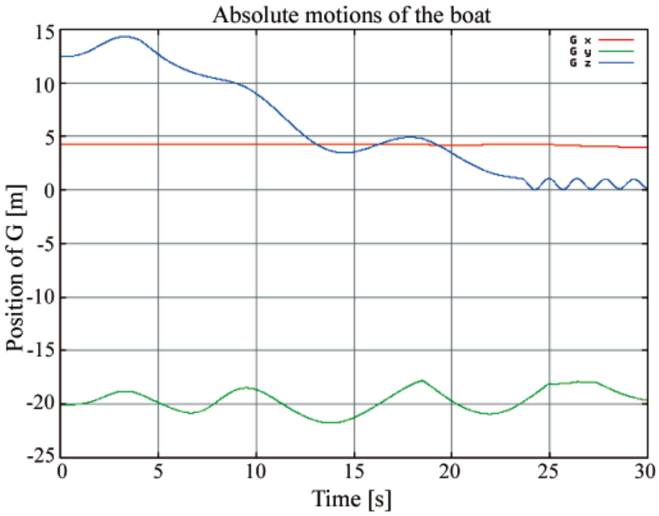

Fig. 11. *Linear and angular motions of the lifeboat. Absolute coordinate system. Diagram of the mass centre motions*

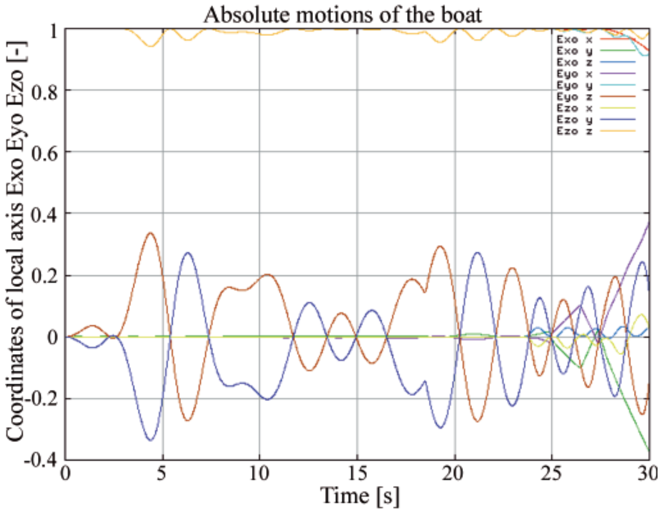

Fig. 12. *Angular motions of the lifeboat. Absolute coordinate system. Unit vectors of the boat's local coordinate system*

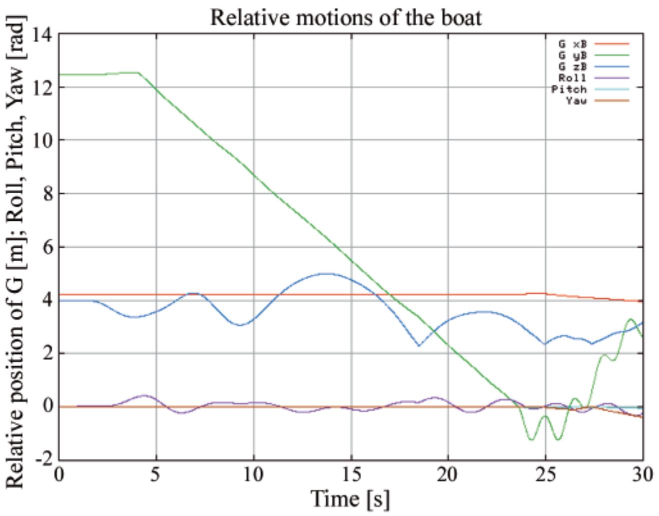

Fig. 13. *Linear and angular motions of the lifeboat. Ship side's coordinate system. Diagram of the relative motions of lifeboat's mass centre and the lifeboat rotations: roll, pitch, yaw*

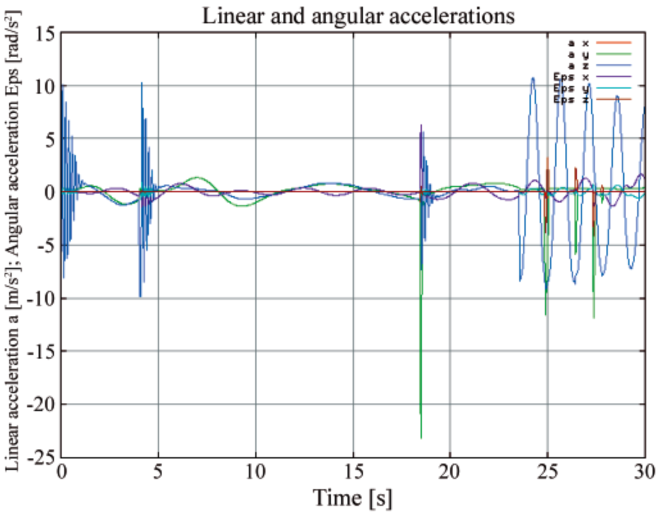

Fig. 14. *Linear and angular accelerations of the lifeboat*

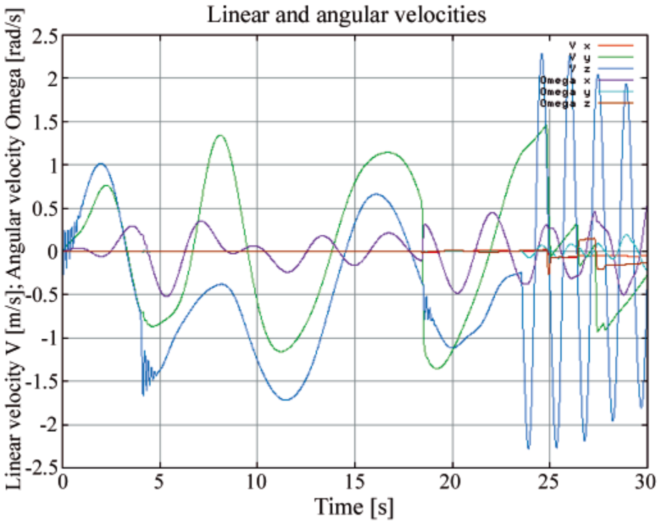

Fig. 15. *Linear and angular velocities of the lifeboat*

DESCRIPTION OF RESULTS AND CONCLUSIONS

- The graphs in Fig. 6 and 11 show position of lifeboat's mass centre in the absolute coordinate system (x, y, z). The graphs in Fig. 8 and 13 show relative, linear and angular motions of the lifeboat in ship side's co-ordinate system. The graph G z B shows sway. During launching (lengthening the rope) we can notice increasing the period and amplitude of the motion. At about 18th second of launching process we observe impact of the lifeboat against ship side.
- The graphs in Fig. 7 and 10 show positions of unit vectors of the local lifeboat coordinate system in the absolute coordinate system.
- The graphs in Fig. 9 and 14 show linear and angular accelerations of the lifeboat. The blue ones (a_z) show vertical accelerations. The green ones show horizontal accelerations (a_y). At about 4th second we can notice start of lifeboat lowering, and at about 18th second - impact of the lifeboat against ship side.
- The graphs in Fig. 10 and 15 show linear and angular velocities of the lifeboat.
- The presented calculation results concern a typical launching operation of lifeboat for two cases which differ to each other with rope system only. The first case concerns the system equipped with an absorber and the other – that without absorber. In view of that the absorber works only under load in the rope greater than nominal one the courses of the functions are reliable and the differences between two presented cases are inconsiderable. In the graphs in Fig. 9 and 14 the main expected difference in lifeboat vertical accelerations can be observed. However it should be stressed that in the presented model elasticity of davit's structural elements was taken into account but their damping properties were neglected as to estimate them was difficult. If the properties are taken into account, then values of calculated accelerations will be lower, hence the difference between the acceleration courses for the two calculated cases will be smaller.
- The program in question is prepared for further development. It is possible to add elements for simulating more complex absorbers (e.g. dampers of longitudinal and transversal motions of the boat or drive and control systems for compensators). It could be useful in elaborating new systems.

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