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Variations of Ship's Deck Elevation Due to Stochastic Process of Containers Loading

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ABSTRACT: The stochastic process of container loading is described in the paper with special emphasis to ship motion when she is lying at a quay. The 3 DOF system was applied to describe rolling, pitching and heaving of a vessel which may cause a significant variations of momentary deck elevation. The realistic range of such variations are assessed for a variety of cargo locations on-board and a phase shift between two independent gantries engaged in cargo operations. The process is modeled with regard to random character of crucial variables affecting ship motion due to cargo loading.

1 INTRODUCTION

Ship stability performance is widely found as one of the key factors influencing safety of sea transport. However, main efforts of researchers aim at some phenomena related to ship complex motions when sailing in rough sea conditions. In regards of a ships safety the greatest concern relates to its rolling oscillations. The main parameters of the commonly considered rolling equation are: inertia, damping, stiffness and excitation. The literature review shows a list of works taking into consideration various aspects of ships rolling motion.

Generally, potentially dangerous situations that may cause capsizing of a ship that remains intact, can be divided into resonant and non-resonant ones [1]. The non-resonant situations are mainly the outcome of a ships rolling motion and a dynamic gust of wind [2] or they are caused by the loss of stability on following or quartering seas when the wave crest is amidships. Furthermore, broaching and surfriding may be classified as non-resonant phenomena which may lead to capsizing [6]. The resonant situations may be divided into parametric resonance and synchronous rolling.

All the mentioned above dangerous situation may take place when sailing in adverse weather condition. Nevertheless, there are many causes for stability problems occurring not only in sea conditions but also during ship's stay in a port. Such a possibility is not obvious at the first sight, however, stability problems are noticed in ports as well. Generally the causes for potential stability related incidents can be divided into several typical groups, as shown in figure 1.

According to the diagram (fig. 1) cargo shifting incidents and some accidents related to cargo and ballast operations are mentioned as the possible hazard to ship's stability. On the other hand, such events are strictly related to cargo operations taking place in ports, which are crucial component of carriage of goods by sea. In case of dry cargo transportation an essential part of the cargo handling is its loading and discharging operation by means of cranes and gantries. Since the global containerization trend has reached a significant share of the market and it is still in progress, there is a point to focus especially on gantry operations. The increasing importance of the subject may justify the long term growing trend in container operations which is noticed in many sea ports, for instance in Poland which is depicted in figure 2.

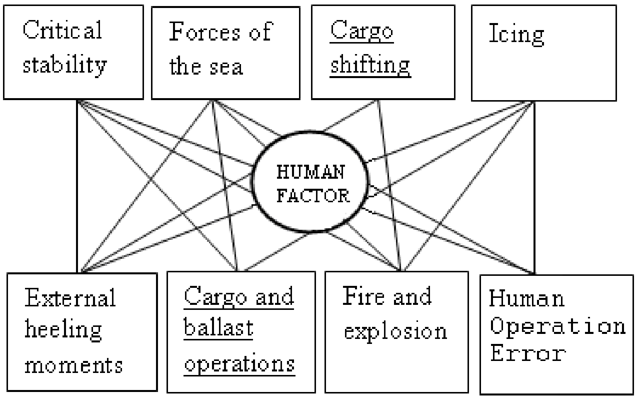

Figure 1. Hazards to stability [4]

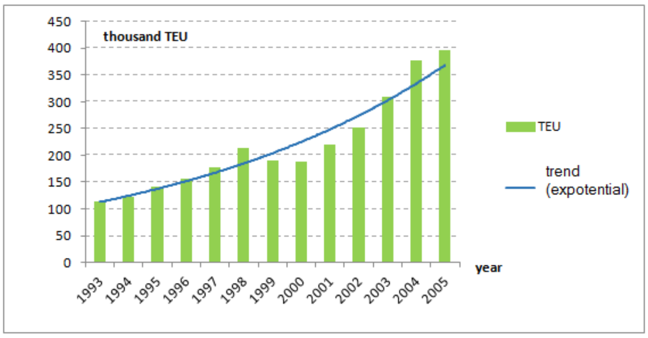

Figure 2. Increase in container operations in the Baltic Container Terminal Ltd. in Gdynia, Poland (source of data: [10])

The gradual evolution of sea transportation market and steady grow in container sector operations results in the modernization of cargo handling equipment. Especially fast moving container gantries are in common use in sea port worldwide.

As a gantry is firmly established on the ground, usually on a dedicated rail system, it seems to allow a smooth cargo shipment down to ship's holds and tweendecks. However, the surface of decks and tank tops persists in permanent movement with the whole body of ship's hull, creating control challenges resulting from this relative motion of the gantry and the cargo destination position. This motion is an integral part of sea vessels cargo operations and thus has to be dealt with as precisely as it is reasonably possible. Any increase in the accuracy of gantry control in terms of relative motion compensation, improves the overall performance of the cargo handling process. The essential problem of gantry control is considered by many authors, nevertheless they omit the problem of a moving base of cargo destination. Even when the dynamic modeling and adaptive control of a gantry is researched and applied the efforts are aimed at the tracking errors reduction with no consideration dealing with unstable position of ship's deck or cargo hold [8].

The contemporary gantry control systems found in sea ports might be relatively advanced and sophisticated but they do not capture any external data describing ship rolling, heaving and pitching. Even is such extreme conditions like cargo transfer carried out on gas and oil offshore fields the moving ships transmit no information enabling her motion estimation. The lack of ship motion estimation during cargo operations in ports is evident too. Both remarks result from authors' sea service experience onboard ships and series of reviews with ship masters and chief mates responsible for cargo loading and stowage.

One of the aspect of interactions taking place between loaded or discharged cargo and a vessel reflects possible hazards to ship and cargo resulting from too impetuous placement of a piece of cargo, for instance a container, on deck or tank top [5]. This may cause some damages to ship construction or loaded cargo and always generates an economical loss. The explanation of such a phenomenon is based on a simple remark, that cargo is smoothly lowered by a gantry to be released when in contact with deck, while the vessel rolls and pitches due to some external excitation or other cargo influence. However, the problem of moving base which impedes and slows down cargo operations in sea port, can be solved by means of gantry control improvement and an application of proper compensation [5].

The main purpose of the paper is to consider how the deck elevation can change due to container loading. The cargo operation is found as a stochastic process with two independent gantries working simultaneously. The feasibility of effective modeling of this elevation is an important step towards elaboration of a gantry control and optimization system.

2 3 DOF MODELING OF SHIP MOTION DUE TO CARGO LOADING IN PORT

The contemporary approach towards modeling of ship behavior under external excitation due to cargo loading in a port is focused on the transverse stability performance. It is an vital issue because the significant rise in a vertical center of gravity is inherently related to cargo loading on-board. The negligence of operators occurring at any stage of the process may lead to very dangerous incidents like for instance capsizing of M/V Stella Mare [9] or M/V Deneb [3]. Both of them suffered an improper operation and rolled over in ports. However, the standard approach based on ship's metacentric height of a righting arm curve does not provide any information in time domain, thus, it cannot be effectively used for the purpose of container gantry control.

Ship motion under excitation forces due to cargo loading in a port needs to be modeled to provide the time-dependent information about momentary ship's deck elevation at any spot. Once a container is loaded on-board its weight acting at a specified location arouses rolling, pitching and heaving of the ship. As a result of these motions any spot of subsequently loaded container alters its elevation in the course of natural oscillation damped by water friction. However in case of relatively high rate of cargo loading and especially with two or more gantry crane working at the same time, it is likely to transfer a container from a quayside to the ship hold in pretty short time one by one. If so, the formerly loaded box excites variations of ship's deck and the successive box needs to be put in its destination elevated higher or lower then it would be found with no motion of the ship. Moreover, the elevation depends not only on the location of previous container but also on time delay between these two gantry operations. The described idea is shown in figure 3.

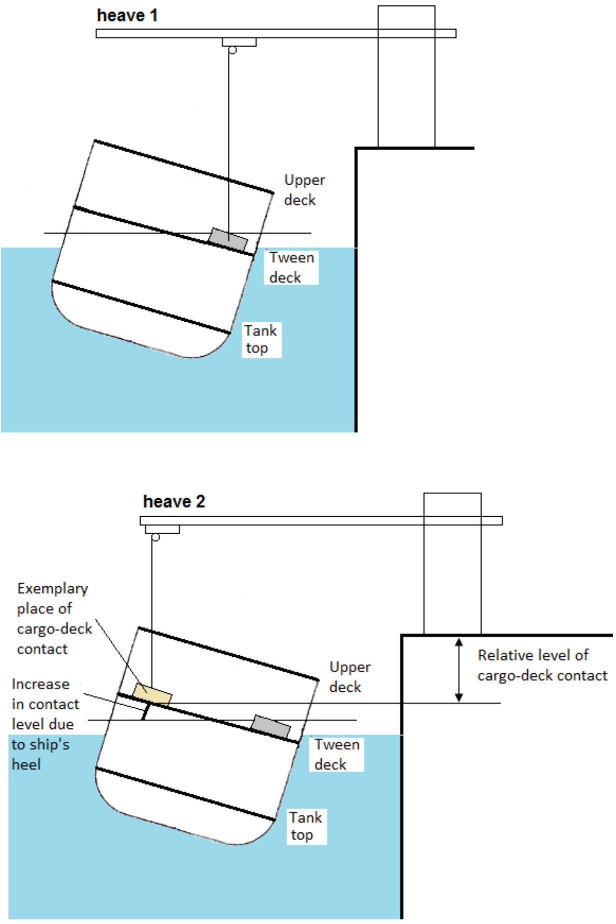

Figure 3. The idea of time dependent variations of ship's deck elevation due to contained loading

The dynamic motion of a free floating vessel in a port or at the sea is affected by a set of forces and moments, both external and internal ones. Generally, the analysis of ship motion is governed by the system of six differential equations. However, the solution of such generally formulated problem is too complex for practical applications, so further simplifications and assumptions are required [7]. By neglected coupling, for the sake of simplicity, the ship's rolling is usually analyzed by the single degree-of-freedom system or three degree-of-freedom system [7]. In this paper three uncoupled equations of ship motion are implemented, e.g. roll, pitch and heave motion is taken into account. According to the theory such an linear theory based approach is valid for the relatively small amplitudes of expected motions. In addition in case of ship rolling, being the most significant motion in the analyzed matter, the strongest coupling could occur with yaw and sway motions which may be neglected due to ship mooring forces so any effects of such coupling are practically next to zero. The remaining motions, e.g. pitching and heaving are expected to be one order of magnitude smaller so the potential effect of coupling between them may be omitted as well.

The governing differential equation of rolling, as the result of equilibrium of moments in direction usually signed "4" (about ship x axis) is following:

$$I_4\ddot{\varphi} + D_4(\dot{\varphi}) + R_4(\varphi) = M_4(t) \tag{1}$$

where:
I_4 – transverse moment of inertia of a ship and added masses;
D_4 – roll damping moment;
R_4 – restoring moment;
M_4 – heeling moment;
φ - angle of heel;
$\dot{\varphi}$ - angular velocity of rolling;
$\ddot{\varphi}$ - angular acceleration of rolling;
t – time.

The equation of ship pitching (motion in direction "5") e.g. about y axis is described by the formula:

$$I_5\ddot{\psi} + D_5(\dot{\psi}) + C_5 \cdot g \cdot M_j \cdot L \cdot \Delta\psi = M_5(t) \tag{2}$$

where:
I_5 – longitudinal moment of inertia of a ship and added masses;
D_5 – pitch damping moment;
C_5 – unit calculation factor;
g – gravity acceleration;
M_j – moment to change trim;
L – ship's length between perpendiculars;
M_5 – trimming moment;
$\Delta\psi$ – change of an angle of trim;
$\dot{\psi}$ – angular velocity of pitching;
$\ddot{\psi}$ – angular acceleration of pitching.

Consequently, ship heaving (linear motion taking place in direction "3") is governed by the formula:

$$m \cdot g = D \cdot \ddot{T} - D_3(\dot{T}) - C_3 \cdot TPC \cdot g \cdot \Delta T \tag{3}$$

where:
m – weight of loaded cargo exciting heave motion;
D – displacement of a ship;
D_3 – heave damping coefficient;
C_3 – unit calculation factor;
TPC – weight to change draft by 1 centimeter;
ΔT – increase in draft (a difference between momentary dynamic draft and a static one resulting from ship displacement);
$\dot{T}$ – linear velocity of heave motion;
$\ddot{T}$ – linear acceleration of heave motion.

It is assumed for the purpose of the research that ship motion excited by a loaded container can be described fair enough by the formulas (1) to (3). Surge, sway and yaw motions are neglected due to the fixed position of a moored ship. The resultant motion of a ship may be obtained by superposing of roll, pitch and heave motions governed by the given formulas (1) to (3). Such mathematical model is the basis for further calculation carried out in this research.

3 SHIP PARTICULARS AND CARGO WEIGHT AND LOCATION ASSUMPTIONS

The calculations of ship motion and then her deck elevation were carried out for a specified vessel and realistic cargo weight. The weight of a typical container ranges from a few tons up to about thirty five tons regardless the size of a vessel carrying the containers. Therefore the influence of one loaded box on container carrier motions has to be significantly different for huge Malacca-max ship and small coastal feeder. For the sake of estimation extreme ship motions due to container loading one rather small size ship is taken into consideration. The ship chosen as an example is Polish semi-container vessel project B-354. One typical case of loading condition is considered (cond. No 11 according to the B-354 stability booklet). It reflects distinctive arrangement of containers on board. The particulars of the vessel are following:

- length between perpendiculars L=140 m;
- breadth B=22 m;
- hulls' height H=12 m;
- displacement D=14124 t;
- mean draft d=6,55 m;
- longitudinal center of floatation LCF=-0,67 m;
- moment to change trim Mj=18044 [tm/m];
- weight to immerse by 1 cm TPC=24,15 [t/cm];
- longitudinal center of gravity LCG=-0,42 m;
- vertical centre of gravity VCG=8,88 m;
- free surface moment Δmh=2439 tm.

The general view of the B-354 ship is shown in is shown in figure 4.

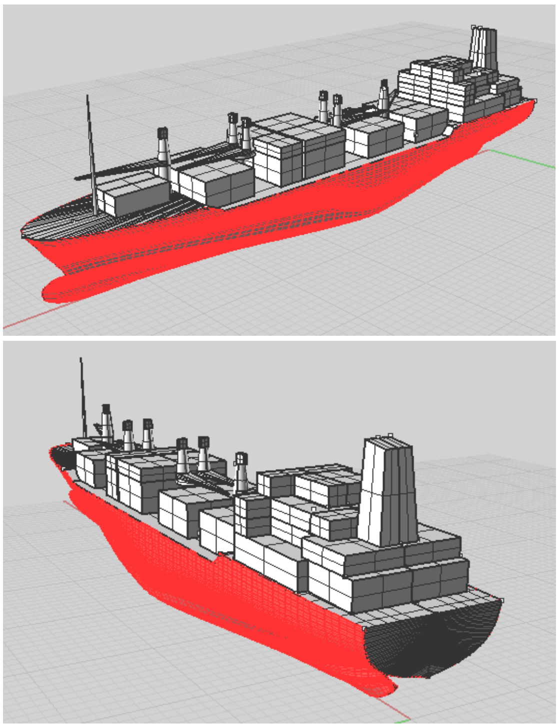

Figure 4. 3D numerical model of the considered vessel (project B-354)

The formulas (1) to (3) were implemented in Matlab script and a set of calculations was carried out. According to the initial assumptions two independent gantries are in use during hypothetical cargo operations. Each of them is about to load one 40-feet container and stow it on ship deck at a random location available on-board within a specified range of co-ordinates. The assumed location and weight of a container to be loaded are following:

- container weight mk=35 [t] each;
- longitudinal co-ordinate of firstly loaded container location xk1=0,4L (40% of ship's length from a midship towards bow);
- transverse co-ordinate of firstly loaded container location yk1=<-0,4B, 0,4B> (yk1 ranging ±40% of ship's breadth to a starboard side);
- longitudinal co-ordinate of firstly loaded container location xk2=-0,2L (20% of ship's length from a midship towards stern);
- transverse co-ordinate of cargo location yk2=<-0,4B, 0,4B> (±40% of ship's breadth to a starboard side).

The longitudinal co-ordinate reflects the relative position of the gantry therefore it is fixed for the purpose of the simulation. This location would shift only when the loaded bay is changed. At the same time the transverse co-ordinate may be different for each gantry move. Thus, this variable is simulated in a random way.

Besides the random location of loaded containers also the time of a second heave is very important. The modeled ship motion consists of three oscillations therefore the exact moment of container touch to deck plays crucial role in terms of the phase of rolling, pitching and heaving. The gain of oscillation or reversely the decrease in their amplitude can be noticed depending on such phase. The random nature of this process is modeled by switching on the second load due to cargo operation in a randomly selected time step of the conducted ship motion simulation. The uniform probability distribution of all the random variables were assumed.

4 RESULTS OF SIMULATIONS

The result of a computation is a history of ship motion in each considered degree-of-freedom. As the formulas (1), (2) and (3) describe three uncoupled motions, the solution is also given in the form of three time-domain curves tracings. The random character of loaded cargo location and the time of the operation results in appearance of two typical patterns of ship motion. One is the increase in the amplitude of considered oscillations and the second one is the decrease. Both possible cases are shown in figures 5 for ship rolling and in figure 6 for her pitching.

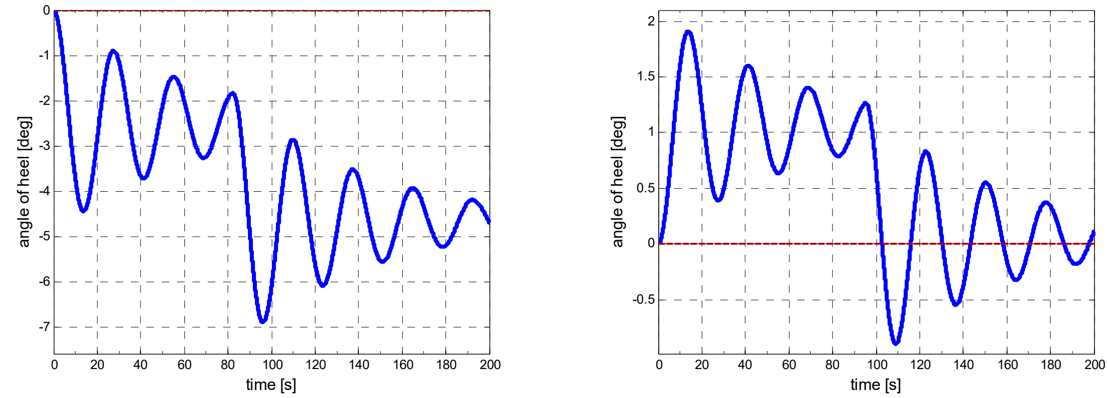

Figure 5. History of roll motion due to cargo loading – two typical cases e.g. increase (left) and decrease in motion amplitude (right)

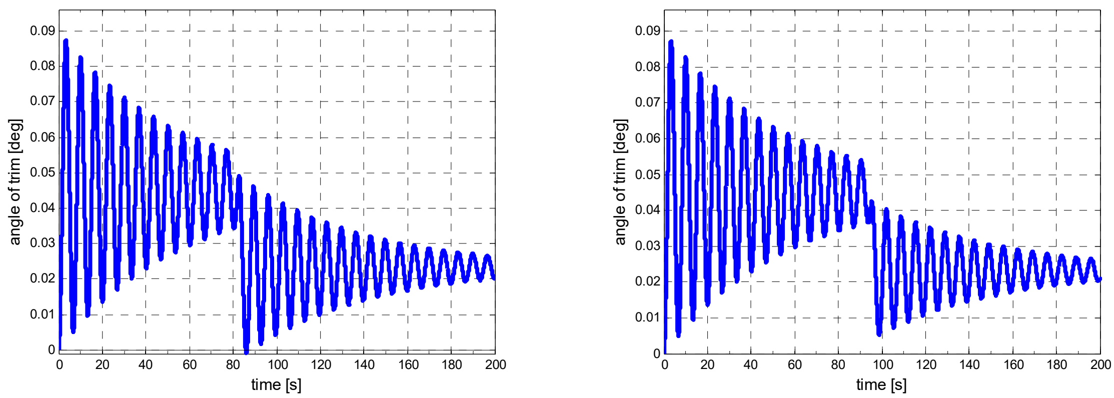

Figure 6. History of pitch motion due to cargo loading – two typical cases e.g. increase (left) and decrease in motion amplitude (right)

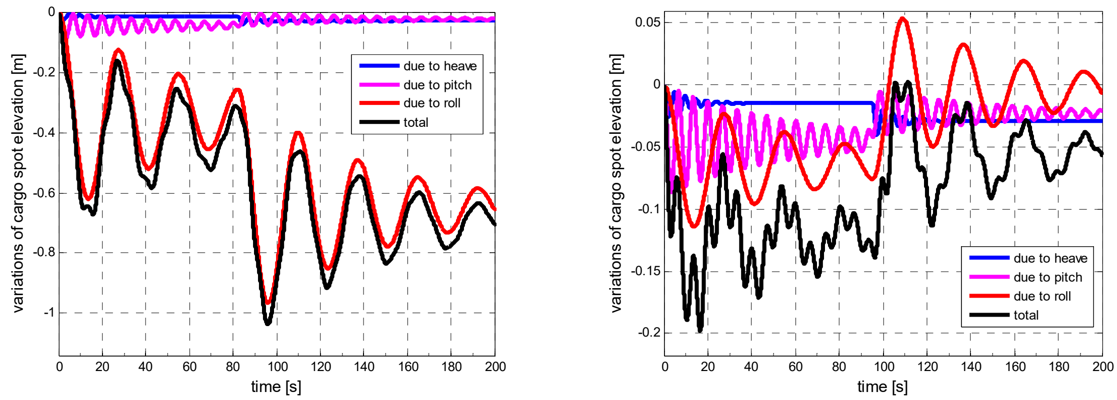

Figure 7. History of variations of ship's deck elevation at a cargo spot – two typical cases e.g. increase (left) and decrease in motion amplitude (right)

An analysis of variations of deck elevations requires some further processing of the motion histories. The elevation of any specified cargo location on ship's deck can be derived on the basis of basic trigonometric functions. The final change of the elevation may be found by superposing of elementary components due to rolling, pitching and heaving. The results of sample calculations carried out for two different cargo loading spots are shown in figure 7.

The sample graphs presented in figure 7 reveals a strong dependence of the deck elevation on location of two loaded containers and the time interval between them. An important characteristic of the process is an extreme value of alteration of deck elevation. I a case of loading of one container the maximum value of variation occurs during the first cycle of motion and it is distinctive for the location of loaded container. Therefore further calculations were carried out for the location of the container covering the whole available area of ship's deck. This area extend reflects the range of container coordinates x_k from -0,4L to 0,5L and y_k from -0,4B to 0,4B. In every single case of computation the extreme value of deck elevation alternation was recorded. The distribution of such extreme values is shown in figure 8.

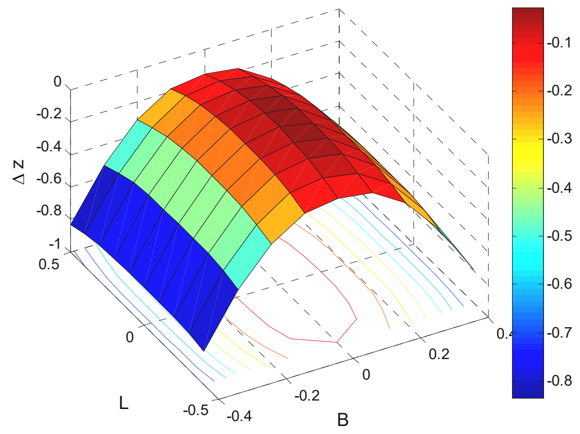

Figure 8. Extreme values of ship's deck elevation variations (Δz at vertical axis) at a cargo loading spot covering whole available space of the deck and one container only – transverse coordinate of container's location yk ranging from -0,4B to 0,4B and longitudinal coordinate xk ranging from -0,4L to 0,5L

Since the maximum value of variation of deck elevation is a deterministic characteristic in case of one container loading it could be shown in figure 8 as a steady graph. However, in case of stochastic process of loading of two containers with the use of two independent gantries the distribution of the maximum variations has a statistical nature. Thus, to obtain the set of results 200 runs of simulations were carried out. Every single case depends on the random location of first container, random location of the second one and random time delay between both gantry moves. The uniform probability distribution was applied for each random variable. Actually the simulation is similar to the Monte Carlo approach.

Every run of the performed simulation produces the full history of rolling, pitching and heaving of the ship and then the history of deck elevation. For the purpose of the research only the maximum value of deck rise was recorded to obtain the distribution of this resultant characteristic for a number of simulations. The histogram of variations of ship's deck elevation and the density of obtained data with the distribution fitting for 200 runs of simulations is presented in figure 9.

The graph in figure 9 shows that the considered variation of deck elevation due to two container loading is significant and reaches more than one meter which should not be neglected in terms of gantry crane control. From the deterministic point of view the maximum value of the variation can exceed even value 1,5 m although it requires a coincidence of extreme locations of both loaded containers in terms of their transverse co-ordinate and moreover the precisely tuned time delay of the second gantry. Such a situation never occurred in the course of the research so the bigger number of simulations is required to reveal such effect.

5 CONCLUSION

The research presented in the paper is focused on the estimation of ship's deck elevation variation due to containers loading. The work of two independent gantries was assumed and numerous variables were random which enables to model the process in a way similar to Monte Carlo approach.

The presented results of computations were obtained with the use of prepared Matlab script running on a standard PC-class desktop. The time of computation of every single case was acceptably short which is an important remark in terms of potentials to commercial realization. The real-time calculations carried out by the gantry control computer are feasible which may be decisive in terms of any potential practical application. Such an application leading to an increase in gantry control accuracy could help to search for a sort of trade-off between safety of operation and effectiveness of cargo handling, especially from the economical point of view. The faster movement of a gantry crane the higher loading rate can be achieved and the ship stay in port is shorter and in consequence cheaper. On the other hand the fast gantry operation is more risky in terms of cargo damage due to excessively impetuous contact of the container with ship's deck.

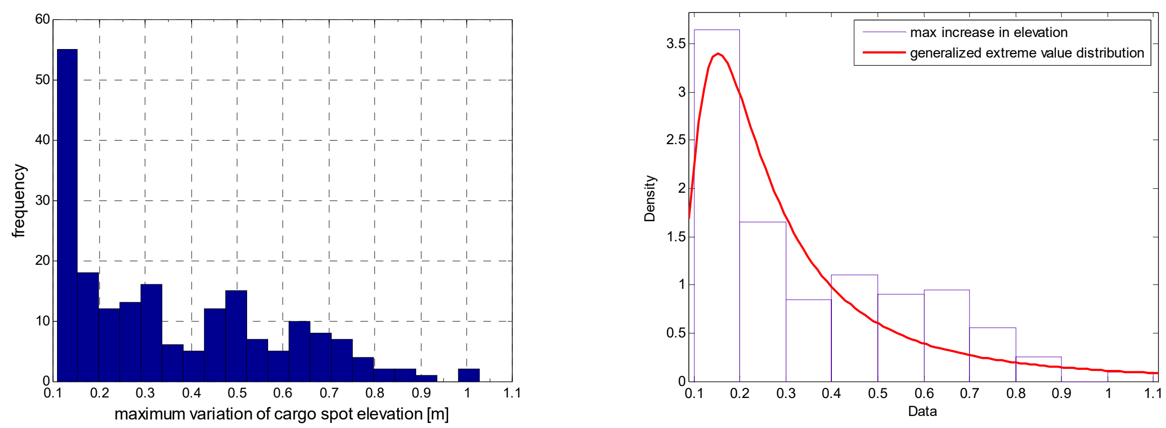

Figure 9. Histogram of variations of variations of ship's deck elevation (left) and the density of obtained data with the distribution fitting for 200 runs of simulations (right)

The presented calculations based on modeling of ship motion in a port reveals that the considered matter may be important during loading of relatively small ship. The extreme values of alternation of deck elevation breaching one meter shall be taken into account by the gantry control system. Otherwise the loaded container would come into contact with ship's deck at quite high velocity causing massive gravity load which can be destructive to the cargo inside the box.

On the other hand any governing-body in a port needs to analyze the cost effectiveness of the potential investment in terms of new gantry control module application. The distribution shown in figure 9 reveals that only about 1% of analyzed random cases leads to rise in deck elevation higher than 1 m and about 18% breaches 0,6m. Thus, the improvement in gantry control system requires further consideration and it is possible that on some cases sole management of time delay between two gantry moves would be sufficient to ensure limited values of variations of ship deck elevations.

ACKNOWLEDGMENT

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