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Computing of momentary ship's deck elevation for the purpose of gantry control during cargo handling operations in sea ports

Określanie chwilowego wzniesienia pokładu statku dla potrzeb sterowania suwnicą podczas operacji ładunkowych w portach morskich

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Key words: ship's loading, stability

Abstract

The paper presents a proposal of a method for the computation of ship's deck elevation at any time and location on-board. The need for such a computation results from an interaction between a ship and cargo being loaded or discharged by a gantry in port, in terms of heeling and rolling of the vessel. The main purpose of such modeling is the need for improvement of gantry control with regard to faster operations thanks to more accurate estimation of level and moment of cargo release from a gantry hook or spreader. The study may be the contribution to the development of gantry control systems in sea ports.

Słowa kluczowe: załadunek statku, stateczność

Abstrakt

W artykule przedstawiono propozycję metody obliczania chwilowego wzniosu pokładu statku podczas operacji ładunkowych w porcie. Potrzeba prowadzenia takich obliczeń wynika ze wzajemnego oddziaływania ładowanego ładunku na statek i odpowiednio – statku na proces załadunku. Statek doznaje bowiem zmiennego w czasie przechyłu wskutek umieszczenia na pokładzie bądź w ładowni dowolnej masy, np. kontenera. Zasadniczym celem opisywanych obliczeń jest poprawa dokładności sterowania suwnicą kontenerową poprzez wyznaczenie chwilowego poziomu pokładu w miejscu przeznaczenia każdego ładowanego kontenera i dalej – precyzyjne określenie wysokości i momentu ustawienia kontenera. Przeprowadzone badania mogą się przyczynić do rozwoju systemu sterowania suwnicami w portach morskich.

Introduction

Maritime transport, especially referred to commercial goods, remains still developing sector of overall worldwide transport. Thus, it plays an important role in economical systems for last centuries. The main discussed characteristics of maritime transport are usually its safety and effectiveness. Nevertheless, the effectiveness of a transportation process can be considered in both an economical and a technical aspect.

Ship's safety and its overall performance influencing widely comprehended safety and effectiveness of a marine transportation process are strictly connected to ships stability characteristics.

Ship's stability is a component of many researches leading to the increase in understanding of the safety qualifying factors. Stability against capsizing and excessive heeling is one of the most fundamental requirements considered by naval architects when designing a ship and operators in the course of sailing and cargo handling [1]. The stability of a vessel belongs to operational characteristics enabling cost effective and safe operation [1]. Moreover, stability as an ability of ship's hull to withstand and counteract external and internal heeling moments shall be considered in terms of sailing and cargo operations undertaken in ports too.

There are many causes for stability problems on board and they can be divided into several typical groups, as shown in figure 1.

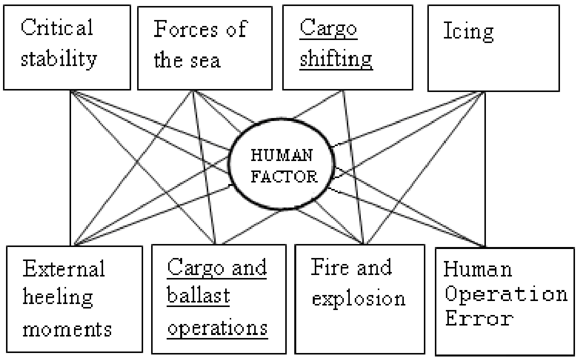

Fig. 1. Hazards to stability [2]
Rys. 1. Zagrożenia dla stateczności statku [2]

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. Such kind of equipment is in common use in sea ports worldwide due to its high loading and discharging rate and a precise cargo handling.

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 tween decks. 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 accurately 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.

Ship's stability – related problems during cargo operations in ports

Since the very beginning of navigation some stability problems occurred and they take place nowadays as well. Taking into account cargo operations in ports, one could mention a couple of typical scenarios leading to the stability accident. One of the most important and dangerous reason for stability accidents in ports is a stability loss due to cargo operation carried out by own cranes. The vertical center of gravity of a vessel may rise so excessively that the righting arm curve is reduced causing ship's capsizing.

The example of such an accident is presented in figure 2. The Dutch heavy lift M/V "Stellamare" was equipped with 2 x 180 tons deck cranes, so the total lifting capacity was relatively high as per such ship being 88.20 meters long overall and 15.50 meters wide overall [3]. The heavy heave – causing vessel to capsize – was the reason for major injury to some crew members and massive financial loss.

Fig. 2. Capsizing of M/V "Stellamare" [3]
Rys. 2. Przewrócenie się statku M/V „Stellamare" [3]

However, the stability loss accident can be easy explained in the case of heavy lift operations, a similar scenario was noticed during container loading too. One of the example can be capsizing of 101 meters long Germany based company owned container ship M/V "Deneb" [4] shown in figure 3.

Fig. 3. Capsizing of M/V "Deneb" [4, 5]
Rys. 3. Przewrócenie się statku M/V „Deneb" [4, 5]

Generally, the interaction between a ship and cargo being loaded on-board can be consider from one of two essential points of view. The first one is an influence of cargo's weight on the transverse and longitudinal ship's stability. Any extra weight discharged or loaded on-board changes vessel's weight distribution and as its result, it modifies her stability performance. Moreover, cargo being stored within the whole space of a hold or a tween deck has to be loaded in all available room in a cargo space. Therefore, it generates transitory extra moments heeling and trimming the ship. The angle of transverse heel is significantly more important due to much lower ship resistance against transverse heeling than longitudinal trimming and for that reason the vessel's transverse stability assessment has to be carried out prior cargo operations in ports, principally in case of heavy lift operations.

The second important 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. 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 could be solved by means of gantry control improvement and an application of proper compensation.

The GZ – based method for cargo and ship's deck elevation computation

The ship's stability assessment is a routine part of chief mate's duties. Nowadays, the transverse stability assessment during cargo operations takes into account the GZ curve (righting arm curve) being a graph presenting the lever of moment restoring the ship to her initial upright position. Subsequently, having obtained values of righting arm (GZ curve) in the full range of ship's angles of heel, the heeling moment and the heeling arm need to be computed. As the GZ curve and the value of heeling arm is calculated, they can be plotted on a common graph to obtain the expected angle of heel to due cargo operation.

As the elevation of all ships decks and tank top above the base line is known, it is enough to take into account a contemporary draft of a vessel and water surface level beneath a gantry basement to obtain the levels of decks related to the construction of the gantry. The only unknown value remains in such a case only the effect of ships heel due to cargo operation. The idea is shown in figure 4.

The increase in level of the cargo – deck contact point can be easy computed on the basis of trigonometry, so the resultant relative level is obtainable. The main problem related to this approach is static character of such computation. Even in a case of very exact estimation of ship's deck elevation, it is reliable after a time sufficient to damp ship's rolling due to cargo operations. Such approach is not very practicable, because it could be applied for slow operation, or when the cargo operation is carried out by means of one gantry only which is not likely in most container terminals worldwide.

The presented way of ship's transverse stability calculation and evaluation is an important part of ship's safety estimation, but it provides no input data to a gantry control system and it is not helpful in terms of cargo operation improvement. The resultant static angle of ship's heel due to loading of cargo is not sufficient to control time-dependent phenomena, like heaving or lowering cargo by a gantry.

The further modification of the approach based on the righting arm curve is an utilization of a dynamical stability curve being just an integral of GZ curve, according to the formula:

$$l_{d(\varphi 0)} = \int_{0}^{\varphi_0} GZ \, \mathrm{d}\varphi \qquad (1)$$

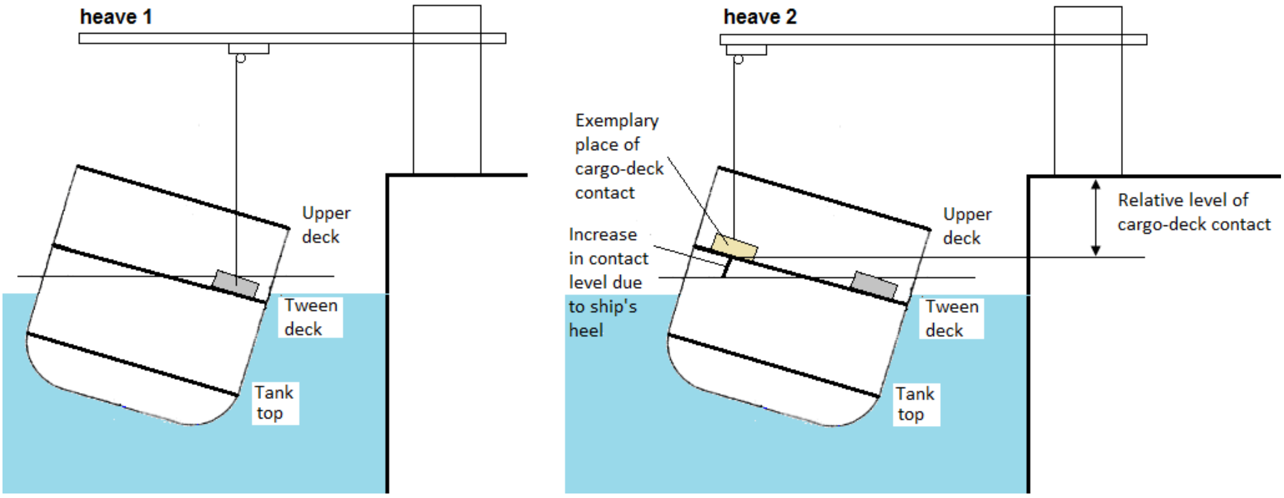

Fig. 4. Estimation of ship's decks levels referred to the gantry-base level
Rys. 4. Wyznaczanie wzniosu pokładu statku względem poziomu posadowienia suwnicy

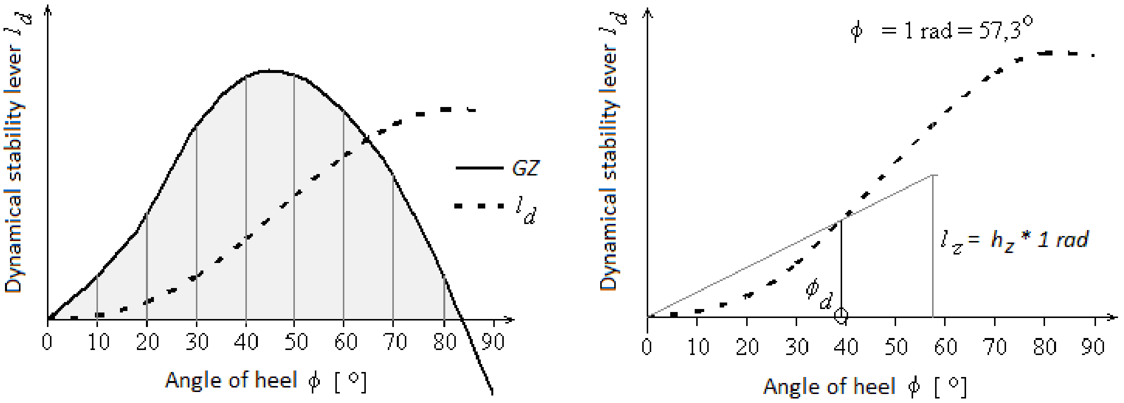

Fig. 5. Dynamical stability curve and dynamical angle of ship's heel
Rys. 5. Krzywa stateczności dynamicznej i dynamiczny kąt przechyłu statku

where:
l_d – dynamical stability lever;
GZ – righting arm;
φ – angle of heel.

The dynamical stability curve allows the estimation of dynamical angle (marked φ_d in the Fig. 5) of ship's heel which is presented in figure 5.

The dynamical angle of heel is interpreted as a maximum value of the angle of heel when certain heeling moment is applied. The dynamical stability curve is plotted versus an angle of heel not time, so it is impossible to find out what a value of heel angle the vessel can achieve just in specified moment, for instance in the moment of cargo lowering and releasing from a gantry. Since the dynamical angle of ship's heel can be obtained, there is only one more element needed to be assessed. This is the momentary value of the angle of ship's heel.

The ship motion theory suggests one of the simplest solution to the momentary angle of heel estimation. One may assume that a ship rolls with her natural period of roll after an application of a force due to contact of any cargo with deck. The natural period of roll may be obtained according to the formula:

$$T_\varphi = \frac{2 \cdot \pi \cdot f}{\sqrt{g \cdot GM}} \approx \frac{2 \cdot f}{\sqrt{GM}} \tag{2}$$

where:
T_φ – natural period of ship's roll;
f – transverse gyration radius of a ship;
g – gravity acceleration;
GM – ship's transverse metacentric height.

As the value of transverse gyration radius of a ship is usually not available on board, the simplified empirical formula recommended by IMO (International Maritime Organization) is in common use [6]:

$$T_\varphi = \frac{2 \cdot c \cdot B}{\sqrt{GM}} \tag{3}$$

with the value of c coefficient:

$$c = 0{,}373 + 0{,}023 \cdot \frac{B}{d} - 0{,}043 \cdot \frac{L}{100} \tag{4}$$

where:

c – coefficient describing ships transverse gyration radius;
B – ship's breadth;
d – mean ship's draft;
L – length between perpendiculars.

Taking into account the natural ship's rolling period and a maximum value of the dynamical angle of heel due to cargo operations, one can estimate the momentary angle of ship's heel and consecutively the relative level of cargo – deck contact point. The location of this point is essential in terms of gantry control improvement enabling more accurate cargo operation and precise releasing of load when just on deck. However, to solve the problem of momentary angle of heel estimation, another assumption has to be done regarding the rate of roll (angular velocity of rolling motion). Generally, the realistic approximation of the rolling rate is possible on the basis of model or full scale tests and also by the use of more sophisticated methods based on ship motion equations. Both approaches are practically feasible. Especially full scale tests can be performed in the course of cargo loading and discharging operation. The suitable measuring equipment is well known and available at reasonable costs.

Equations of ship motion

The dynamic behavior 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. The most accurate analysis of ship's motion should be based on the differential equations of motion which are given by the complex in the form of six differential equations [7]:

$$\begin{aligned}
& m\frac{\mathrm{d}V_x}{\mathrm{d}t} + m\,(\omega_y V_z - \omega_z V_y) = F_x \\
& m\frac{\mathrm{d}V_y}{\mathrm{d}t} + m\,(\omega_z V_x - \omega_x V_z) = F_y \\
& m\frac{\mathrm{d}V_z}{\mathrm{d}t} + m\,(\omega_x V_y - \omega_y V_x) = F_z \\
& I_{xx}\frac{\mathrm{d}\omega_x}{\mathrm{d}t} - I_{zx}\frac{\mathrm{d}\omega_z}{\mathrm{d}t} + \omega_y\omega_z(I_{zz} - I_{yy}) - \omega_x\omega_y I_{zx} = M_x \\
& I_{yy}\frac{\mathrm{d}\omega_y}{\mathrm{d}t} + \omega_z\omega_x(I_{zz} - I_{xx}) - (\omega_z^2 - \omega_x^2)I_{zx} = M_y \\
& I_{zz}\frac{\mathrm{d}\omega_z}{\mathrm{d}t} - I_{zx}\frac{\mathrm{d}\omega_x}{\mathrm{d}t} + \omega_x\omega_y(I_{yy} - I_{xx}) + \omega_y\omega_z I_{zx} = M_z
\end{aligned} \tag{5}$$

where:

F_i – resultant external force along appropriate axes ($i = x, y, z$);
M_i – resultant moment about appropriate axes referred to the center of gravity G;
I_{ii} – moment of mass inertia about appropriate axes ($i = x, y, z$);
I_{ij} – moment of mass deviation about appropriate axes ($i \neq j$);
m – mass of the ship and added masses;
V_i – velocity of point G about appropriate axes ($i = x, y, z$);
ω_i – ship's angular velocity about appropriate axes ($i = x, y, z$);
t – time.

The solution of such general formulated ship motion equations is impossible at the contemporary state of the art. By neglected coupling, for the sake of simplicity, the ship's rolling is usually analyzed by the single degree-of-freedom system. The governing differential equation of motion, as the result of equilibrium of moments, is [8]:

$$I_4\ddot{\varphi} + D_4(\dot{\varphi}) + R_4(\varphi) = M_4(t) \tag{6}$$

where:

I_4 – transverse moment of inertia of ship and added masses;
D_4 – transverse damping moment;
R_4 – transverse restoring moment;
M_4 – rolling excitation moment;
t – time;
φ – angle of heel;
$\dot{\varphi}$ – angular velocity of heel (the first time derivative of and angle of ship's heel);
$\ddot{\varphi}$ – angular acceleration (the second time derivative of an angle of heel).

The resultant excitation moment $M_4(t)$ consists of as many components, as many influences rock the ship. In the considered case of cargo being loaded or discharged causing ship's rolling, the moment due to cargo operation needs to be taken into account.

For the purpose of researching the potential of the rolling equation in the formulation (6) the Matlab script was prepared. The ship taken as an example was Polish semi-container vessel project B-354. One typical case of loading condition is taken into consideration (cond. No. 11 from the B-354 stability booklet). It reflects distinctive arrangement of containers on board. The particulars of the vessel are following:

- length $L = 140$ m;
- breadth $B = 22$ m;
- displacement $D = 14124$ t;

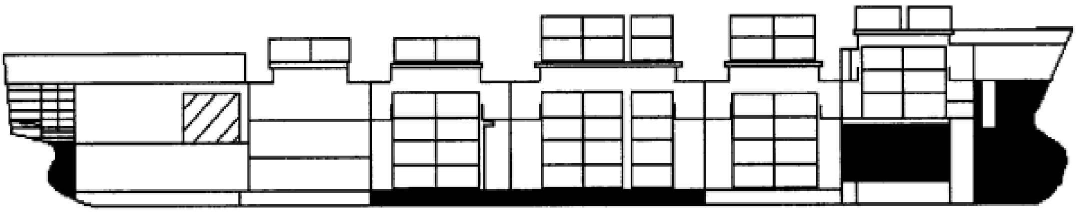

Fig. 6. Ship project B-354 in loading conditions No 11 (according to the stability booklet)
Rys. 6. Statek projektu B-354 w stanie załadowania nr 11 (na podstawie informacji o stateczności dla kapitana)

- draft $d = 6,55$ m;
- vertical centre of gravity $VCG = 8,88$ m;
- free surface moment $\Delta mh = 2439$ tm.

The general view of the B-354 ship is shown in the figure 6.

First of all, a short estimation of possible rise or drop in deck elevation due to reasonable values of angels of ships' heel was carried out. The computation are based on simple trigonometric formulas and their results are presented in the figure 7.

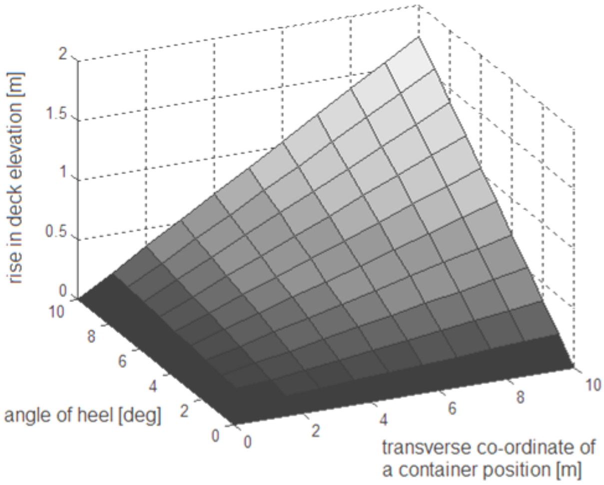

Fig. 7. Possible rise in deck elevation due to ship's heel versus an angle of heel and a transverse co-ordinate of cargo destination
Rys. 7. Możliwe wzniosy pokładu wskutek przechyłu statku w funkcji kąta przechyłu i poprzecznego umiejscowienia ładunku wywołującego przechył

It can be easy seen that the rise in ship's deck elevation may be significant for cargo stacked quite close to ship's sides even for relatively small angles of heel. For this reason, there is a strict need for realistic estimation of rolling of the considered ship due to cargo operations like for instance loading of one full container.

For the purpose of rolling history computation versus time the dedicated Matlab script implementing rolling equation (6) was run. The assumed weight of a 40-feet container was equal 36 tons which reflects the maximum weight in sea transportation. The lateral position of a container row of destination on deck was 40% of ship's width.

The cross curves of stability were implemented from ship's stability booklet and then GZ curve could be computed. Moreover, some technical assumptions were accepted regarding linear characteristic of damping moment versus angular roll velocity, fixed weight of added water layers. The GZ curve with corresponding metacentric triangle is presented in the figure 7 on the left side and the static angle of heel due to loading of one full container on-board is shown in the figure 8 on the right side.

In spite of rolling history (Fig. 9 – right), the developed Matlab script for rolling computation allows also determination of dynamic and static angel of ship's heel due to any external heeling moment and a spectrum of rolling (Fig. 9 – left). On the basis of this spectrum, the rolling period can be

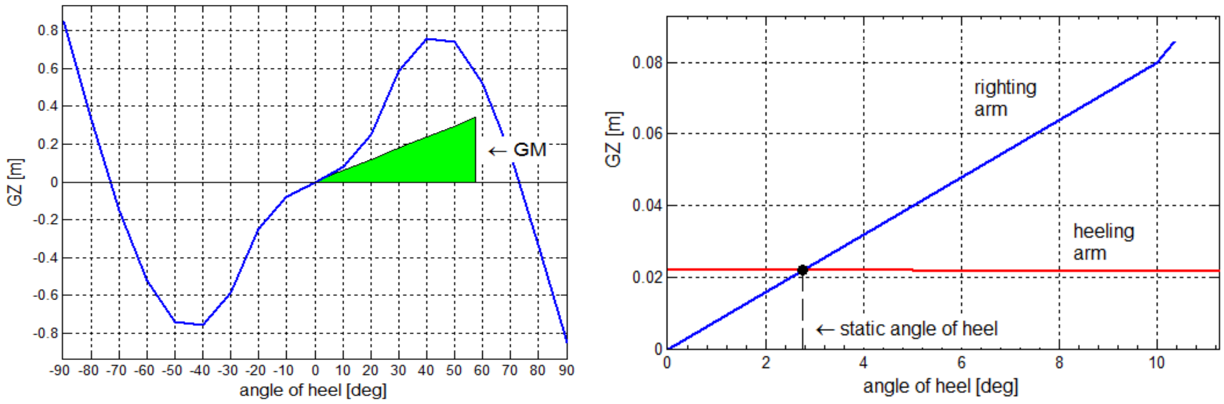

Fig. 8 GZ curve of the ship B-354 in loading condition No 11
Rys. 8. Krzywa ramion prostujacych statku B-354 w stanie załadowania nr 11

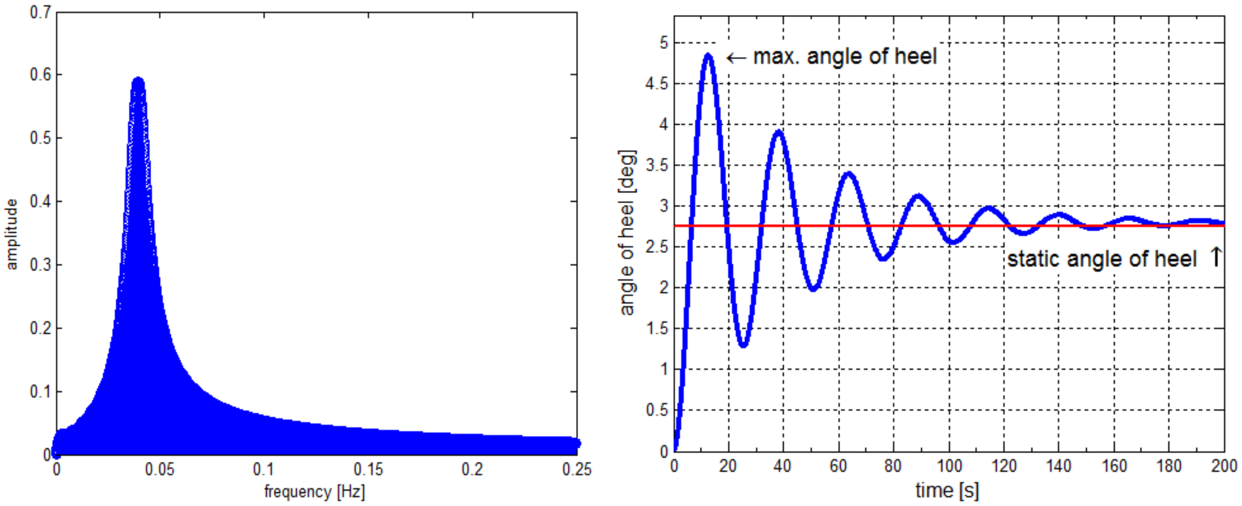

Fig. 9. Rolling spectrum of considered ship (left) and a history of her roll (right)
Rys. 9. Spektrum kołysań bocznych statku (z lewej) i przebieg czasowy kołysań (z prawej)

obtained which is an important characteristic for any tasks carried out in time domain, like gantry control or more precisely cargo movement compensation due to ship's deck level fluctuations.

The evaluation of obtained results could be based on model test or better full scale tests. Such a procedure is feasible in the course of ship exploitation and the proposed approach seems to be practical and not excessively complicated. The real-time calculated correction describing the momentary deck level at any container row can be an input to the gantry control unit to enable proper adjusting speed and range of cargo lowering at any time.

Conclusions

The paper presents the background of the needs for the interest in ship's stability in ports as an important element revealing a potential to improve gantry control during cargo operations, especially loading of containers. Any efforts leading to the more accurate estimation of elevation of the deck are worthy to be undertaken to make the cargo operations safer and faster which benefits in terms of costs of a transportation system.

The proposed approach to the problem solution is based on the numerical computation of ship's rolling with the use of a differential equation of rolling. The method is quite sophisticated and requires some adjustment in the course of its application. The moment of inertia of a vessel should be maintained and constantly updated, as it is an important factor affecting ship's rolling performance. The damping moment coefficient needs to be obtained in the course of full scale tests as well. The measurements are rather simple and the required equipment affordable.

The results of computation can be relatively easy verified on-board which makes this approach reliable. Both, the static angle of heel and the rolling period can be measure independently to the numerical calculations and they might be the critical criteria of the computation correctness. The empirical technique seems to be practical though.

An application of the described method of cargo – ship interaction modeling enables to improve gantry control systems and makes the cargo operations faster and more precise. The need for ship's motion compensation in the course of gantry operation will probably create the demand for such kind of technical solution. The study may be the contribution to the development of gantry control systems in sea ports.

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