Scientific Journals
Maritime University of Szczecin

Zeszyty Naukowe
Akademia Morska w Szczecinie

2012, 29(101) pp. 88–94

2012, 29(101) s. 88–94

Ship's ballast tanks size and dimensions review for the purpose of model research into the liquid sloshing phenomenon

Przegląd kształtów i wymiarów okrętowych zbiorników balastowych dla potrzeb badań modelowych zjawiska sloshingu

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Key words:

Abstract

The paper presents the pending stage of a study into the influence of liquid sloshing phenomenon taking place in ships' tanks on ship transverse stability. The research is carried out at the Gdynia Maritime Academy and it comprises both numerical simulations and experimental test. A number of problems needs to be addressed and one of them is proper planning of geometry of a model tank utilized in the course of experimental tests. It shall refer to the real ships' tanks shapes to model liquid sloshing phenomenon fair enough. The typical groups of ships' tanks are analyzed and presented as well as the free surface correction effecting vessels' transverse stability.

Słowa kluczowe:

Abstrakt

W artykule przedstawiono element prowadzonego projektu badawczego dotyczącego wpływu zjawiska sloshingu zachodzącego w niepełnych zbiornikach okrętowych na stateczność poprzeczną statku morskiego. Badania realizowane w Akademii Morskiej w Gdyni obejmują zarówno symulacje numeryczne, jak i nieodzowne badania eksperymentalne. Jednym z zagadnień jest zaprojektowanie zbiornika modelowego wykorzystywanego w eksperymencie, który winien prawidłowo odzwierciedlać kształty i proporcje zbiorników okrętowych. Poddano zatem analizie populację statków morskich i ich zbiorników balastowych, wyróżniając charakterystyczne cechy tych zbiorników, w tym poprawkę od swobodnych powierzchni cieczy.

Introduction

Maritime transport plays an important role in political and economical systems for last couple of millennia. It is still developing and especially in recent decades is marked by a globalization sign, therefore the importance of overseas transportation of goods is vital. The main commonly discussed features of maritime transport are usually its safety and effectiveness. However, the effectiveness of a transportation process is a complex and important matter, the ships safety issues are crucial from the operational point of view and they can be considered as one of the most prospective technical affairs. One of the most critical features of seagoing ships related to her safety is stability influencing ship's overall seakeeping performance.

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]. The accuracy of ship's transverse stability assessment is an important problem in vessels' operation process. The ship's loading condition of insufficient stability may induce a list, a strong heel and even her capsizing. Contrary to such state, the excessive stability causes high values of mass forces acting on cargoes and machineries due to strong accelerations.

Taking into account the importance of ships stability matters the research project is undertaken in the Department of Ship Operation at the Gdynia Maritime University. It comprises both numerical simulations and experimental tests, thus a number of problems needs to be addressed. One of the problem is proper planning of geometry of a tank utilized in the course of experimental tests. It shall refer to the real ships' tanks shapes to model liquid sloshing phenomenon fair enough.

Liquids free surfce correction – contemporary approach

Vessels' stability calculation and evaluation, made on-board nowadays, is based on the stability criteria published by the ship's classification societies. These criteria are mainly based on the A749(18) Resolution of International Maritime Organization. The resolution and their later amendments – including last edition dated 2009 – are known as the Intact Stability Code [2].

According to the IMO recommendations the righting lever curve should be corrected for the effect of free surfaces of liquids in tanks. The free surface correction needs to be applied in case of partly filling of any tank while a tank is considered as partly filled up to the level equal 98% of its volume. The correction may be done by any of the accepted methods [2]:

- correction based on the actual moment of fluid transfer calculated for each angle of heel;
- correction based on the moment of inertia of tank's horizontal projection.

The last method is very common since the correction is based on the same formula which is applied in the course of initial stability calculation (for a metacentric height correction):

$$\Delta GM = \frac{i_B \cdot \rho}{D} \tag{1}$$

where:

i_B – moment of inertia of tank's horizontal projection at the 0 degrees angle of heel,
ρ – density of a liquid in partly filled tank,
D – displacement of a ship.

Regardless the explicit computational formula for free surface correction, the liquid surface is always assumed flat and depends only on an angle of ship's heel not the time. The idea is presented in the sketch (Fig. 1).

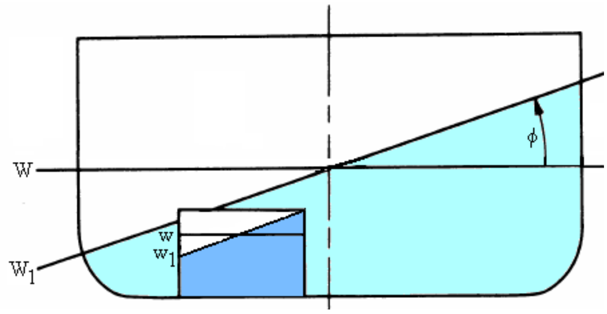

Fig. 1. Flat surface of waterline and liquid's free surface in partly filled tank
Rys. 1. Nieodkształcona powierzchnia cieczy ze swobodną powierzchnią w zbiorniku

Generally the formula (1) based on ΔGM correction ought to be applied only for relatively small angels of ship's heel. Nevertheless, for the sake of simplicity, it is in common use worldwide. The literature review reveals that the correction ΔGM is found as safer then the correction based on the moment of fluid transfer (for each angle of heel) due to some extra stability margin provided. However, both static methods create exactly the same results when a set of conditions is satisfied:

- a tank is wall-sided;
- there is a lack of contact of liquid surface with tank's bottom or roof (see Fig. 2);
- an angle of ship's heel is small enough to accept $\tan\varphi \approx \sin\varphi$.

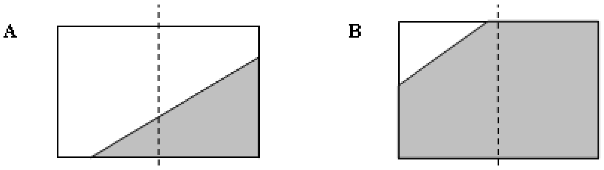

Fig. 2. Possible contact of liquid surface with tank's bottom (A) or its roof (B)
Rys. 2. Warianty kontaktu swobodnej powierzchni cieczy z dnem (A) bądź sufitem (B) zbiornika

The specified conditions ensuring equal value of a free surface correction calculated with the use of any of recommended methods can be satisfied only for limited range of angles of heel. Moreover, the range depends on tanks height to breadth ratio. The following figures 3, 4, 5 present the ranges of equal values of free surface corrections calculated with the use of both IMO-recommended methods for particular tank's geometry. The dashed line presents the limitation of tank's bottom (Fig. 3.A) and the solid line – tank's roof respectively (Fig. 3.B), whereas other symbols mean: *b* – tank's breadth, *h* – tank's height, h_z – liquid depth in a tank, φ – angle of heel.

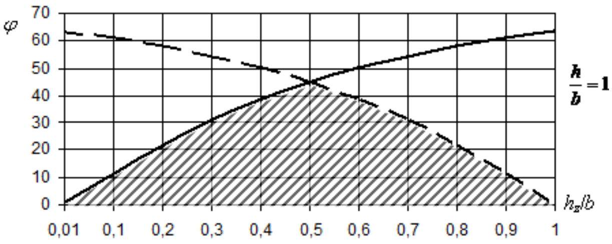

Fig. 3 The range of equal values of static free surface corrections computed according to both IMO-recommended methods for a rectangular tank with the ratio *h/b* = 1 [3]

Rys. 3. Obszar jednakowych wartości statycznych poprawek od swobodnych powierzchni cieczy dla zbiornika prostopadłościennego o proporcjach *h*/*b* = 1, wyznaczonych obydwiema metodami zalecanymi przez IMO [3]

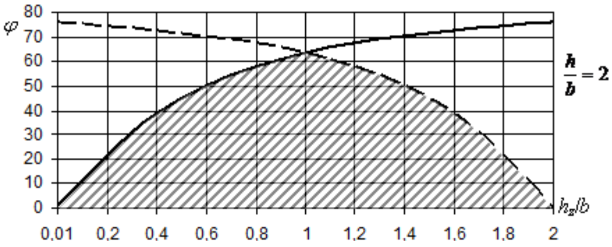

Fig. 4. The range of equal values of static free surface corrections computed according to both IMO-recommended methods for a rectangular tank with the ratio *h/b* = 2 [3]

Rys. 4. Obszar jednakowych wartości statycznych poprawek od swobodnych powierzchni cieczy dla zbiornika prostopadłościennego o proporcjach *h*/*b* = 2, wyznaczonych obydwiema metodami zalecanymi przez IMO [3]

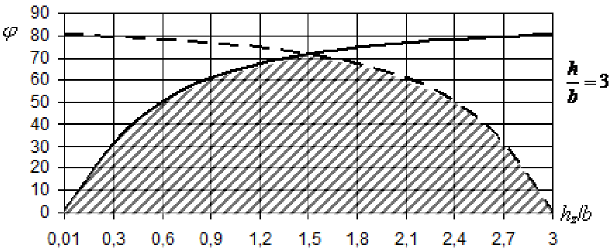

Fig. 5. The range of equal values of static free surface corrections computed according to both IMO-recommended methods for a rectangular tank with the ratio *h/b* = 3 [3]

Rys. 5. Obszar jednakowych wartości statycznych poprawek od swobodnych powierzchni cieczy dla zbiornika prostopadłościennego o proporcjach *h*/*b* = 3, wyznaczonych obydwiema metodami zalecanymi przez IMO [3]

It can be easy seen that the greater value of the *h/b* ratio the wider range of the agreement between free surface corrections computed with the use of both IMO-recommended methods. Thus, the most significant differences are observed for relatively wide and low double bottom tanks and the least ones for high and narrow side deep-tanks.

Both IMO-recommended methods of free surface correction calculation consider the static attitude towards the liquid sloshing phenomenon only. They also do not consider the location of the tank within the hull of the ship and the location of a rolling axis. The only advantage of current compulsory corrections is the simplicity of their calculation. However, even in a case of static free surface correction application the tanks' geometry plays and important role and it needs to be taken into account.

Research into the liquid sloshing phenomenon

The noticeable weaknesses of the static approach towards the free surface correction and its application in the course of ship stability assessment are commonly known, therefore a number of studies is still undertaking worldwide. Generally the main stream of researches comprises two corresponding trends i.e. numerical simulations of liquid sloshing phenomenon and experimental tests. Both approaches are coupled and they support each other.

At the present state-of-the-art numerical simulations require an experimental validation allowing adjusting of a computational mesh, a time step and a set of input parameters. The features being usually validated are dynamic pressure at some selected points and a shape of the free surface of liquid. An example of such study is described by Kim in [4] and by many other authors. Some assorted results of this work are shown in figure 6 [4].

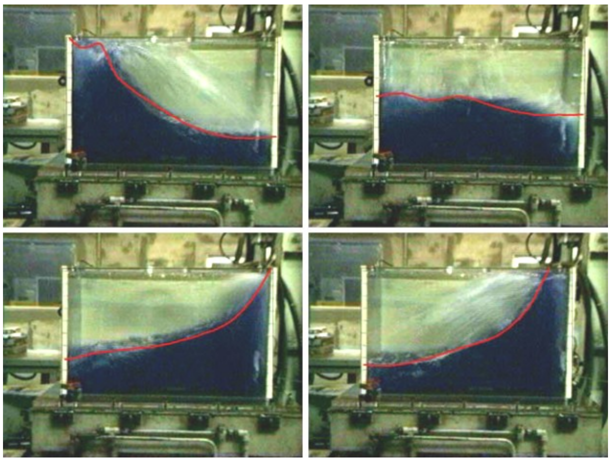

Fig. 6. Comparison of free-surface profiles obtained in the course of numerical simulation of sloshing flow with the experiment [4]

Rys. 6. Porównaie kształtu swobodnej powierzchni cieczy wyznaczonego poprzez symulacje numeryczne z wynikiem eksperymentu [4]

The research project carried out in the Department of Ship Operation at the Gdynia Maritime University is focused on the ship stability issues with regard to liquid sloshing phenomenon in partly filled tanks. The core idea is based on similar approach with numerical simulations providing a wide set of data for analysis and an experimental test utilized for validation and adjustment of simulations. Once purchasing a proper software and a powerful work station, the application of numerical simulations of liquid sloshing flow is relatively cost-effective technique, one may effort many runs of simulations covering the wide scope of conditions. Contrary to this, the experimental tests are extremely costly and time-consuming, therefore every single run of experiment needs to be carefully planned and justified.

One of the essential element of experimental setup preparation is proper classification of a model tank geometry. It has to refer to typical shapes of tanks of prevailing ships, therefore an analysis of existing tanks arrangement was carried out.

Typical ships' tanks geometry

Tanks specification

One of the first stage of an experimental setup design was a review of many existing ships specification. An effort was put on ballast tanks, their shapes and dimensions. The data collected in the course of a study cover following items:

- general specification of a ship;
- total number of ballast tanks;
- number of ballast tanks in every listed group, i.e. double bottom tanks, side deep-tanks, wing tanks, fore and after peaks;
- possibility of ballasting of cargo holds;
- tanks dimensions (breadth, height and length of each tank);
- location of tanks in ship's hull;
- shape of each tank;
- free surface correction values according to ships stability booklet provided on-board;
- recommended algorithms of computation of a free surface effect for partly filled tanks.

Location and function of ships' tanks

On the basis of collected data describing the most significant characteristics of ships' tanks the classification of tanks were prepared. The very first criterion distinguishing groups of tanks is their location and shape which is strictly related to the location. According to such assumption several groups of tanks can be listed:

- fore and after peaks;
- double bottom tanks;
- side tanks;
- deep-tanks;
- wing tanks (however, frequently they are deep-tanks according to their shape);
- cofferdams (tanks surrounding cargo holds).

The combinations of two types are also noticed. Additionally there is always a number of tanks in a machinery rooms but they can be neglected due to their small volume.

The next criterion applied for ships' tanks classification is their purpose or function:

- trimming tanks (fore and after peaks) which are utilized very often as partly filled due to the need for precise trimming of a ship, so the ballast water level is adjusted according to the variable requirements, thus providing free surface of liquid;
- stability tanks improving ship's stability performance due to a decrease in the vertical center of gravity (usually double bottom tanks located between an engine room and a fore peak creates this group); quite often the breadth of these tanks equals half breadth of a ship or even sometimes it equals full ship's breadth (in ship's fore region) therefore the free surface of liquid can be massive in these tanks so generally they should be full or empty during voyage;
- list control tanks (side tanks) which are usually located amidships and due to their function quite often partly filled with free surface;
- strength control tanks utilized to adjust longitudinal weight distribution (fore and after peaks, double bottom tanks, side tanks and sometimes even cargo holds prepared for ballasting) which are very often partly filled to reduce excessive sheering force and bending moment and routinely they provide free surface of liquid;
- special purpose tanks like for instance anti-rolling tanks (flume) or anti-heeling tanks, which are usually filled up to the 50% level, providing free surface.

Shapes of ships' tanks

In the light of the conducted investigation in majority of cases the cross section of ship's tank is rectangular or L-shaped, which is presented in figure 7.

There are some apparent discrepancies and they are usually related to the shape of a stern or bow part of a hull and moreover to the arrangement of ship inner space. The examples of such neither rectangular nor L-shaped tanks are shown in figure

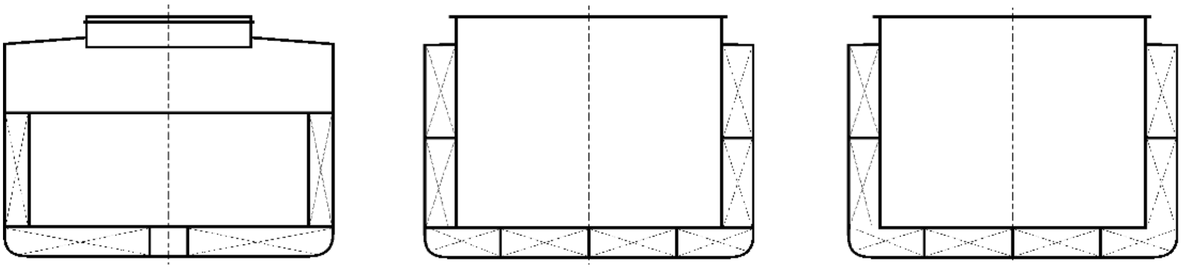

Fig. 7. Prevailing simple shapes of ballast tanks
Rys. 7. Przeważające proste kształty zbiorników balastowych

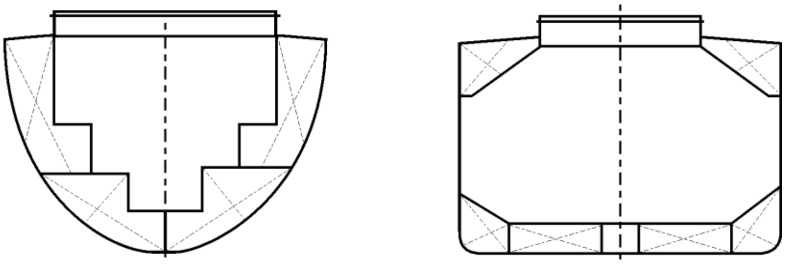

Fig. 8. Typical complex shapes of ballast tanks
Rys. 8. Typowe złożone kształty zbiorników balastowych

8. In the case of bow and stern part of a hull the tanks' shapes can be actually odd. In the case of special ship's construction like for instance self-trimming holds of some bulk carriers, tanks can be approximated by trapezoidal or triangular shapes.

The longitudinal sections of ballast tanks reveals even stronger unification then their cross sections. Regardless fore and after peaks the majority of remaining tanks longitudinal sections is rectangular or very rarely L-shaped. Fore and after peaks are usually irregular and their shape depends on bow and stern form.

Ships' tanks size evidence

Besides the considered shapes of ships' ballast tanks the matter of their size is essential for proper modeling of liquid sloshing phenomenon. The longitudinal extend of tanks is typically limited by the location of watertight bulkheads demarcating individual cargo spaces, i.e. holds and tweendecks. The dissimilarities noticed in the course of the research concerns mainly wing tanks and generally tanks onboard ships with very long cargo spaces, e.g. ro-ro with their extremely long cargo decks or special purpose tanks (like for instance anti rolling tanks). In such cases the longitudinal extend of tanks is basically smaller in length than the distance between transverse watertight bulkheads.

The vertical extend of considered tanks is imposed by division of hulls inner space arrangement, namely: the height of double bottom, the general height of the hull, the occurrence of tweendecks. Occasionally fore peaks might be split into two separate tanks, the upper fore peak and the lower one. The height of double bottom tanks is to some degree imposed by the classification society rules. For example, PRS recommends that the height of double bottom is not less than 650 mm. In addition, it is recommended that the height of the longitudinal girder should not be less than given by the formula [5]:

$$h_d = 250 + 20B + 50T \quad \text{[mm]} \qquad (2)$$

where:
B – ship's breadth,
T – summer draft of a ship.

In the analyzed group of ships the height of double bottom ranged from 1.50 m to 2.40 m. Such variety of height of double bottom tanks seems to be typical for cargo vessels.

When considering the liquid sloshing phenomenon in partly filled ships' tanks one of the most significant tank's dimension is its breadth. It mainly depends on tanks location and its purpose. The crucial characteristics found out in the study are as follows.

The space of a double bottom generally is divided crosswise into two or four symmetrical tanks, however, it may be also divided into three tanks. In case of bulk carriers in the tapered fore part of the double bottom also a single double bottom tank may be used with its horizontal cross-section similar to the trapezoidal shape and a maximum width up about 80% of the width of the hull amidships.

The breadth of fore and after peaks corresponds to the breadth of ships' hulls. These tanks are narrow in their lower part and the width increases significantly upwards, although their cross section can be simplified to describe by an isosceles triangle or trapezoid.

The tanks operated as passive anti-rolling system have very large transverse extend reaching from side to side of a ship, however when properly tuned the phase shift of liquid movement and ship's rolling improves her stability performance. On the other hand the improper operation may lead to unexpected increase of rolling amplitude and even to a capsizing of a ship [6].

The average breadth of side tanks varies about 8% to 9% of the maximum width of the hull. In the considered population of ships the noticed values were mainly about 2 m to 3 m. Due to the small width of these tanks their impact on the stability performance is insignificant from the liquid sloshing research point of view.

Regardless the individual dimensions of ballast tanks it is important to assess the weight of ballast water on-board in comparison to the weight of a vessel. Such relation is shown in figures 9 and 10 in relation to the lightship weight and to the summer draft displacement.

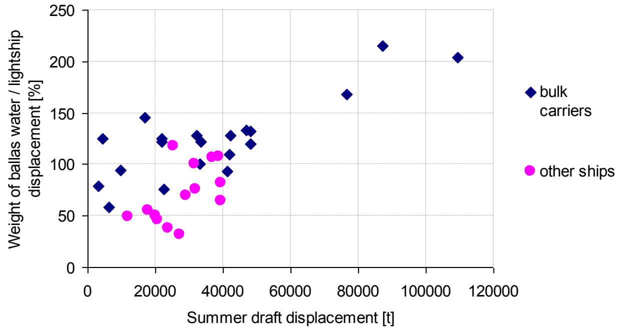

Fig. 9. Relation of ballast water weight to the lightship weight
Rys. 9. Stosunek masy wody balastowej do masy pustego statku

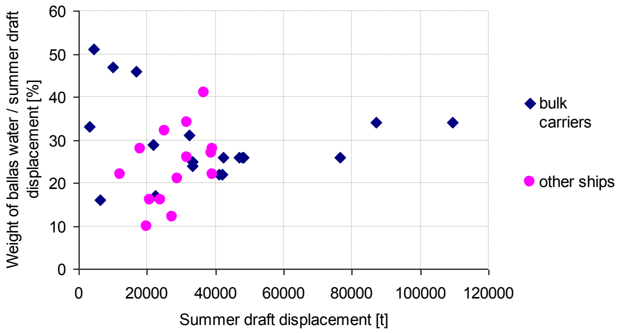

Fig. 10. Relation of ballast water weight to the summer draft displacement
Rys. 10. Stosunek masy wody balastowej do wyporności statku do letniej linii ładunkowej

According to the graphs (Figs 9 and 10) it is clearly seen that the total weight of ballast water is significant and may reach up to double lightship weight or even halt weight of an entire ship displacement. The remark does not influence the shape of a model tank utilized in the course of the experiment but it suggests an importance of the considered problem.

As the total weight of ballast water cannot be direct indicator of potential decrease in ship stability, the free surface correction apparently can be. The values of corrections were calculated for a number of investigated vessels according to the formula (1). However, not all ships' tanks were assumed as partly filled but only some of them according to the proper practical use of ballast tanks which may be also called good seamanship. The results of the computation are shown in figure 11.

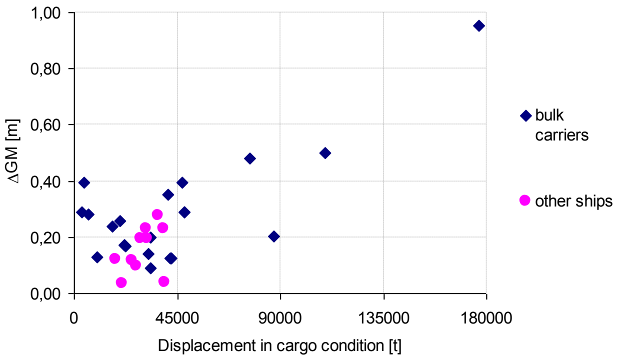

Fig. 11. Free surface correction versus vessel size (expressed by the summer draft displacement)
Rys. 11. Poprawka od swobodnych powierzchni cieczy w zależności od wielkości statku (wyrażonej poprzez wyporność do letniej linii ładunkowej)

The graph reveals that the free surface correction in cargo condition of ships is typically greater then the minimum IMO requirements regarding the metacentric height or a righting arm [2]. Is such case the accuracy of liquid sloshing effect estimation may play an important role when assessing ships' stability according to the recommendations published by ship classification societies as stability standards.

Cargo holds as ballast tanks

Many cargo ships, especially bulk carriers are designed for ballasting with the use of a relatively small or moderate size cargo hold located amidships. Such structural variant is one of possible way to solve ships overall strength problems or a problem of insufficient draft for proper operation when carrying small amount of cargo or sailing in ballast condition.

Among investigated group of ships over 80% of bulk carriers were designed and constructed to ballast one hold amidships. Almost all remaining bulk carriers without such functionality were relatively small having their length between perpendiculars less then hundred meters. However, in the analyzed group of ships other then bulk carriers only 12% has a construction suitable to ballast any cargo holds. Sporadically ships other then bulk carriers with an engine room located far in the aft, have a possibility to ballast cargo holds close to the bow. The purpose of such construction is an attempt to avoid excessive trim and resulting from it slamming and potentially destructive bow flare impacts.

The cargo hold adopted to be ballasted is the most likely the largest ballast tank on-board since it is the most interesting from the researchers point of view. The extend of such hold exceeds other tanks dimensions therefore the free surface correction is anticipated as massive as well. The values of the correction were computed for analyzed vessels and the effect is shown in figure 12 justifying such expectation.

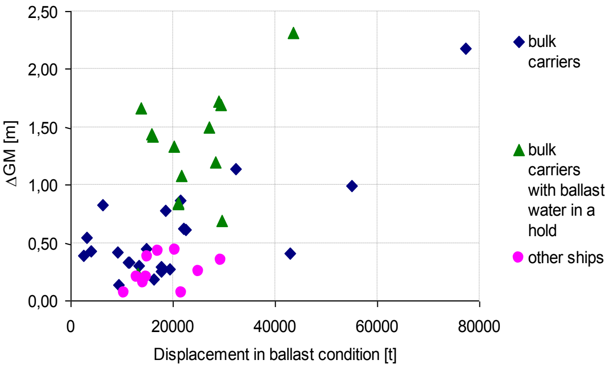

Fig. 12. Free surface correction including cargo hold ballasting versus vessel size
Rys. 12. Poprawka od swobodnych powierzchni cieczy z uwzględnieniem zabalastowanych ładowni w zależności od wielkości statku

The analysis of ballast condition of ships with additional use of one cargo hold if it is suitable for ballasting demonstrates the massive values of free surface corrections. This suggests that the size and geometry of ballast tanks affects ships stability significantly.

Conclusions

The conducted investigation described in the paper is focused on ballast tanks geometry for the purpose of proper planning model tank geometry to utilize it in the course of experimental tests. The typical shapes of tanks were found out which needs to be taken into account during experimental test due to the proper adjustment of movement excitation parameters providing appropriate scale calculation. The longitudinal, transverse and vertical extend of typical groups of ships tanks was established.

In the light of analyses carried out in the concerned matter, the model tank is planned as rectangular with a height to width ratio about 1:2 and preferably supplied with adjustable side wall and a bottom which is shown in figure 13.

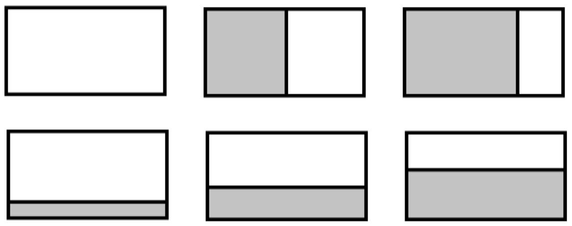

Fig. 13. Planned model tank with adjustable bottom and side
Rys. 13. Planowany zbiornik modelowy z regulowanym dnem i ścianą

The construction of the model tank will enable to carry out series of experimental tests for a wide variety of typical ships' tanks.

The additional result of the investigation is an assessment of realistic values of free surface corrections. The study reveals special importance of the investigated matter for bulk carriers sailing in ballast conditions. The free surface effect in partly filled tanks may be so massive that even the discrepancies ranging up to about 20% result in inaccuracy of stability parameters greater then their values required by stability standards. This undoubtedly justifies continuation of the research.

The research project was funded by the Polish National Science Centre.

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