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The Second Trim Correction in Draught Survey Procedure – Accuracy Analysis

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ABSTRACT: The basic method for determining the mass of dry bulk cargo, loaded on the ship or unloaded from the ship, is the Draught Survey procedure. This procedure is quite simple, however is highly susceptible to mistakes and accidental errors. Moreover, it is also affected by some systematic errors. The difference between the mas of cargo at the loading and discharging port (cargo shortage) bigger than 0.5% then such cargo shortage generally becomes the subject of a Cargo Claim. In this study the systematic error that concerns the formula of second trim correction in Draught Survey procedure is discussed. The results of calculations performed with the commonly used the second trim correction formula are compared with the results obtained during calculations with the use of Bonjean Scale. The calculations carried out with the use of Bonjean Scale, have been validated based on the ship's documentation. For the purpose of this study the small bulk carrier was selected. The results of performed calculations shows the significance of the systematic error of the second trim correction for a ship with higher trim values.

1 INTRODUCTION

Dry bulk cargo constitutes the significant part of maritime transport and includes any cargo carried in bulk in solid form, e.g. coals and cokes, grains, bulk minerals (e.g. sand, gravel), iron ore, cements, chemical fertilizers or bauxite. Generally, ships designed/built to carry such cargo are called bulk carriers, although a part of them have independent type name which is directly related to the type of transported cargo e.g. ore carrier, ore-bulk-oil carrier (OBO) or cement carrier. In Chapter IX of the SOLAS Convention (the International Convention for the Safety of Life at Sea) a bulk carrier is defined as "a ship constructed with a single deck, top side tanks and hopper side tanks in cargo spaces and intended to carry dry cargo in bulk primarily; an ore carrier; or a combination carrier" (IMO, 2013). It should be noted here that some light dry bulk cargoes sometime are carried also by general cargo ships. The EQUASIS (Electronic Quality Shipping Information System) provides information about the world's merchant fleet. Their database includes most of the world's merchant ships. Reports and statistics are published every year and are generally available. According to the EQUASIS 2021 database, the dry bulk carriers includes 12 874 ships and represent 10.8% of the total number of ships, however in terms of gross tonnage it is already 34.4%.

Dry bulk cargo is transported unpackaged in large quantities and the significant issue is determining the mass of the cargo loaded on (unloaded from) the ship. Practically in most cases, the basic method for determining the mass of the transported dry bulk cargo is the *Draught Survey* (DS) procedure.

The *Draught Survey* procedure is based on the ship's draughts read from the draught marks placed on the ship's hull, at the bow and stern and in the case of large ships also at the midship. Using these draughts, the current ship displacement is determined where heel, trim, hull deformation and water density are considered. The weight of loaded/unloaded cargo usually is calculated as the difference between ship displacement determined before and after loading/discharging. Such an approach eliminates from the calculations a number of masses that are unknown or known with insufficient accuracy and generally are called ship constant (silt and mud in tanks, bilge water, minor changes in construction and equipment made during stays at the shipyard, auxiliary equipment and some supplies, etc.). A short description of the standard *Draught Survey* procedure is provided in the next Section, while a broad description with additional notes about actions performed under the *DS* procedure and possible errors can be found in (UNECE Committee on Energy, Working Party on Coal 1992; Isbester 1993; Dibble and Mitchell 1994; The International Institute of Marine Surveying 1998; Puchalski and Soliwoda 2008; Barras and Derrett 2012).

Considering the number and total tonnage of bulk carriers it is easy to notice the enormous importance of the *Draught Survey* procedure accuracy. According to Japan P&I Club (2016), if the quantity of loaded cargo is shown by mass and the difference between the quantity measured at the loading and discharging port is bigger than 0.5% (Trade Allowance most often used for dry bulk cargo) then such cargo shortage generally becomes the subject of a Cargo Claim. Whereas the West of England P&I Club (2018) reports that using *Draught Survey* procedure the accuracy of calculated cargo mass usually varies between 0.5% and 1%. However, Ivče et al. (2011) stated that the accuracy of calculated cargo mass varies between 0.1% and 1%. This seems more reliable because the range of 0.5-1% would mean that the Trade Allowance limit is practically always exceeded. Nevertheless, the error equal to 0.5-1% of total cargo mass, at the maximum ship displacement, corresponds to a value of 4 to 8 TPC (the mass in tons required to change the ship mean draught by one centimeter) where the accuracy of draught measurement assumed in DS procedure is ±0.5 cm. Obviously, in real conditions, such draught measurement accuracy is most often not achievable.

The ship draught measurement accuracy was the main issue of the study (Ivče et al. 2011). Although Ivče et al. (2011) pointed that the ship draught measurement error is one of the main errors causing the *DS* procedure inaccuracy, the authors still claim that measuring cargo mass by means of draught gives a smaller error than measuring the mass by cargo weighting. The reasons for the measurement error of the ship's current draughts may be: parallax phenomenon, waves and related ship movements, strong current, reduced visibility (e.g. night conditions) or rain. Ivče et al. (2011), based on their experimental discoveries, claims that error in draught readings can be up to ±10 cm. This is likely but only in extreme weather conditions. To reduce the error in draught readings, authors suggest using the optical fiber technology. They believe this may be a way to eliminate errors that may occur during the visual draught reading. Unfortunately, the study does not contain any comparative data, based on the real measurements.

No doubt, the draughts that have been measured are a substantial factor since they are the only input parameter for ship displacement calculations. However, there are also other issues that may significantly affect the accuracy of *Draught Survey* procedure and finally the mass of cargo that is determined. A considerable number of them have been accurately indicated by the West of England P&I Club (2018), however these are mainly operational issues where potential errors may be classified as mistakes (errors caused by inattention, inexperience, carelessness, misjudgment, distraction) or accidental errors. These issues concern: mass of ballast on board, water density, unfactored masses (e.g.: bilge water, water in swimming pool, anchor and anchor cable on the seabed, silt and mud in the double bottom tanks), squat, trim by the head (the tanks suctions and sounding pipes are located at the aft end of the tanks), the nature of cargo (for certain types of cargo, water could migrate from the cargo to the hold bilges and be subsequently pumped overboard) and others (West of England P&I Club 2018).

The *Draught Survey* procedure not only is susceptible to mistakes and accidental errors but it is also affected by systematic errors. Systematic errors may be caused by inaccuracies and even considerable errors in the ship's documentation - the hydrostatic data and tank sounding tables may not be accurate (e.g. because of changes to the ships structure made in shipyards). Another source of the systematic error may be one of the assumptions of the DS procedure, that the hull deformation (deflection) is symmetrical, that the deformation maximum is placed exactly at the midship cross section. Whereas the location of the hull deformation maximum very often is placed outside the midship cross section. This issue most often affects smaller ships because of large engine room in relation to the hull size (West of England P&I Club 2018) but it can also be caused by the cargo distribution on large ships. The issue of correction for hull deformation in the DS procedure was discussed in (Soliwoda 2016; Wawrzynski 2011).

Apart from papers mentioned earlier, a few more studies that address the accuracy of the *Draught Survey* procedure can be found in (Li et al. 2014; Elnoury and Gaber 2018; Xu et al. 2018; Canımoğlu and Yıldırım 2021), but generally the number of advanced studies is quite small. In (Li et al. 2014) the fuzzy comprehensive evaluation method was adopted to analyze the DS procedure error. Authors of this study claim that this method can be used to calculate the error risk in different condition, ensuring the *DS* procedure error will be below 0.5%. Canımoğlu and Yıldırım (2021) used the extended fuzzy analytic hierarchy process (FAHP) method to develop the hierarchical structure establishing the recommendations for reducing errors in the DS procedure. In this study, like in (Ivče et al. 2011; Xu et al. 2018), it is stated that errors occurring during the draught reading stage are the main source of the DS procedure errors. The errors priority weights have been defined, where for draught readings it is 0.40, for ballast measurement 0.29 and only 0.12 for the error made during displacement calculations. However, these values are questionable since it seems that

Canımoğlu and Yıldırım (2021) assume that the mathematical formulas used in the calculation part of DS procedure are fully valid (free from systematic errors).

Returning to the issue of systematic errors in the *Draught Survey* procedure, the inaccuracies in the ship's documentation or deformation maximum outside the midship cross section may or may not be present (this depends on the ship documentation or/and the current loading condition). However, there is another systematic error that directly concern the mathematical formula used in the calculation part and more specifically the second trim correction. This analysis shows the significance of this error based on calculations performed for the selected bulk carrier.

Finally, it should be highlighting that this study omitted alternative procedures for determining the ship's displacement on the base ship's draughts. For example, these procedures may use data of a trimmed ship (Firsov diagram) or ready-made the displacement correction tables which are sometimes included in the ship stability booklet. Although some reference to these procedures will be made in the conclusions section

2 STANDARD DRAUGHT SURVEY PROCEDURE

Regardless of the *Draught Survey* procedure is susceptible to mistakes and accidental errors the calculation part of it is very simple. Generally, there are two versions of the *DS* calculation part that differ in the way the hull deformation is considered. However, in this research the trim correction is the issue, therefore it was assumed that the hull is free of deformation. If so then both *DS* calculation versions come down to one where only the draughts at aft and fore marks are used.

To consider the possible ship list, the arithmetic mean of the mark draught on the port and starboard sides are calculated, independently for the stern and bow. Next, both arithmetic means are converted into draughts on the perpendiculars (T_{aft} and T_{fore}) and then the mean draught T_M (draught at midship) is calculated:

$$T_M = \frac{T_{aft} + T_{fore}}{2} \quad (1)$$

The mean draught is the parameter the displacement is taken from the *Hydrostatic Table* of even-keel ship (*HyTa*). For trimmed ship this displacement is incorrect due to the trimming axis is not at midship but at the cross section of the center of flotation (geometric center of the waterplane area). The longitudinal coordinate of the center of flotation (*LCF*) is given in *HyTa*.

As stated above the displacement taken from *HyTa* is incorrect, so the two trim corrections are applied, called 1st and 2nd trim correction (ΔD_1 and ΔD_2). First trim correction ΔD_1 (2) considers the difference in draught between the midship and *LCF* cross section. The idea of this correction is logical and obvious. However, in the formula (2) the *LCF* taken from the *Hydrostatic Table* of even-keel ship is used. For trimmed ship the waterplane area changes its shape and size. Consequently, the center of flotation changes its position too. To take this into account the second trim correction (3) is used. It should be noted here that formula (3) was developed using some simplifications and is no longer so obvious as formula (2).

$$\Delta D_1 = 100 \cdot TPC \frac{t}{L_{PP}} LCF \quad (2)$$

$$\Delta D_2 = 50 \cdot \frac{t^2}{L_{PP}} \left(MTC_{T_M+0.5m} - MTC_{T_M-0.5m} \right) \quad (3)$$

In the above formulas t is the trim (negative for aft trim and positive for forward trim), *LCF* is the longitudinal center of flotation measured in relation to midship (negative when towards the stern and positive when towards the bow), L_{PP} is the length between perpendiculars, *TPC* is the mass in tons required to change the ship mean draught by one centimeter and *MTC* the moment to change the trim one centimeter. The remarks on the trim sign given in brackets are very important. Unfortunately, for most ships, the arrangement of trim sign and *LCF* sign that is used gives the wrong sign of 1st trim correction. To avoid this error a simple rule can be used: if the trim and the position of center of flotation relative to midship are in the same "direction" than the sign of 1st trim correction is positive, otherwise it is negative.

Moreover, it is worth noting here that the formula (3) is incomplete. This is easy to see when looking at the units. Performing unit's calculation of (3) we will get (t·m) while it should be (t). The complete formula of 2nd trim correction has the form (4) however, due to ΔT is one meter, it is commonly reduced to (3). The ΔT equal to 1 m implies that 2nd trim correction is dedicated for the small values of trim.

$$\Delta D_2 = 50 \cdot \frac{t^2}{L_{PP}} \cdot \frac{\left(MTC_{T_M+0.5m} - MTC_{T_M-0.5m} \right)}{\Delta T = 1m} \quad (4)$$

Both trim corrections are added to the displacement taken from the Hydrostatic Table of even-keel ship (5):

$$D' = D\left(T_M\right) + \Delta D_1 + \Delta D_2 \quad (5)$$

The last step is to consider the water density that is measured at the draught reading stage (ρ_m). If ρ_m is equal to water density used in HyTa (ρ_{HyTa}) then the final value of displacement *D=D'* and if not then:

$$D = D' \frac{\rho_m}{\rho_{HyTa}} \quad (6)$$

This study is intended to show the accuracy of the 2nd trim correction (3), (4).

3 SHIP SELECTED FOR ANALYSIS

For the purposes of trim correction analysis in the *Draught Survey* procedure the small bulk carrier *Armia Krajowa* was chosen. Ship length between perpendiculars L_{pp}=176.65 m, breadth B=30.00 m, summer maximum draught $T_{max}(\rho$=1.025 t/m^3)=10.50 m and maximum displacement D=49 212.7 t. As basic, it was assumed that the data provided in the ship's documentation are correct and accurate.

The volume of immersed part of the hull calculated using *Bonjean Scale* (*BS*) is the moulded volume of hull. It does not include volumes of shell plates and appendages (bilge keel, rudder, propeller, propeller shafts and struts, roll fins). On the other hand, the hull volume calculated using Bonjean Scale should be reduced by the volumes of tunnels that accommodate bow thrusters. Volumes of the hull given in the ship *Hydrostatic Table* the most often are the moulded volumes.

To determine the total ship displacement, the moulded volume calculated using the *Bonjean Scale* or taken from *HyTa*, should be multiplying not only by the water density but also by an additional coefficient c_{sa} (shell and appendages coefficient). For operational ships draughts, the volume of immersed appendages is almost constant while the volume of immersed part of the hull is highly depend on the current draught. Therefore, c_{sa} is dependent on the draught too. It is worth noting that for many small ships, especially general cargo ships, most often a constant value of c_{sa} is assumed.

For ship used in the presented research the c_{sa} dependence on draught is shown in Fig. 1. The graph was developed based on the ship *HyTa* (even-keel), using a simple formula:

$$C_{sa}\left(T\right)=\frac{D\left(T\right)}{\rho_{HyTa}\cdot V\left(T\right)} \tag{7}$$

where *D(T)* and *V(T)* are the displacement and moulded volume taken from *HyTa* (even-keel) for the draught *T* and ρ_{HyTa} is the water density used in *HyTa*.

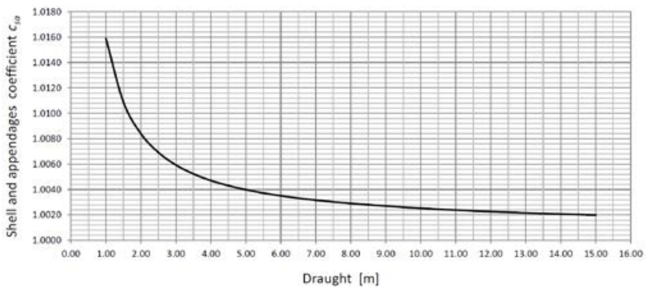

Figure 1. Shell and appendages coefficient csa for the bulkcarier Armia Krajowa

Unfortunately, the data in *HyTa* of *Armia Krajowa* are given only for draughts every 0.5 m. To increase the accuracy of the displacement calculations for intermediate draught values, c_{sa} coefficient has been approximated by the following formula:

$$c_{sa}\left(T\right)=1.00084+\frac{0.0187742}{T}-\frac{0.0258258}{T^2}+\frac{0.0675878}{T^3}-\frac{0.0763044}{T^4}+\frac{0.0308097}{T^5} \tag{8}$$

In the range of *Armia Krajowa* operational draught, the formula (8) gives the c_{sa} values with a deviation below 0.003%, in points used for approximation.

4 CALCULATION METHOD AND ITS VALIDATION

The moulded volume of hull underwater part, for the ship without heel, was calculated using the *Bonjean Scale*. In *Armia Krajowa* documentation, the *Bonjean Scale* includes curves of cross section area (presented as a function of draught) for up to 44 cross-sections and the volume calculation formula is as follows:

$$V=\sum_{n=1}^{m-1}\frac{A_n\left(T_n\right)+A_{n+1}\left(T_{n+1}\right)}{2}d_n \tag{9}$$

where $A_n(T_n)$ is the transverse area of *n* cross section taken from *BS* for the draught at this section T_n, d_n is the distance between cross sections (*n* and *n+1*) and *m* is the total number of cross sections.

It needs to be highlighted that the volume calculations accuracy significantly depends on the number of cross sections in the stern and bow part of hull, where the greatest variability of the hull cross sections shape can be observed. To check if the number of sections given in *BS* of *Armia Krajowa* is sufficient, the calculations of the hull moulded volumes were carried out for even-keel ship at draughts same as given in *HyTa*. Moulded volumes calculated with the use of *BS* and taken from *HyTa* turned out to be very close, so to show the divergence, the graph of moulded volumes differences ($\Delta V=V_{HyTa}$ - V_{BS}) will be better (Fig. 2). In Fig. 2 the solid line shows ΔV for calculations performed according to formula (9) where the interpolation between $A_n(T_n)$ and $A_{n+1}(T_{n+1})$ is linear and the dashed line shows ΔV for calculations performed using spline interpolation (a curve between every two points were approximated by a second degree polynomial based on 3 consecutive points):

$$V=\sum_{n=1}^{m-2}\left(\int_{x_n}^{x_{n+1}} f_n\left(x\right)dx\right)+\int_{x_{n=m-1}}^{x_m} f_n\left(x\right)dx \tag{10}$$

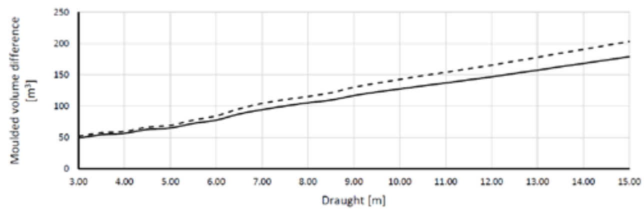

Figure 2. Differences of moulded volumes ΔV, calculated using *Bonjean Scale* and given in *Hydrostatic Table* of the even-keel ship (ΔV =V_{HyTa}-V_{BS}). Solid line – linear interpolation; dashed line – spline interpolation

In Fig. 2 its clear that the linear interpolation provides results closer to *HyTa*, so this method has been chosen. Additionally, Fig. 2 shows that the moulded volumes difference increases with draught (volume of immersed part of hull) increase. However, if the difference of moulded volumes showed in Fig. 2 will be replaced by the coefficient of relative difference (11) than it can be seen that the convergence of the V_{HyTa} and V_{BS} increases with draught increase (Fig. 3, solid line). This is fully justified since the shape of the hull shows greater variability in the range of small draughts.

$$c_{mv}\left(T\right)=1+\frac{\Delta V\left(T\right)}{V_{HyTa}\left(T\right)} \tag{11}$$

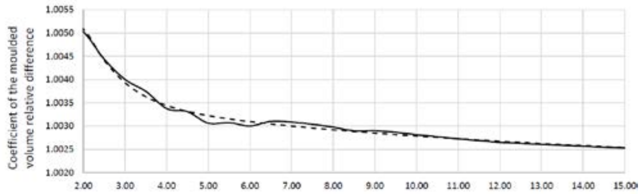

Figure 3. Coefficient of the moulded volume relative difference c_{mv}. Solid line – actual; dashed line – approximated by formula (12)

Because the exact values of coefficient c_{vm} can be calculated only for draught selected in *HyTa* table, for convenience, a function (12) approximating its value was developed. The curve of the approximated values of c_{mv} is shown in Fig. 3 (dashed line). Despite minor differences between actual and approximated value of cmv, the use of (12) caused that ΔV in any case was not greater than 4.6 m³ (Fig. 4). This corresponds to approximately 0.1 *TPC*.

$$c_{mv}\left(T\right)=1.0017+\frac{0.018593}{x}-\frac{0.112466}{x^2}+\frac{0.370059}{x^3}-\frac{0.496174}{x^4}+\frac{0.223627}{x^5} \tag{12}$$

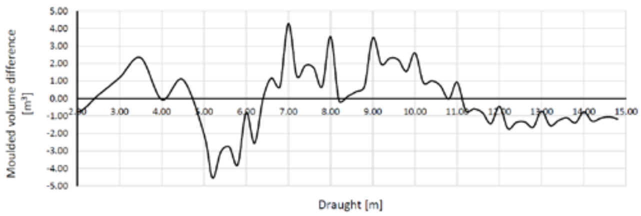

Figure 4 Difference between the moulded volume given in *Hydrostatic Table* (even-keel) and calculated with the use of *Bonjean Scale*, after using the coefficient of relative difference c_{mv} (12)

In the *Armia Krajowa* stability booklet, apart from even-keel *HyTa*, the *Hydrostatic Table* for trimmed ship (*HyTa_t*) are also given, for trim -1.00, -2.00 and -3.00 m. Fig. 5 shows difference between the moulded volume given in the trimmed ship *Hydrostatic Table* and calculated using *Bonjean Scale* and the c_{mv} coefficient (12), for trim -2.00 and -3.00 m. This time the differences are slightly greater than for even keel ship and are clearly related to the trim value. Nonetheless, it can still be concluded that the applied calculation procedure gives satisfactory results since the ship average *TPC* is close to 50 t/cm (hull volume change is close to 50 m³ for 1cm draught change).

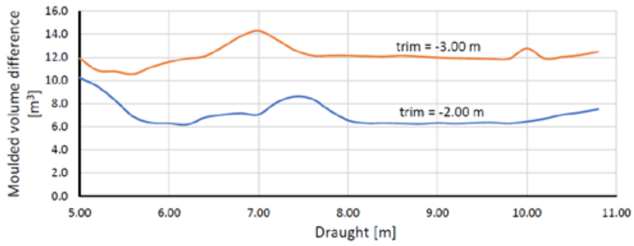

Figure 5. Difference between the moulded volume given in trimmed ship *Hydrostatic Table* and calculated using *Bonjean Scale* and the coefficient of relative difference c_{mv} (12). Volume 10 m³ corresponds to approximately 0.2 *TPC*

5 CALCULATIONS

The displacement of trimmed ship was calculated using two methods, with the use of *Bonjean Scale* and *Draught Survey* procedure. Calculations were carried out for the mean draught (draught at midship) from 5.00 to 11.80 m with the spacing 0.2 m and trim from -6.00 m (aft trim) to 2.00 m (forward trim) with the same 0.2 m spacing. The differences between ship displacement calculated by both methods are shown in Fig. 6. However, because the difference in displacement expressed directly in tones is strongly related to the ship size, it was considered better to present those differences in *TPC* units. It should also be noted, due to the difference sign, that the displacement difference Δ_{disp} was calculated as follows:

$$\Delta_{disp}=D_{Bonjean\ Scale}-D_{Draught\ Survey} \tag{13}$$

It can be seen in Fig. 6 that apart from small and medium values of trim ($\left|t\right|$ < 2.00 m) where Δ_{disp} is small and in the most cases negligible (Δ_{disp} < 0.25 *TPC*) the displacement difference quite increases for bigger trim values. Also, it's easy to see that for small draughts (T_M < 7.40 m) the displacement difference is positive and for higher ones it is negative. Although a certain tendency of changes can be identified, the problem is to observe the exact relation between Δ_{disp} and the draught. For example, for mean draughts 7.60 and 11.80 m the displacement differences are quite similar while for T_M = 9.00 m Δ_{disp} is clearly bigger.

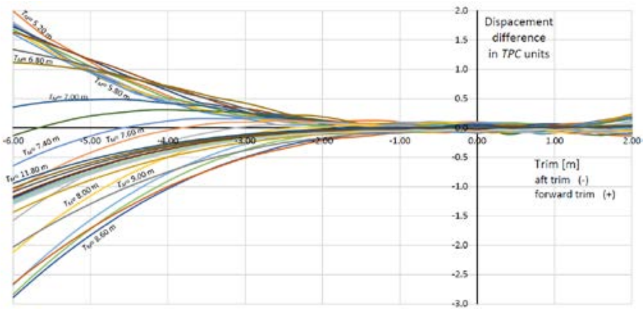

Figure 6. Difference between ship displacement calculated using *Bonjean Scale* and *Draught Survey* procedure for the mean draught from 5.00 to 11.80 m with 0.2 m spacing, as a function of trim, in *TPC* units

The calculation results showed in Fig. 6, but in a different arrangement, are presented in Fig. 7 and 8.

These figures show the displacement difference for different trim values as a function of the ship mean draught. In Fig. 7 it is clearly visible that the changes may be difficult to describe with a mathematical formula. Moreover, an unfavorable phenomenon is the Δ_{disp} sign change. For $T_M < 7.20$ m the sign of Δ_{disp} is positive while above is negative. This mean that displacement calculation inaccuracy for ship before and after loading will add up.

Fig. 8 shows the same graphs as Fig. 7 but for the trim absolute value limited to 3.00 m. Visible, the small local deviations of graphs are probably caused by the discrete data format used in the ship *Hydrostatic Table* and *Bonjean Scale* as well as the precision of this data. Moreover, some of the visible differences may also be caused directly by the calculation method used. Apart from the issue of deviations, Fig. 8 strengthens the conviction that describing the Δ_{disp} using a mathematical formula may be impossible.

Finally, it is worth adding that since the 1st trim correction is logical and obvious, Δ_{disp} presented in Fig. 6, 7 and 8 is directly related to the not entirely correct 2nd trim correction and may be considered as an error of 2nd trim correction.

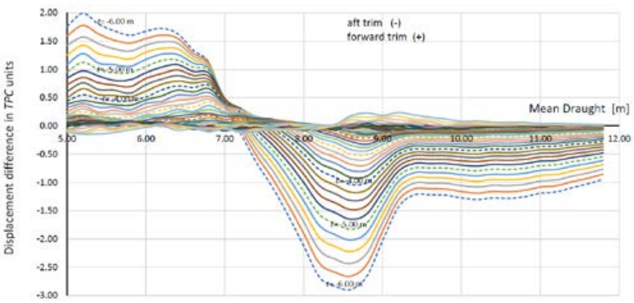

Figure 7. Difference between ship displacement calculated using *Bonjean Scale* and standard *Draught Survey* procedure, for trim from -6 m (aft trim) to 2 m (forward trim) with 0.2 m spacing, as a function of draught, in *TPC* units

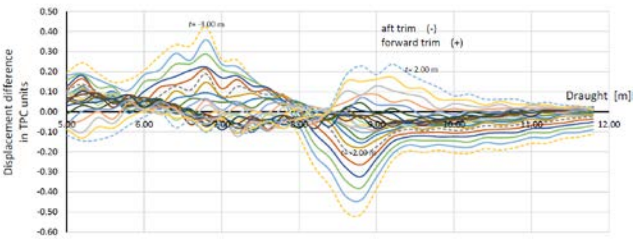

Figure 8. Difference between ship displacement calculated using *Bonjean Scale* and standard *Draught Survey* procedure, for trim from -3 m (aft trim) to 2 m (forward trim) with 0.2 m spacing, presented as a function of draught, in *TPC* units

6 SECOND TRIM CORRECTION

In the previous section it was stated that the difference between ship displacement calculated using *Bonjean Scale* and *Draught Survey* procedure (Δ_{disp}) may be difficult or even impossible to describe using a mathematical formula. Moreover, this approach would require to develop an additional correction formula to the *Draught Survey* procedure (3rd trim correction). Focusing on the differences in the results obtained using two different calculation methods (Fig. 6, 7 and 8) is not always conducive to finding a solution.

Fig. 9 shows the 2nd trim correction calculated according to the formula (3) while Fig. 10 shows the difference between the ship displacement calculated with the use of *Bonjean Scale* and the displacement taken from *HyTa* increased by 1st trim correction (2):

$$\Delta D_2' = D_{BS} - \left(D_{HyTa}\left(T_M\right) + \Delta D_1\right) \tag{14}$$

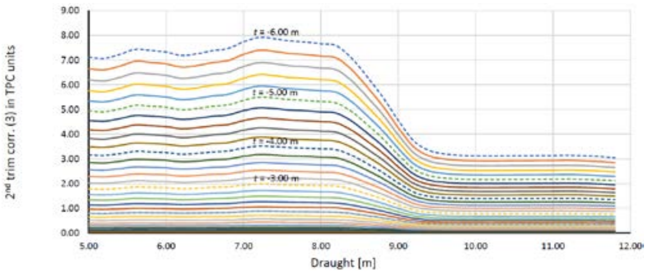

Figure 9. Second trim correction in the *Draught Survey* procedure calculated according to formula (3)

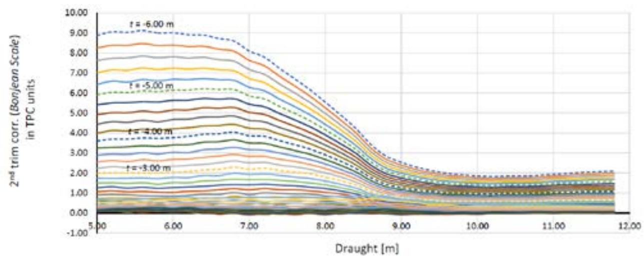

Figure 10. Difference between the ship displacement calculated with the use of Bonjean Scale and the displacement taken from *HyTa* increased by 1st trim correction (2) → 2nd trim correction calculated on the base of *Bonjean Scale*.

Considering what was written earlier, it can be assumed that Fig. 10 shows the correct values of 2nd trim correction $\left(\Delta D_2'\right)$. Therefore, it is worth considering whether the formula (3) can be modified to obtain the calculation results as close as possible to those presented in Fig. 10.

Formula (3) is a direct derivative of formula (4) where it was assumed that ΔT is one meter. This assumption implies that 2nd trim correction (3) is dedicated for small values of trim, and it must be admitted that for the such trim values it gives satisfying results (Fig. 6 and 8). Nevertheless, it can seem that formula (4) with small modification can be better for larger trim values, maintaining good results for small and medium values of trims. To test this, formula (4) was modified to:

$$\Delta D_{2.1} = 50 \cdot \frac{t^2}{L_{PP}} \cdot \frac{\left(MTC_{T_M + 0.5 \cdot \Delta T} - MTC_{T_M - 0.5 \cdot \Delta T}\right)}{\Delta T} \tag{15}$$

The idea of formula (15) was to consider changes in the size and shape of the waterplane area over the bigger range of current ship draughts, not only over 1 m range. This can be important since the aft part of stern can begin more than 0.5 m above the horizontal plane of mean draught T_M. In the first attempt it was assumed that $\Delta T = |t|$ (Fig. 11). Fig. 11 clearly shows that for such assumption formula (15) did not give good results. The graphs are smoothed and the characteristic changes, visible in Fig. 10 in the draught range from 7 to 11 m, did not show up.

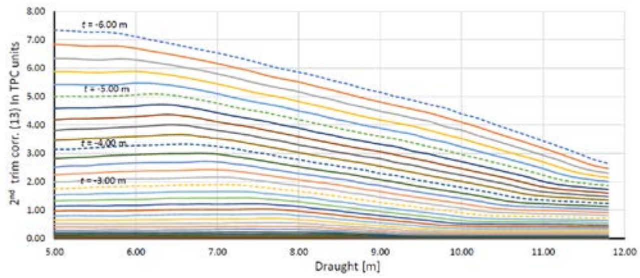

Figure 11. Second trim correction in the Draught Survey procedure calculated according to formula (13)

To test the formula (15) more thoroughly, the ΔT value was varied from 0.1 to 1 of the trim absolute value. The summary results of calculations performed for trim -6, -4 and -2 m are presented in Fig. 12. It can be seen that ΔT value bigger than 1 m only slightly affect the maximum difference between 2nd trim correction calculated using *Bonjean Scale* and formula (15):

$$\Delta D_{2^{nd}\,trim\,corr.} = \Delta D_2' - \Delta D_{2.1} \qquad (16)$$

For $\Delta T \geq 1$ m and t =-6 m, the total value of $\Delta D_{2^{nd}\,trim\,corr.}$ varies with a deviation smaller than 0.2 *TPC* and for t =-2 m smaller than 0.02 *TPC*. Also, worth noting is that reducing ΔT value below 1 m causes a clear and fast increase in value of $\Delta D_{2^{nd}\,trim\,corr.}$

The different values of ΔT, connected with vertical shift, were also tested, but without satisfying results. The results of all calculations which were performed suggest that the *LCF* changes caused by the ship trim can't be accurately determined using *MTC* changes.

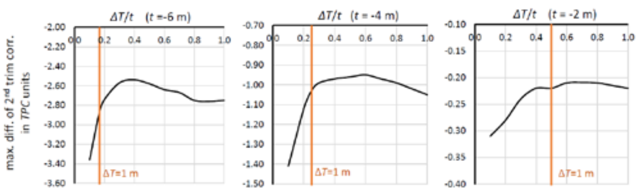

Figure 12. Maximum difference between 2nd trim correction determined using *Bonjean Scale* and calculated using formula (15)

Of course, when analyzing the 2nd trim correction for a specific ship, as in the case of this work, formula (3) can be modified based directly on the results of calculations which were carried out. In Fig. 7 and 8 it is enough to consider the draught at which the graphs change the sign. The modified formula (3) has now the form:

$$\Delta D_{2.2} = 50 \cdot \frac{t^2}{L_{PP}} \cdot \frac{T_{+/-}}{T_M} \cdot \left(MTC_{T_M+0.5m} - MTC_{T_M-0.5m} \right) \qquad (17)$$

where $T_{+/-}$ is the draught at which the graphs change the sign.

Although the modification placed in formula (17) is based on the observation of changes in the graphs in Fig. 7 and 8, it seems reasonable. The ship trim has a greater impact on the waterplane area (size, shape, geometric center) for smaller draughts than for bigger ones. This is related to greater variability of the hull shape in the range of small and medium draughts and can be confirmed by the *LCF* graph (Fig. 13).

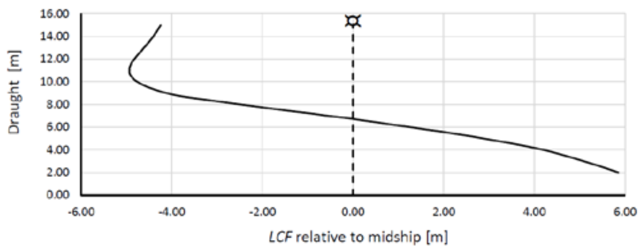

Figure 13. Longitudinal center of flotation (*LCF*) of the bulk carrier *Armia Krajowa*, relative to midship

However, the value of $T_{+/-}$ in formula (17) is not obvious. This is because the individual graphs change the sign at slightly different draught (Fig. 7 and 8). For the ship which is used in this research the calculations were performed for several values of $T_{+/-}$ and the best results were obtained for $T_{+/-}$=6.60 m (Fig. 14 and 15).

Comparing the differences in the ship displacement obtained after using the standard 2nd trim corr. formula (3) and the proposed one (17), it is clearly visible that formula (17) gives better results. Although for $|t| \leq 3m$, the maximum differences practically don't change (Fig. 8 and 15), at bigger values of the trim the improvement if quite significant (Fig. 7 and 14). For trim -6 m, the maximum spread of differences in Fig. 7 is almost 5 *TPC* while in Fig. 14 it is less than 3 *TPC*.

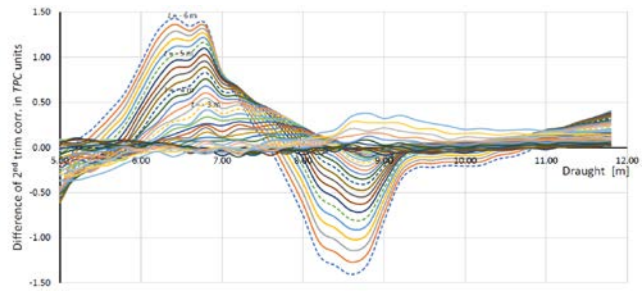

Figure 14. Difference between ship displacement calculated using *Bonjean Scale* and *Draught Survey* procedure with 2nd trim corr. calculated using formula (17) where $T_{+/-}$=6.60 m, for trim from -6 m (aft trim) to 2 m (forward trim) with 0.2 m spacing, presented in *TPC* units

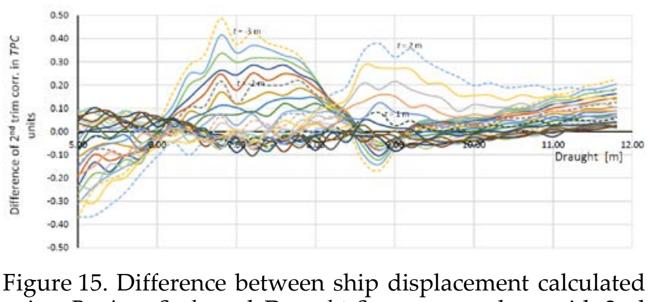

Figure 15. Difference between ship displacement calculated using *Bonjean Scale* and *Draught Survey* procedure with 2nd

trim corr. calculated using formula (17) for $T_{+/-}$=6.66 m and trim from -3 m (aft trim) to 2 m (forward trim) with 0.2 m spacing, presented in *TPC* units

7 CONCLUSIONS

At the beginning, it should be noting that the conclusions given below apply to the ship used in the research. To treat them as general conclusions, similar calculations should be performed for a large group of ships (of various types).

In Section 4, it was shown that the ship volume (displacement) calculated with the use of quite simple formula (9) based on the *Bonjean Scale* placed in the ship documentation gives accurate results. For even keel ship the displacement differences in relation to *Hydrostatic Table* were smaller than 0.1 *TPC*. For trimmed ship differences were bigger and increases with increasing trim, however for 3.00 m stern trim, the maximum difference is smaller than 0.25 *TPC*. It is quite small error since the assumed accuracy of the draughts measurement, during the *Draught Survey* procedure, is ±0.5 cm. However. at this point it should be emphasized that *Armia Krajowa* documentation includes *Bonjean Scale* with data for up to 44 cross-sections. This is a significant and rather the rare number of cross sections applied.

The standard version of 2nd trim correction (3) used in the *Draught Survey* procedure provide good results for the ship with trim not bigger than 3 m. For such trim the value of error caused by 2nd trim correction (Δ_{disp}) should be smaller than 0.5 *TPC* (Fig. 8 and 15). Moreover, for $|t| \le 2m$ the error should be smaller than 0.25 *TPC* and for $|t| \le 1\,m$ the error should be smaller than 0.1 *TPC*. For ship trim bigger than 3 m the error increasing rapidly in accordance with trim (Fig. 6), for most values of the ship mean draught T_M. However, within a small range of T_M the error of 2nd trim correction can be very small and almost independent of the ship trim (Fig. 7, draught between 7.00 and 7.20 m)

The commonly used form of 2nd trim correction (3) uses the difference of *MTC* taken for draughts spread equal to 1 m, independently from the current ship trim value. Using formula (15), where the draughts spread value is assumed equal to the absolute value of current ship trim, does not reduce the calculation error. Moreover, using formula (15) for ΔT <1 m causes an increase in error.

Fig. 7 shows an additional issue regarding the 2nd trim correction and consequently the calculation part of DS procedure. For small draughts the sign of the error (Δ_{disp}) is positive while for bigger draughts is negative. This means that displacement calculation errors for ship before and after loading will add up.

The ship used in this work is a bulk carrier. It is known that the hull of bulk carriers has the quite full form and the shape of the stern and bow shows less variability with respect to draught than for e.g. container or ro-ro ships. This means that differences between displacement calculated for trimmed ship using *Bonjean Scale* and standard *Draught Survey* procedure can be significantly bigger then obtained in the presented study. Obviously, during standard operation of container or ro-ro ships the *Draught Survey* procedure is not needed. Nonetheless, if there was a need to determine the displacement of a trimmed ship, a larger error should be expected when using the standard *Draught Survey* procedure.

Regardless of the analysis presented in the paper, one wonders. Why in the case of ships for which the *Draught Survey* procedure may be necessary for practical use, the tables with accurate values of 2nd trim correction or summed both trim corrections are not included in the documentation. The calculations discussed in the paper can be performed by the shipyard's design office without much trouble. In this study 2nd trim corr. is presented in the graph form (Fig. 10) however it can have the table form as well. Another solution could be, a bit forgotten, Firsov Diagram. Actually, the ship documentations with ready-made trim correction (summed 1st + 2nd) can be found, but values of this correction are calculated using the standard *Draught Survey* procedure, formulas (2) and (3).

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