Weight and buoyancy is the foundation in design: Get it right

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ABSTRACT: Stability and cargo carrying capacity are fundamental in vessel design and are governed by the vertical centre of gravity (VCG), identified through performing the inclining experiment. It is well known that the current method for calculating the VCG following inclining experiments is limited by assuming an unchanged metacentre position when the vessel is heeled and may produce error prone results. This paper will present alternative calculation methods which have been tested together with the *Classical* method on a range of vessels to highlight their accuracy and flexibility. The worst-case result using the *Classical* method will be utilised to highlight the implications such errors may have on stability and cargo carrying capacity performance. The results demonstrate the importance of correct VCG calculation for a safe and optimal vessel design, as even minor errors in the order of millimeters may translate into extensive weights and moments compromising stability and cargo carrying capacity.

1 INTRODUCTION

Modern ships are complex systems and their design comprise of a range of design variables and constraints. However, there are two main aspects that could be considered most critical in ship design, namely the cargo carrying capacity and the level of safety. The cargo carrying capacity is a measure of payload that can safely be carried in excess of the vessels lightweight, while safety is highly linked to the ability of the vessel to remain afloat and upright in any condition of loading including damaged condition. As such, these are closely linked parameters and will clearly affect one another.

Buoyancy and weight are the two key parameters governing both stability and carrying capacity of the vessel due to their well-known interplay in terms of flotation, heeling and righting moments. Buoyancy is solely dependent on the underwater hull shape, and is today easily assessed using modern software tools that replicate the hull shape with great accuracy. The vessel's design lightweight, however, is more difficult to assess in any detail and is only roughly calculated through the design process. It is not until the vessel is close to completion that it can be identified more accurately by performing the classic inclining experiment.

It is a well-known fact that the so called *Classical* method, in which the vertical centre of gravity (VCG) is calculated following inclining experiments, has its limitations on performance in terms of applied heel angle magnitude, applied loading condition and accuracy for certain hull forms. This is due to the assumption made of unchanged metacentre position when the vessel is heeled. In an attempt to ensure the correct application of the *Classical* method, various requirements have been set out in the 2008 IS Code Part B Ch. 8 and Annex I (IMO, 2008).

Recently, as a result of the limiting assumptions in the *Classical* calculation method, more accurate and flexible calculation methods have been proposed. A detailed study on such methods has been presented by Karolius & Vassalos (2018), highlighting possible dangers inherent in the *Classical* method whilst demonstrating due flexibility and higher accuracy through the use of the new methods. In this paper, higher focus will be placed on design implications in terms of stability and cargo carrying capacity.

The test undertaken in the aforementioned study, enabled establishment of an error potential for each method using a purely technical software-simulated inclining experiment. Using the established error potential, a corrected operational VCG could be calculated from actual inclining VCG values, which were evaluated against the loading conditions for each vessel to see if the stability margins had been compromised. Only the two calculation methods showing highest accuracy and flexibility are addressed in the following; namely the *Generalised* method, and the *Polar* method. This paper will in addition utilize the vessel identified in the study as having highest error potential in the operational VCG values to show how this may affect the stability and loading capacity, and highlight the importance in achieving correct VCG value following the inclining experiment for a safe and optimal vessel design.

2 DESIGN IMPLICATIONS

2.1 *Wrongful assumptions in the Classical method*

To assess possible implications on stability and carrying capacity the, the limitations of the *Classical* method need first to be reviewed. The *Classical* method validity is based on the assumption that the position of the metacentre is unchanged when the vessel is heeled, as illustrated in Figure 1.

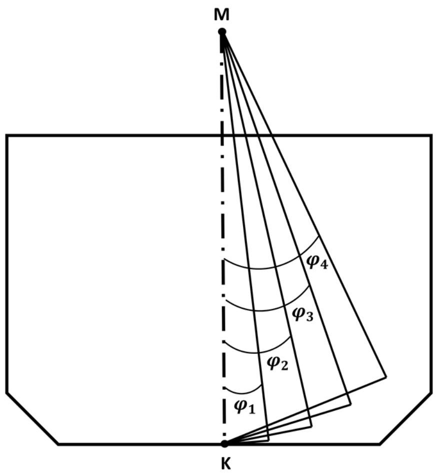

Figure 1. Assumption of unchanged metacentre position.

The position of the metacentre can be represented by the metacentre-radius (BM) given by the well-known relationship (1) between the transverse second-moment of the waterplane area I_{XX} and the vessel displaced volume (∇):

$$BM = \frac{I_{XX}}{\nabla} \quad (1)$$

As the vessel displaced volume is constant during the incline, the change in the metacentre position is proportional to the change in the second moment of the waterplane area and consequently the waterplane area itself. For any heel angle, there will be a change in the waterplane area, which is crucial in obtaining a righting lever arm and subsequent righting moment, as it is directly related to the movement of the buoyancy position. This is highlighted by the fact that only a completely circular hull-shape will have unchanged waterplane area but also unchanged buoyancy position when heeled. A more realistic movement of the metacenter with increased waterplane area is illustrated in Figure 2.

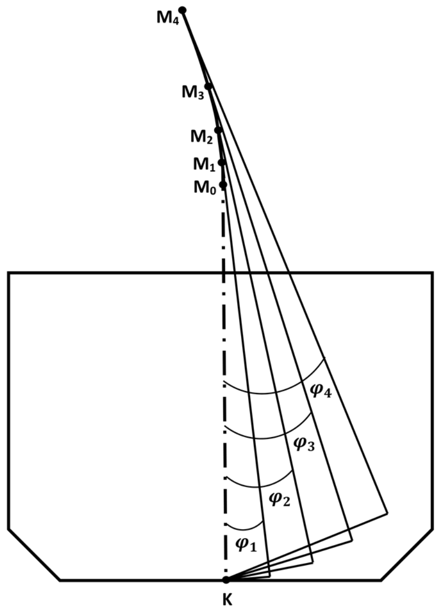

Figure 2. More realistic movement of metacentre position.

The assumption in the *Classical* method, however, relates to smaller heel angles, which in more traditional vessel designs may hold to a satisfactory level. This is also the main reason for the IMO requirements set out in the 2008 IS Code, setting requirements in terms of heel angle magnitude, initial heel angle and loading condition used to ensure a minimal change in waterplane area.

There is further a misconception in the industry that the assumptions hold for completely wall-sided vessels, and this appears to have given rise to the so-called "wall-sided" assumption in relation to the inclining experiment. This is not the case, as even a completely box-shaped vessel will experience change in the waterplane area when heeled and a subsequent movement of the metacenter as is illustrated in Figure 3.

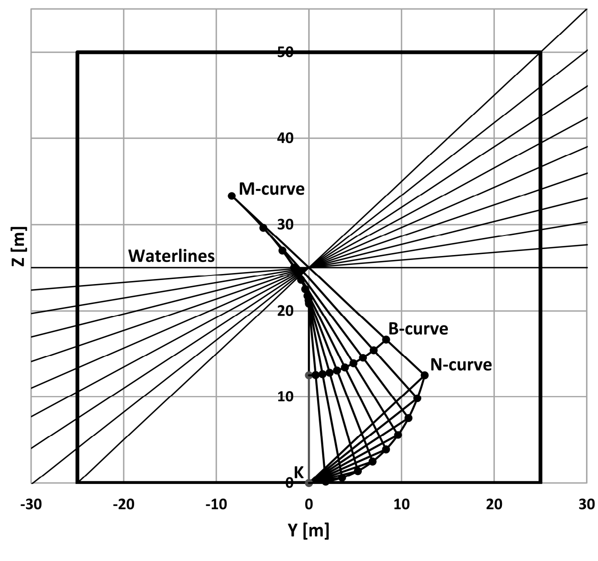

Figure 3. Actual movement of metacentre for box-shaped vessel, 0-45° heel.

The movement of the metacentre shown in Figure 3 is for extensive heel angles ranging from 0° to 45° heel for a box-shaped vessel with length and breadth of 100 and 50 meters respectively. If smaller heel angles, in the range of 0°-4° are considered in line with the maximum allowed heel in accordance with the IMO requirements, a significant smaller movement can be seen, as illustrated in Figure 4 represented by an increase in KM of 0.3% in this specific case.

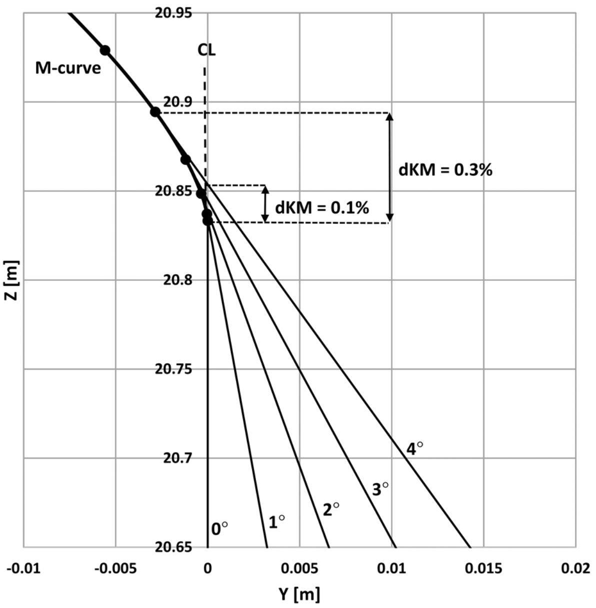

Figure 4. Actual movement for box-shaped vessel, 0°-4° heel.

The main reason for the assumptions in the *Classical* method is to utilise a simplified trigonometric relationship as illustrated in Figure 5. This facilitate a formula for VCG to be derived as shown next.

$$\tan(\varphi) = \frac{G_0G_\varphi}{G_0M_0} \quad (2)$$

$$G_0M_0 = \frac{G_0G_\varphi}{\tan(\varphi)} \quad (3)$$

$$G_0G_\varphi = \frac{w \cdot d}{\Delta} \quad (4)$$

$$GM = G_0M_0 = \frac{w \cdot d}{\Delta \cdot \tan(\varphi)} \quad (5)$$

$$\tan(\varphi) = \frac{r}{L} \quad (6)$$

$$VCG = KM - GM \quad (7)$$

where w = inclining weight, d = movement distance, Δ = displacement, r = pendulum reading, and L = pendulum length. Remaining parameters are explained by Figure 5.

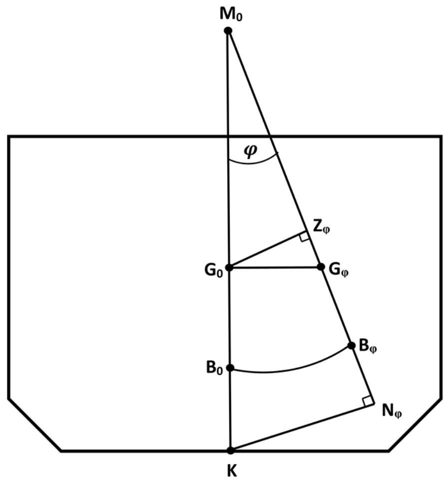

Figure 5. Simplified trigonometric relationship for deriving the *Classical* formula for GM.

The assumption of unchanged waterplane area further enables the use of upright hydrostatics in the calculation for GM for every weight shift. As a simplified trigonometric relationship is used, it is clear that the rise in KM of 0.3% mentioned earlier is not the actual increase inherent in the formula. The increase in question is rather found at the intersection with the centerline, which results in an increase in KM of 0.1%. Based on this, it may be argued that the assumptions may be considered valid for a completely box-shaped vessel and may well be the reason for the emergence of the wall-sided assumption in relation with the inclining experiment.

It is important, however, to note than no vessel is completely box-shaped, nor circular and it is rather a combination of the two, with various design features that may result in much higher change in the waterplane area than should be accepted even for smaller heel angles. This is the main reason for the *Classical* method being subjected to scrutiny and debate. Such design features may include:

- Chine lines and knuckles
- Large fore- and aft flare
- Misc. appendages
- Large change in trim during heel
- Other unconventional hull forms

As the *Classical* calculation method was developed in the late 17th century (Hoste, 1693) when detailed software models were not available, the limiting assumptions makes sense as it enables upright hydrostatics to be utilised. Today, however, the strife is towards higher accuracy and there exists a range of tools for this purpose, making such simplifications and requisite assumptions obsolete.

2.2 *Implications on stability and cargo carrying capacity*

In the aforementioned examples, a clear increase in the KMT is seen as a result of an increase in the waterplane area. In reality the waterplane area may both increase or decrease depending on heel magnitude and which specific design features are emerged or submerged. As a general rule the following is true:

Case 1: Increase in waterplane area:

$$BM_0 < BM_\varphi \quad (7)$$

$$GM_0 < GM_\varphi \quad (8)$$

$$VCG_0 > VCG_\varphi \quad (9)$$

Case 2: Decrease in waterplane area:

$$BM_0 > BM_\varphi \quad (10)$$

$$GM_0 > GM_\varphi \quad (11)$$

$$VCG_0 < VCG_\varphi \quad (12)$$

It is clear that Case 1 above will by using the *Classical* method, overestimate vessel stability, thus producing a lower VCG value than is the actual case, while Case 2 will underestimate the vessel stability leading to a higher VCG than is the actual case. Cases 1 and 2 therefore translates directly into possible implications for stability and cargo carrying capacity respectively. These are explained in the following.

2.2.1 *Stability*

The VCG of a vessel is the parameter of highest importance in assessing intact and damage stability, this being the baseline for any condition of loading. It is also governing in other important aspects such as vessel motion behaviour through its effect on rolling period and hence the new second generation intact stability criteria. The VCG is utilised in most intact and damage stability requirements through enforcing requirements on the GZ righting curve. The GZ curve is represented by (13) and it is clear that any error in VCG will lead to subsequent errors in the GZ-curve, and therefore also incorrect assessment against relevant stability criteria.

$$GZ(\varphi) = KN(\varphi) - VCG \cdot \sin(\varphi) \quad (13)$$

From the formula above, it is clear that over- and underestimation of the VCG will result in under- and overestimation in the GZ-curve respectively.

For most vessels, it is the damage stability requirements that is governing and limiting the operational envelope. Using the probabilistic damage stability and the attained index A as a basis, it is possible to gauge the impact using (14). This approach is utilised and presented in section 7.3 to highlight implications in stability.

$$Risk = 1 - A \quad (14)$$

2.2.2 *Cargo carrying capacity*

A vessel's cargo carrying capacity is limited by volumetric constraints, but also by its safety requirements, especially those related to intact and damage stability. To best illustrate this, a traditional VCG stability limit curve can be used as shown in Figure 6.

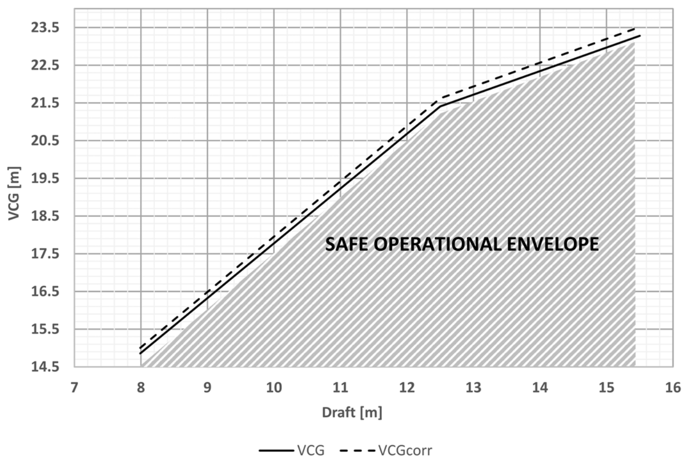

Figure 6. Underestimation of stability limit curve and subsequent reduction in operational envelope.

The limit curve serves as the safe operational envelope for a vessel and represents the operational conditions for which the relevant intact and damage stability requirements are fulfilled. The black curve represents the limit curve prepared using the lightweight VCG, as obtained from the *Classical* method. For the sake of argument, an error of 1% overestimation in VCG is assumed. The actual curve is then represented by the stapled line as the overestimation of the lightweight VCG has resulted in a more stringent operational limit.

It is clear that more restrictions will be imposed to the operational envelope if the VCG is overestimated. Another way to illustrate the implications in cargo carrying capacity is to translate the overestimated VCG into potential reduction in cargo carrying capacity. This is the cargo that could have been carried if the VCG were calculated correctly. As most vessels have a maximum summer draught decided by load-line and strength requirements, the additional draught would have to be maintained whilst ballast-water with a lower VCG can be exchanged by additional cargo with a higher VCG. This approach is utilised and presented in section 7.4 to highlight implications in cargo carrying capacity.

3 ASSESSMENT OF CALCULATION METHODS

The study assessing the various calculation methods comprises two parts. Firstly, identifying the potential errors inherent in each method. This is achieved using a purely technical, software-simulated inclining experiment using a stability model with known lightweight parameters. Each calculation method is then used in an attempt to replicate the actual VCG values, given as known input parameters to the software. An error potential is then developed using the percentage difference in actual and calculated VCG values using (14). The various methods are applied for 2, 4 and 10 degrees of maximum inclining heel angles.

$$Error[\%] = \frac{VCG_{actual} - VCG_{calculated}}{VCG_{actual}} \cdot 100\% \qquad (14)$$

Secondly, by calculating the error potential using an identical floating position and heel magnitude as was used in actual inclining experiments for the particular test vessels as approved by the administration, the ensuing error is assumed to be present in the operational VCG values of the test vessels. The operational VCG values for each test vessel can therefore be corrected for either over- or underestimation using the error potential and to assess whether the vessels stability or loading capacity are affected.

4 UNCERTAINTY AND ERRORS

The inclining experiment is subject to a range of sources of uncertainties and errors originating from external influences such as wind, waves, current and human measurement errors. This paper focuses only on the error originating from the choice of calculation method. Other sources of uncertainty and errors have been reviewed and discussed in many publications, such as Shakshober & Montgomery (1967) and Woodward et al. (2016).

For more detailed information on the range of uncertainties related to the inclining experiment, the above mentioned publications are recommended but in order to highlight the most common sources of uncertainty, Figure 7 has been borrowed from Woodward et al. (2016). The figure shows the various sources of component uncertainty contribution in the vertical centre of gravity for various inclining experiment parameters for five case-study vessels. The figure clearly indicates that the highest contribution is originating from the heel angle and draught, in terms of uncertainties related to pendula and draught marks.

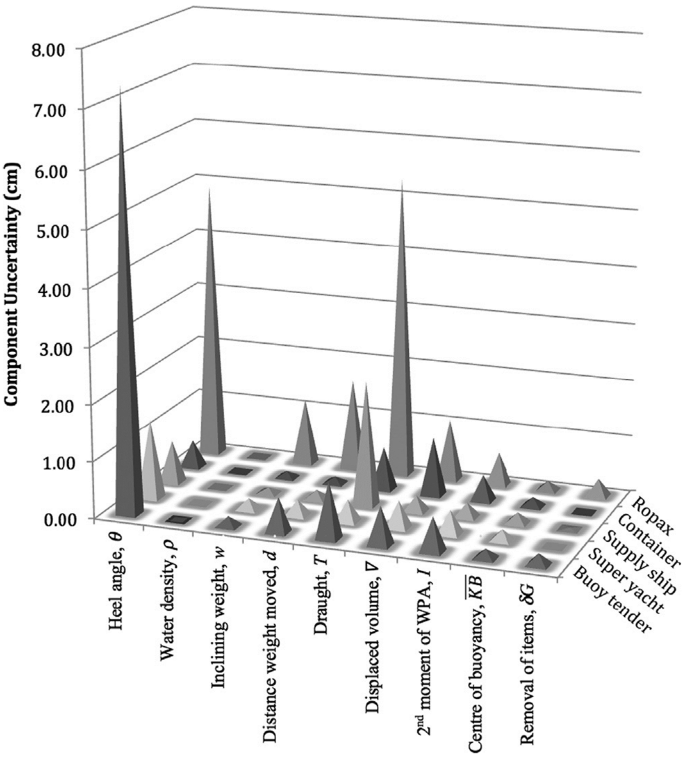

Figure 7. Component uncertainty contribution for various inclining experiment parameters. Reprinted by permission from Woodward (2016, fig. 2).

5 CALCULATION METHODS

The *Classical* method has already been reviewed in section 2.1. In this section, the alternative methods will be covered. Among these, there were two methods that showed highest accuracy and flexibility from the aforementioned study; namely the *Generalised* and the *Polar* method, both described in the following.

5.1 *The Generalised method*

The *Generalised* method was initially proposed by R.J. Dunworth (2013) and further expanded by Dunworth (2014, 2015) and Smith, Dunworth & Helmore (2016). The method utilizes the fact that in equilibrium position for each weight shift, the vessel's righting arm GZ and heeling arm HZ must be equal. Using the trigonometric relationships, as illustrated in Figure 8, the following can be derived:

$$HZ = KN - VCG \cdot \sin(\varphi) - TCG \cdot \cos(\varphi) \qquad (15)$$

$$VCG \cdot \sin(\varphi) = KN - HZ - TCG \cdot \cos(\varphi) \qquad (16)$$

$$HZ = \frac{w \cdot d \cdot \cos(\varphi)}{\Delta} \qquad (17)$$

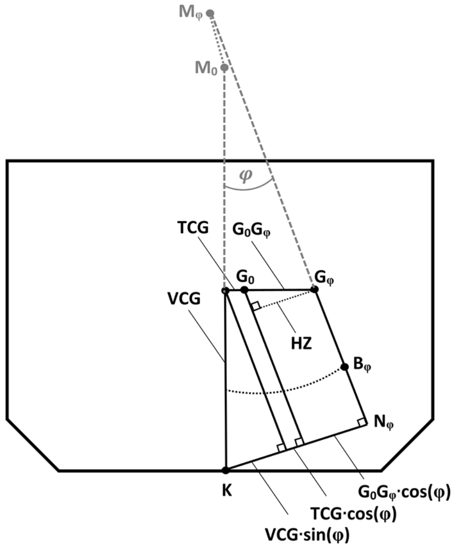

Figure 8. Main parameters for the *Generalised* method. Adopted from Dunworth (2014).

From the above, it is apparent that this method does not make any reference to the metacentre in the calculations and should, therefore, not be influenced by any change in the waterplane area during the weight shifts, as is the case for the *Classical* method. To this end, actual KN values are needed from a stability software model, corresponding to equilibrium floating position for each weight shift. The heeling angle is determined from pendulum deflection readings similar to the *Classical* method.

For each shift VCG · sin(φ) is calculated using equation (16) and plotted against sin(φ). The final value of VCG can be directly calculated as the regression slope using a least squares fit similar to the *Classical* method. Dunworth (2013) further suggests an alternative method for calculating the TCG offset, by plotting the calculated HZ values corresponding to each weight shift against the heeling angle. The TCG offset for the whole system comprising ship and inclining weights are then found at the y-axis intercept, i.e. HZ for φ = 0. The curve fitting is suggested to be obtained using a 3rd order polynomial fit.

5.2 *The Polar method*

The *Polar* method was presented in the study by Karolius & Vassalos (2018), and is derived utilising the line PL illustrated in Figure 9. This line can be represented in polar coordinates using (18), and if corrected for actual KN and HZ values for each weight shift using (19), the line will pass through the point (x, y) for any arbitrary weight shift from the neutral position, which results in (20). Knowing that the x-coordinate is equal to TCG, and the y-coordinate equal to VCG, equation (21) is obtained.

$$z = x \cdot \cos(\varphi) + y \cdot \sin(\varphi) \quad (18)$$

$$z = KN - HZ \quad (19)$$

$$KN - HZ = x \cdot \cos(\varphi) + y \cdot \sin(\varphi) \quad (20)$$

$$KN - HZ = VCG \cdot \cos(\varphi) + TCG \cdot \sin(\varphi) \quad (21)$$

This method takes advantage of the fact that both VCG and TCG need to be located on the PL line in the initial condition and to be kept constant in this position for each individual weight shift, i.e. the initial VCG_0 and TCG_0 are kept constant on this line, while the overall system TCG is shifted a distance G_0G_i for each shift *i* as represented by (22) and (23).

$$TCG_i = TCG_0 \quad (22)$$

$$VCG_i = VCG_0 \quad (23)$$

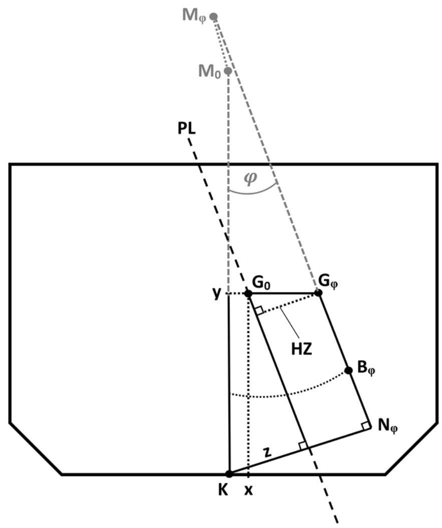

Figure 9. Main parameters from the *Polar* method.

There are, as a result, two equations to derive the two unknown parameters and by using (21) and following some deduction, (22) results in a solution for VCG given by (24), and (23) in a solution for TCG given by (25) in their most general form:

$$VCG = \frac{(KN_i - HZ_i)\cdot\cos(\varphi_0) - (KN_0 - HZ_0)\cdot\cos(\varphi_i)}{\cos(\varphi_0)\cdot\sin(\varphi_i) - \sin(\varphi_0)\cdot\cos(\varphi_i)} \quad (24)$$

$$TCG = \frac{(KN_i - HZ_i)\cdot\sin(\varphi_0) - (KN_0 - HZ_0)\cdot\sin(\varphi_i)}{\cos(\varphi_i)\cdot\sin(\varphi_0) - sin(\varphi_i)\cdot cos(\varphi_0)} \quad (25)$$

The equations can further be simplified using the trigonometric relations in (26) and (27) and knowing that the heeling arm resulting from weight movement in the neutral position HZ_0 needs to be zero, this results in (28) and (29).

$$\cos(\varphi_0)\cdot\sin(\varphi_i)-\sin(\varphi_0)\cdot\cos(\varphi_i)=\sin(\varphi_i-\varphi_0) \quad (26)$$

$$\cos(\varphi_i)\cdot\sin(\varphi_0)-sin(\varphi_i)\cdot cos(\varphi_0)=\sin(\varphi_0-\varphi_i) \quad (27)$$

$$VCG=\frac{(KN_i-HZ_i)\cdot\cos(\varphi_0)-KN_0\cdot\cos(\varphi_i)}{\sin(\varphi_i-\varphi_0)} \quad (28)$$

$$TCG=\frac{(KN_i-HZ_i)\cdot\sin(\varphi_0)-KN_0\cdot\sin(\varphi_i)}{\sin(\varphi_0-\varphi_i)} \quad (29)$$

The *Polar* method can in theory be used to calculate VCG directly for any arbitrary shift from the neutral position, but to account for other sources of error and uncertainty as was discussed in Section 4, it is recommended to utilize a least squares linear regression also for the *Polar* method by plotting the denominator against the numerator.

6 TEST VESSELS

The test vessels used in the study comprise 9 vessels of various type, size and hull form in an attempt to account for the ship specific problematic design features, such as knuckles, large flare angles, sharp chine lines. More conventional wall-sided hull forms have been included as well for comparison. The vessels main particulars are presented in table 1.

Table 1. Test vessel particulars

Vessel type	L_{BP} [m]	B [m]	D [m]	C_B [m]
Fishing vessel	40.20	12.00	7.50	0.73
Yacht	36.60	7.70	4.20	0.54
RoPax	195.30	25.80	14.80	0.79
Bulk carrier	223.50	32.30	20.20	0.92
Passenger vessel	320.20	41.40	11.60	0.74
Naval I	54.10	10.60	5.00	0.65
Naval II	71.00	12.00	6.20	0.58
Container vessel	320.00	48.20	27.20	0.76
Supply vessel	76.80	19.50	7.75	0.69

Despite covering the problematic design features, the chosen designs are still fairly conventional and it is clear that much larger errors would be evident for even more unusual hull shapes, especially for vessels under 24 m in length or of higher novelty such as high-speed or leisure craft. Line plans of the test vessels can be seen in Figure 10.

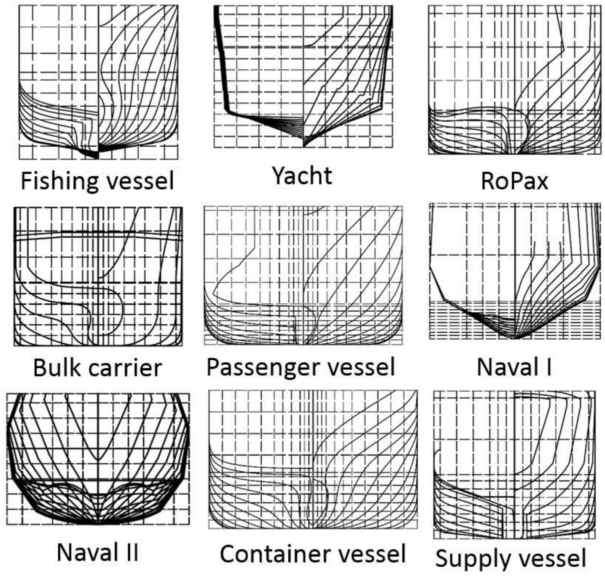

Figure 10. Lines plan of test vessels.

7 RESULTS

In the following section, only a summary of the results obtained in the study is presented to highlight the errors obtained. For more comprehensive result, including results for various initial heel angles, reference is made to Karolius & Vassalos (2018). In order to compare the methods against each other, the results from the software simulated inclining experiment are represented by the absolute value of the error potentials, irrespectively of over-, or underestimation. The errors have then been used to correct the operational VCG values for the vessels and are presented in section 7.2. Finally, sections 7.3 and 7.4 illustrates how the worst case may translate to stability and capacity implications.

7.1 *Software simulated inclining experiment*

In the following, results obtained for each method are presented together for comparison. In the presented result, initial heel of 0 degrees was used, i.e. vessel upright in neutral position. From Figure 11, it is clear that all methods produce accurate results, with the highest error below 0.5%, obtained by the *Classical* method for the Naval II vessel. In Figure 12, maximum heel angle of 4 degrees is presented.

The results still show good accuracy for all methods but the error using the *Classical* method is now increased to 1.5% for the Naval II vessel. In Figure 13, maximum heel angle of 10 degrees is presented. As expected, the results show much lower accuracy for the *Classical* method, with a maximum error above 6% for the Naval II vessel. The other methods still show high accuracy, with only an error of below 0.02%.

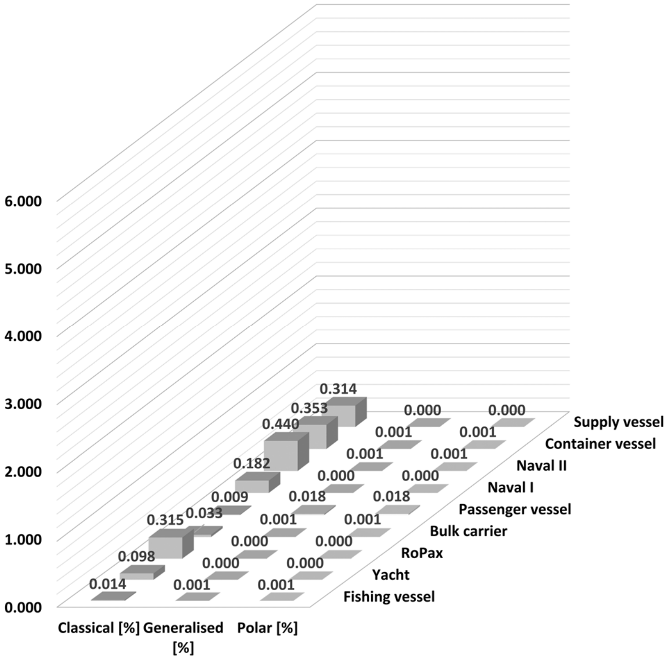

Figure 11. Percentage error for VCG, 2 degrees maximum heel angle and 0 degrees initial heel angle.

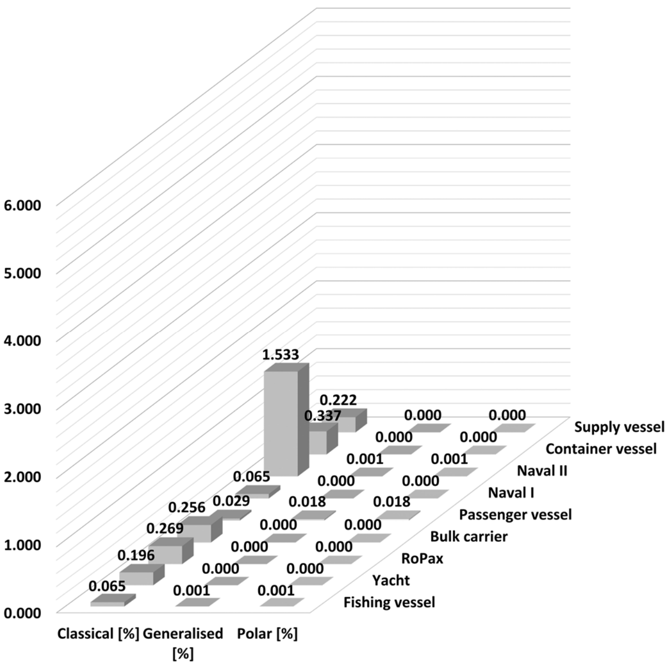

Figure 12. Percentage error for VCG, 4 degrees maximum heel angle and 0 degrees initial heel angle.

To summarize, Figure 14 presents the error potential averaged over all vessel types for all methods for the various inclining heel angles. It is clearly shown that the *Classical* method is highly dependent on the inclining heel angles compared to the other methods, and produces results with increasing errors.

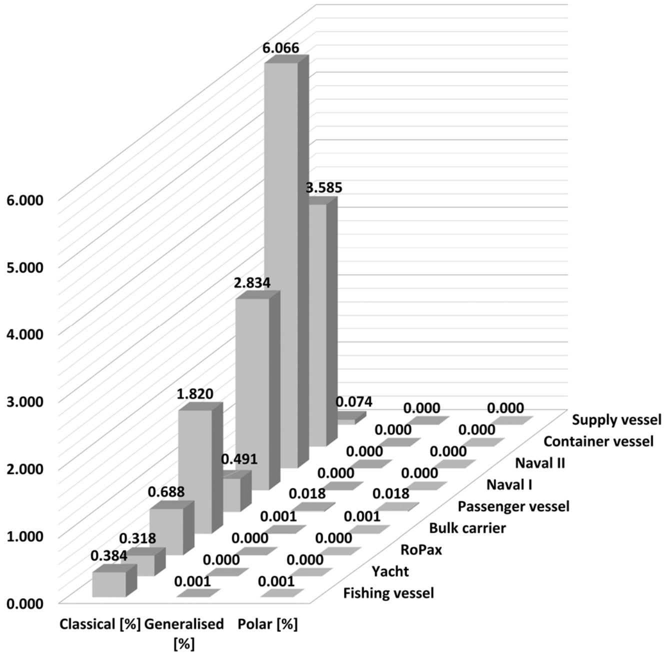

Figure 13. Percentage error for VCG, 10 degrees maximum heel angle and 0 degrees initial heel angle.

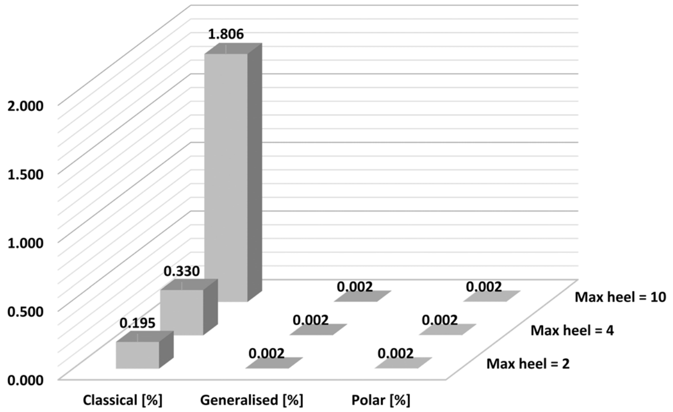

Figure 14. Error potential averaged over vessel types for various heel angles and methods.

7.2 *Actual inclining experiment corrections*

Corrected operational VCG values are presented in Table 2. It is clear that there are potential errors in the operational VCG values as a result of using the *Classical* method. The highest error is obtained for the RoPax, Naval II and Container vessel, with 41, 22 and 61 mm errors respectively. The VCG of the Naval II vessel is overestimated, while the VCG for the RoPax and Container vessels are underestimated. As the container vessel shows the highest error, this has been used for illustrating possible design implications.

Table 2. Corrected VCG values obtained using error potentials for the *Classical* method.

Vessel type	VCG	Correction	VCGcorr
	[m]	[mm]	[m]
Fishing vessel	5.753	0.373	5.754
Yacht	3.747	4.207	3.752
RoPax	13.171	41.478	13.213
Bulk carrier	11.632	2.789	11.634
Passenger vessel	22.221	-3.084	22.218
Naval I	4.500	8.605	4.509
Naval II	4.934	-21.705	4.912
Container vessel	17.228	60.813	17.288
Supply vessel	7.592	7.897	7.600

7.3 *Error implication on stability*

The container vessel in question should comply with the probabilistic damage stability requirements in accordance with SOLAS Reg. II-1/7-8 (IMO, 2009), and for the sake of illustrating possible implications on stability, the attained index A for the operational VCG and the corrected VCG have been calculated. Knowing that 1-A can be regarded as a representation of the ensuing risk, this allows obtaining a measure of false safety inherent in the vessel as a result of the inaccurate VCG calculated using the *Classical* method as is seen in Table 3.

Table 3. Underestimated VCG translated to overestimated probabilistic damage stability performance, i.e. false safety.

Lightweight case	A	Risk = 1-A	Capsize cases
VCG	0.711	0.289	896
VCG_{corr}	0.702	0.298	933
Difference [%]	1.28	3.02	3.96

It is seen that an error in safety estimation of 3% is seen due to the error in VCG. The table further presents the difference in number of capsize cases and it is seen that the vessel actually has 37 additional capsize cases not accounted for due to the error in VCG.

7.4 *Error implication on carrying capacity*

Despite having an underestimated VCG as presented in the former sections, the Container vessel will be utilised in order to examine what the error of 61 mm in lightship VCG yields in terms of lost cargo carrying capacity if, for the sake of argument, this were an overestimated error. As highlighted in section 2.2.2, a vessel draught is often restricted by its maximum summer draught governed by load-line-, and strength requirements. As such, the draught and subsequent displacement needs to be maintained, while ballast-water can be replaced with cargo until the maximum permissible VCG is achieved.

For simplicity, the ballast water is subtracted from the global ballast VCG, while the additional cargo is added to the global container load VCG. The added cargo and reduced ballast is presented in table 4. This difference, if considering an average weight of 12 tonnes per TEU, corresponds to over 11 TEU's.

Table 4. Overestimated VCG translated to underestimated cargo carrying capacity, maintained draught.

Lightweight case	Cargo	BW	Draught
	[t]	[t]	[m]
VCG	103716	9530.6	15.25
VCG_{corr}	103851	9395.6	15.25
Difference	135	135	0.00

If the vessel had available margins in terms of draught it may be possible to keep the ballast whilst adding cargo until the maximum permissible VCG is achieved. This results in a quite extensive loss in cargo carrying capacity as is seen in table 5. Again, this difference, if considering an average weight of 12 tonnes per TEU, corresponds to over 56 TEU's.

Table 5. Overestimated VCG translated to underestimated cargo carrying capacity, increased draught.

Lightweight case	Cargo	BW	Draught
	[t]	[t]	[m]
VCG	103716	9530.6	15.25
VCG_{corr}	104399	9530.6	15.30
Difference	683	0	0.05

8 CONCLUDING REMARKS

As can be seen in the results from the software simulated inclining experiment, the *Classical* method is highly dependent on heel angle magnitude and may produce unacceptable errors that could affect important design parameters such as cargo carrying capacity and stability. This is highlighted by the corrected VCG values presented in the actual inclining experiment corrections seen in table 2. It is important to highlight that all test vessels have been approved by class, and that IMO requirements have been adhered to. If for some reason the requirements in terms of heel magnitude, initial heel angle and loading condition were not followed, significant higher error would be expected. This also applies to the vessel designs. There exist numerous and more unconventional designs that would produce increasingly higher errors.

The additional measures imposed by IMO are unnecessary when applying the alternative methods, as they do not make reference to the metacentre in the equations. They produce very accurate results for any floating position, in terms of draught, heel magnitude and initial heel as they utilise actual KN values corresponding to each floating position. This reduces the possibility of making mistakes and they can therefore be considered to be more reliable and flexible than the *Classical* method.

The results further highlight the importance of achieving correct VCG value following the inclining experiment for a safe and optimal vessel design, as even minor errors in the order of millimeters may translate into extensive weights and moments compromising both stability/safety and cargo carrying capacity. The most common argument for maintaining the *Classical* method is that the errors are small and insignificant in comparison with the random errors mentioned in section 4, but the validity of this argument can be questioned.

As designers, it is our responsible to reduce errors that may compromise or undermine safety to the lowest possible degree, especially when the means to do so are available. Considering the results from this study, the industry should be more critical when applying the *Classical* method and it may even be time to replace it with better and more flexible calculation methods. It is at least important for the industry to know that there are other more reliable alternatives to the *Classical* method and should be accounted for in the regulations and guidelines in use today.

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