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Comparison Between the Classical Method of Inclining Experiment with the Recent Alternative Methods

Abstract

The classical method of inclining experiments has been used to determine the position of the ship's vertical center of gravity for many years. The method contains some basic assumptions, which is why the accuracy of the method has been debated in the last few years. Modern ships often have chines, or pronounced flare at fore and aft extremities, that can lead to a significant change in the waterline. The position of the metacenter changes on these ships as they incline. Therefore, the calculation of the ship's center of gravity by the classical method may be inaccurate.
In this paper, three different methods that are not based on the assumption of an unchanged metacenter are examined. Using a graphical, polar, and general method, the position of the ship's center of gravity system can be determined for any ship without determining the position of the metacenter. The three methods mentioned in this paper were observed and tested on four different ships. In addition, the results of the classical method are compared with the results obtained from recently developed methods.

Keywords: stability, inclining experiment

1. Introduction

In order to determine a ship's stability attitude, the inclining experiment is performed on a vessel to obtain the lightship weight and the coordinates of the centre of gravity. The test is applied to new constructions, and to ships that have gone through a major redesign. Inclining experiments are specified for all ships by the IMO and other international associations and mandatory as of 2009 (SOLAS Reg. II-1/5 (IMO, 2009)) for each merchant ship over 24 meters in length and for all passenger ships [1].

The procedure for determining the lightship condition centre of gravity, defined as the centre of mass of the vessel and its cargo, dates to a couple of hundred years ago. The need for such a procedure stems from the inherent errors in measured mass and position of individual items, while performing the summation of moments applied by individual loads.

The classical method has been in use almost as a dogma that was accepted by naval architects without really being questioned or doubted. Probably the reason behind it was its convenience, despite the well-known fact that the current method for calculating a ship's vertical centre of gravity following inclining experiments has its limitations in magnitude of applied heel angle and reliability accomplished for certain hull-forms (chines, knuckles, deadrise). The change in the metacentre with constant displaced volume during the incline is proportional to the change in the second moment of the waterplane area. Furthermore, the change in the waterplane area can be disregarded especially for wall-sided vessels due to equal immersed and submerged wedges of buoyancy volume thus, the so-called wall-sided assumption. However, the wall sided assumption has nothing to do with a constant waterplane area nor metacenter position.

Quite recently, three novel methods were proposed. The first method was originally proposed in a paper titled Up Against the Wall [2], where the need for an alternate method was discussed. A more thorough explanation of Dunworth's proposed method was later published as Back Against the Wall [3]. Using a preliminary experimental model validation, Beyond the Wall was presented in [4]. Note that all the papers have the "wall" appellation. As the titles suggest, an emphasis is given to challenge such a norm. It has its meaning considering that the Classical method uses the wall-sided assumption due to the hypothesis of unchanged metacentre position when the vessel is heeled. "Up against the wall" was an attempt to challenge the classical method, even more so in "Back Against the Wall", and finally a confirmation was published with "Beyond the Wall", containing numerical and model validation. The last paper was by Smith et al. [5] set out to confirm the validity of the newly-proposed method through the work-up of results to explore the potential issues of implementation and broader utility in future application.

When initial results turn out to be promising, the resources that might have been consumed by a large initial study are often better directed toward follow-up studies that further develop the idea, such as the work of Kanifolskyi and Konotopets [6]. Their method is deemed as Graphical method.

Also, an independent validation of promising initial results is essential. For the more common situation, where the idea fortunately turns out to be on-target, a validation and novel propositions may be even more useful. Therefore, the work from Karolius, and Vassalos "Tearing down the wall" [7] resulted with the method called Polar method. In this case, the "wall" is again highlighting the need to tear down the wall-sided assumption implicit in the Classical method.

When the idea is a fundamental breakthrough, this will usually be apparent from a relatively small study. However, there was some follow up work (Another blow on the torn wall) from Ozsayan and Taylan [8] where all three methods were tested along with uncertainty analysis.

A much larger sample size does not produce much additional value. Therefore, the aim of this paper is to validate the methods on four river vessels which will be explained in the following sections.

2. Inclining experiment procedure

In order to achieve accuracy, the inclining experiment is performed free of mooring restraints, in calm weather and still water condition. Basically, by moving weights transversely as illustrated in Figure 1., the metacentric height *GM* is obtained. By using known hydrostatic curves and by reading the draft, the displacement of a vessel Δ can be readily determined. The *GM* magnitude, which dominates stability, can be estimated from the design, but the inclining test gives a more reliable value of this parameter [9].

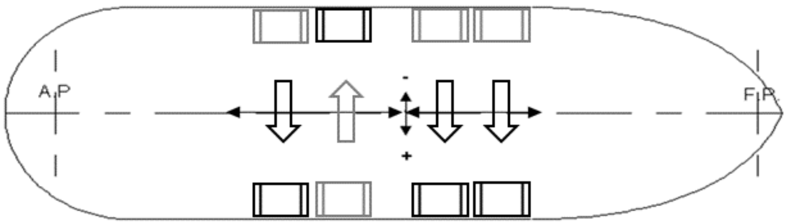

Figure 1. Sequence of weight shift

Each weight shift sequence is noted as in Table 1., where the heel values are measured typically by pendulum, but also by U-tubes or inclinometer.

Table 1. Inclining experiment calculation for each weight shift

Movement (n)	Mass Group	Direction moved P -> S or S->P	Incline Mass (t) (w)	Distance moved (m) (d)	Heeling Moment (m) = (w) × (d)	Pendulum reading m (+,-)	Pendulum deflection (m) (x)	$\frac{w \times d}{x} = x_z$	Running Average $\frac{1}{n}\sum_{i=1}^{n} x_z$	Running Deviation	Deviation from Final Average
x											
x+1											
						Final sum of $\frac{w \times d}{x}$					
						Final average $\frac{w \times d}{x}$					

The heeling angle for each load movement and for each pendulum separately is determined by the expression:

$$tg\delta\theta_i = \frac{s_i}{\lambda} \tag{1}$$

where the paramteres are:
s_i - actual deflection, mm
λ - excess length of wire from the hanger to the upper edge of the measuring rod, mm

3. Inclining experiments methods

3.1. Classical method

The individual metacentric height is determined by the expression:

$$GM_i = \frac{p_i \times e_i}{\Delta \times g \times tan\delta\theta_{si}} \tag{2}$$

where the values are as follows:
p_i - weight of test load, kN
e_i - load transfer arm, m
Δ - displacement of the vessel, t
g - acceleration of gravitational force, m / s^2
$tan\delta\theta_{si}$ - mean tangent of the angle of inclination for individual measurement, °.

The position of the center of gravity of the vessel is calculated according to the formula:

$$VCG = KM - GM \tag{3}$$

where:
$VCG = KG$ - vertical center of gravity of the system, m
KM – vertical position of the metacentre, m
GM - metacentric height, m

When certain tanks have to be left partially filled, it is necessary to correct the height of the center of gravity of the system due to the influence of the free surfaces of liquids, using the expression:

$$VCG = KM - GM - FSC \tag{4}$$

in which:
FSC - free surfaces correction, m

Some individual measurements may prove inaccurate when performing the experiment, and therefore may not be taken into account when processing the experimental data. In order to detect such inaccurate measurements, it is useful to create a control graph, in which the values of the heeling moment are plotted against *tan* ϕ obtained from the pendula deflection relationship (1). An example of performing a control chart is shown in Figure 2 for portside and starboard respectively.

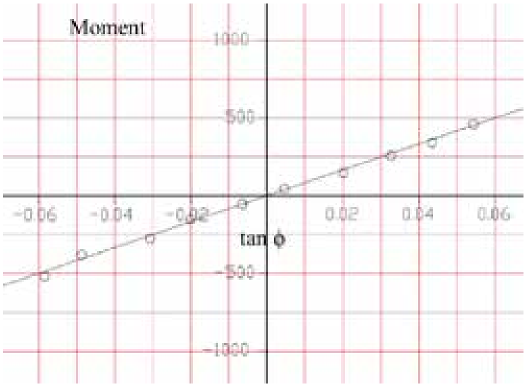

Figure 2. Moment versus tan ϕ diagram

The *GM* value can be calculated as the regression slope using a least square fit:

$$GM = \frac{1}{\Delta R_{slope}} \tag{5}$$

The Classical method is dependent on the heel angle magnitude and doesn't depend on the value of the transversal center of gravity (*TCG*) but instead it depends on the direction and extent of the metacentre shift.

Even though the three new methods specifically target the wall-sided assumption in the classical method, there is no assumption of wall sidedness in the method itself. The wall sided assumption comes from the simplified formula for calculating *GZ* for wall sided vessels. A form, in which *GZ* can be analytically derived, such as a box shaped pontoon for example, also has a change in the waterplane area when heeled which leads to subsequent change in metacentre position.

The 2008 IS Code provides, both mandatory requirements and recommended provisions relating to intact stability in which the change in metacenter position is shown to be small within the 4-degree heel limit for wall sided vessels. As mentioned in [7] a "possible problem" stems from the fact that specialized hull-forms might have excessive changes in the waterplane when heeled due to the chines, flares, and it is not an indictment of the wall-sidedness of a vessel, therefore it should be allowed even within the IMO constraints.

3.2. Generalised method [2,3,4,5]

After shifting the weights, the vessel returns to equilibrium, which means that for each moment of heeling there is a righting moment equal to the amount of heeling moment, and this equality is shown in (6).

$$\Delta \times HZ = B_M GZ \tag{6}$$

where the displacement is equal to the buoyancy force, so the equation reduces to:

$$HZ = GZ \tag{7}$$

That is, the heeling moment arm is equal to the righting moment arm, the tilt moment is:

$$M_{ng} = w \times d \times cos\varphi \tag{8}$$

when the heeling moment is divided by the displacement, the heeling moment arm is obtained:

$$HZ = \frac{w \times d \times cos\varphi}{\Delta} \tag{9}$$

Displacement, draft and initial inclination of the vessel are determined from the hydrostatic curves, after the draft has been read. For each weight movement, the slope change is determined by the excess and summed with the initial slope to obtain the actual slope. The average value of the angle of inclination is used for the calculation, for all cases of measuring the angle of inclination. Each time the weight is moved, the vessel can be tested for exact displacement, trim and heel, and the *KN* values can be determined using a specific software package or hydrostatic data. *KN* refers to the cross curves of stability, and it is defined as the distance from the keel point to the point of intersection of the two directions. The first direction is parallel to the waterline and passes through the keel point, the second direction passes through the center of gravity and is perpendicular to the first direction as seen on Figure 3 [3].

Thereafter, the arm of the upright moment and the inclination can be determined using the equations:

$$GZ = KN - VCG_1 sin\varphi - TCG_1 cos\varphi \tag{10}$$

$$HZ = KN - VCG_1 sin\varphi - TCG_1 cos\varphi \tag{11}$$

When $\varphi = 0$, then $sin\ \varphi = 0$ and $cos\ \varphi = 1$, we have:

$$TCG_1 = KN_0 - HZ_0 \tag{12}$$

Duckworth proposed plotting the *HZ* values as a third order polynomial where intercept point of y-axis for $\phi = 0$ corresponds to HZ_0.

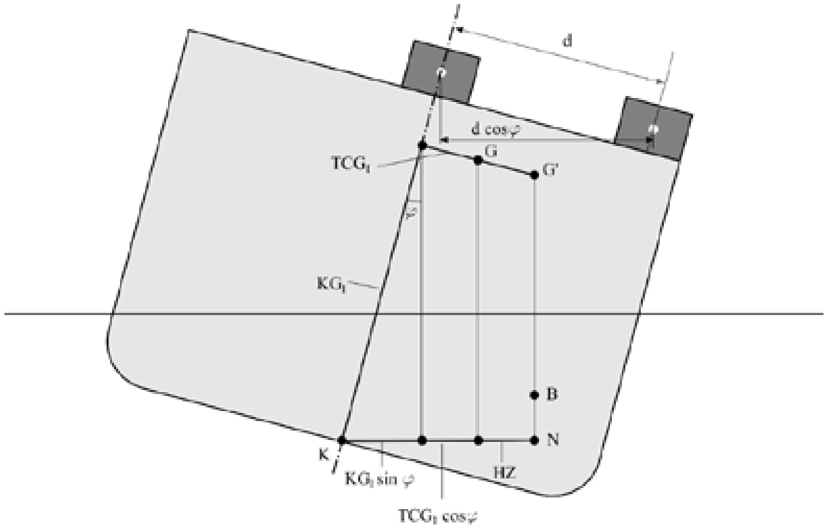

Figure 3. Overview of the generalized method as in [5]

$$VCG_1 sin\varphi = KN - HZ - TCG_1 \times cos\varphi \tag{13}$$

The proposed method does not refer to the metacenter and has no associated errors, and can be used for any shape and form and up to any angle of inclination.

3.3. Graphical method [6]

The graphical method calculates the height of the center of gravity directly through the *KN* and the heeling moment of the vessel. *KN* is determined with the help of hydrostatic data or using a software package. According to the proposed method five steps are shown in the Figure 4.

1. Draw a *KN* for the deflection of an angle equal to the slope of the vessel or of the slope of the waterline, given that the cross section of the vessel is shown vertically,
2. Draw a vertical line on the *KN*,
3. Using equation (9) calculate the value of *HZ*.
4. In the fourth step, it is necessary to draw *HZ* on the drawing parallel to *KN* and place it so that it connects the symmetrical axis with the perpendicular to *KN*.

5. The *VCG*, the intersection of the symmetrical axis and *HZ* is the position of the center of gravity in height.

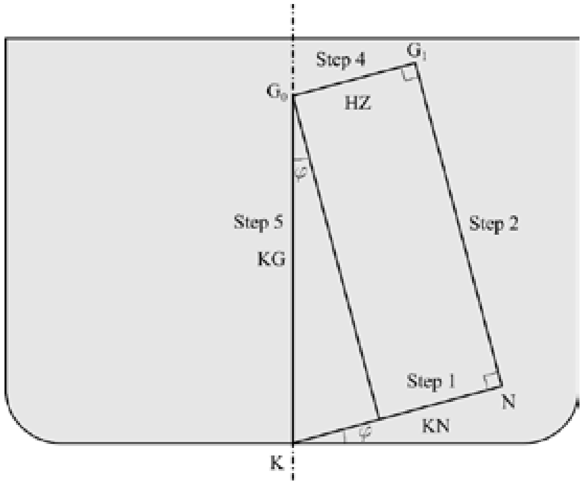

Figure 4. Graphical method display as in [6]

The final value of *KG* is obtained as the average value of all values obtained by the inclining experiment and is calculated by the equation:

$$VCG = \frac{\sum_{i=1}^{n} VCG_i}{n} \tag{14}$$

Also KG can be determined within the graphical method by calculation through trigonometric relations, when we know KN and the angle of inclination φ, KG is then determined using the equation:

$$VCG = \frac{KN - HZ}{\sin \varphi} \tag{15}$$

$$VCG sin\varphi = KN - HZ \tag{16}$$

By comparing equation (16) of the graphic method with equation (13) of the general method, we can conclude that these are similar methods, but the graphical method does not take into account the position of the center of gravity over the breadth of the vessel. Therefore, the graphical method is accurate only for those vessels where the initial angle of inclination of the vessel is half a degree. For those vessels with a higher initial angle of inclination errors occur when calculating the value of the vertical center of gravity.

3.4. Polar method [7]

The polar method was the last of the three proposed methods. The method considers a line parallel to the metacentric radius, shifted up to the distance of heeling lever *HZ*, and this is shown in polar coordinates. The method is based on the fact that the position of the vertical and transverse center of gravity is in that direction in the initial position and remains constant in that position for each individual movement of weights during the experiment. That is, the starting position of the center of gravity lies constantly on the line while the total position of the center of gravity changes by the distance G_0G_i for each weight movement. The method is shown in Figure 5.

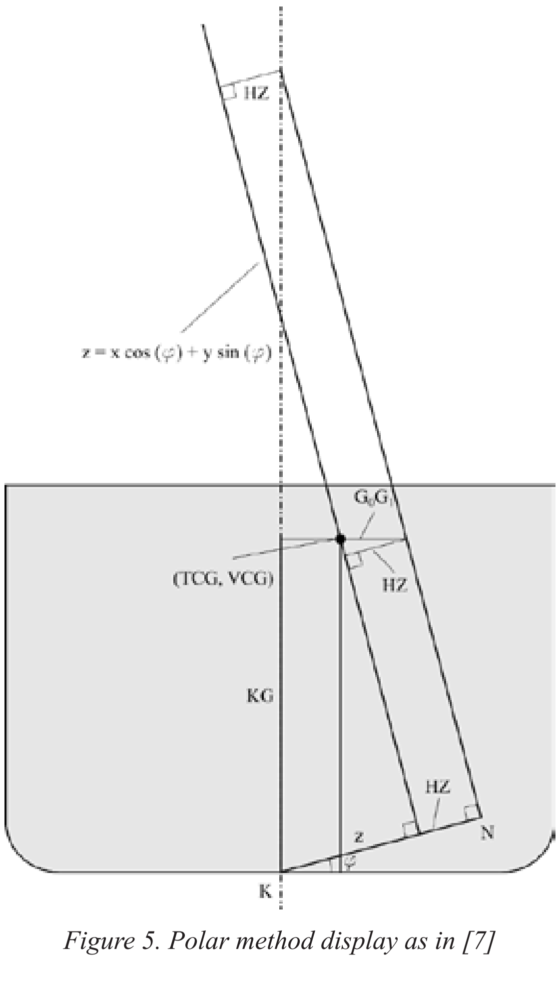

Figure 5. Polar method display as in [7]

The equation of line is given by the expression:

$$z = x\cos\varphi + y\sin\varphi \tag{17}$$

and knowing that the *x* coordinate is equal to the position of the transverse center of gravity and y vertical center of gravity at the following expression is obtained:

$$z = TCG\cos\varphi + VCG\sin\varphi \tag{18}$$

Also, *z* can be calculated using the following equation:

$$z = KN - HZ \tag{19}$$

that is, by including equation (18) in (19) we obtain:

$$KN - HZ = TCG\cos\varphi + VCG\sin\varphi \tag{20}$$

From known conditions:

$$TCG_0 = TCG_i \tag{21}$$

$$VCG_0 = VCG_i \tag{22}$$

The final equations can be established:

$$VCG = \frac{(KN_i - HZ_i)\cos\varphi_0 - (KN_0 - HZ_0)\cos\varphi_i}{\cos\varphi_0\sin\varphi_i - \sin\varphi_0\cos\varphi_i} \tag{23}$$

$$TCG = \frac{(KN_i - HZ_i)\sin\varphi_0 - (KN_0 - HZ_0)\sin\varphi_i}{\cos\varphi_i\sin\varphi_0 - \sin\varphi_i\cos\varphi_0} \tag{24}$$

If the vessel is symmetrical, i.e. the initial angle of inclination equals zero, the expressions are reduced to:

$$VCG = \frac{(KN_i - HZ_i)}{\sin\varphi_i} \tag{25}$$

$$TCG = 0 \tag{26}$$

As with the previous methods, *KN* is calculated using a stability software model, i.e. actual 3D stability model and *HZ* using equation (9). The model should be free to equilibrate in terms of trim when heeled. Values from a stability booklet originating from a stability 3D model may be used (interpolated values), but would introduce additional errors, and should be highlighted [7].

The polar method is general and applies to any initial inclination of the vessel.

4. Implementation of the methods

The calculation of the ship's center of gravity system is calculated according to the procedures and equations proposed in Section 3. The main particulars for the vessels chosen for testing of the calculation methods are presented in Table 2. The calculation is made for the following four ships:

Table 2. Ship characteristics

	LOA, m	*D,* m	*B,* m	*T,* m
Work vessel	42.0	2.0	8.0	0.78
Tugboat	54.8	3.85	16.2	2.8
Passenger ship	26.6	1.64	4.14	0.8
F41Container ship	163.0	18.6	32.0	11.8

Due to the extensive report for all those ships the results using each of the novel methods will be presented for container ship only. The container ship is chosen due to the design features, such as knuckles, larger flare angles, sharper chine lines and other nonconventional hull attributes. Additionally, the results will be presented for the work vessel using the generalized method, the tugboat with the graphical method and the passenger ship by implementing polar method.

For the real physical inclining experiment, the readings the *VCG* results are presented. With the influence on the stability margins whilst considering the error potential, the new corrected *VCG* values are included for each implemented method.

Table 3 shows the results of the calculation for the container ship by the general method. The value of *VCG* calculated by the generalized method for the container ship is 10,024 m.

Table 3. Calculation of the center of gravity of a container ship obtained by the generalized method

	tan φ	φ	Σ φ	φ	*HZ*	*KN*	sin φ	*VCG* sin φ
		°	°	rad	m	m		
0	0.000	0.000	0.032	0.001	0.072	-0.002	0.001	-0.002
1	-0.009	-0.521	-0.490	-0.009	-0.039	-0.110	-0.009	-0.081
2	-0.018	-1,003	-0.971	-0.017	-0.074	-0.239	-0.017	-0.171
3	0.009	0.493	0.525	0.009	0.037	0.135	0.009	0.088
4	0.002	0.091	0.123	0.002	0.000	0.200	0.018	0.186
5	0.008	0.464	0.496	0.009	0.034	0.123	0.009	0.084
6	0.018	1,020	1,052	0.018	0.074	0.275	0.018	0.187
7	-0.009	-0.498	-0.467	-0.008	-0.037	-0.126	-0.008	-0.078
8	0.000	0.000	0.032	-0.001	-0.072	-0.002	0.001	-0.002

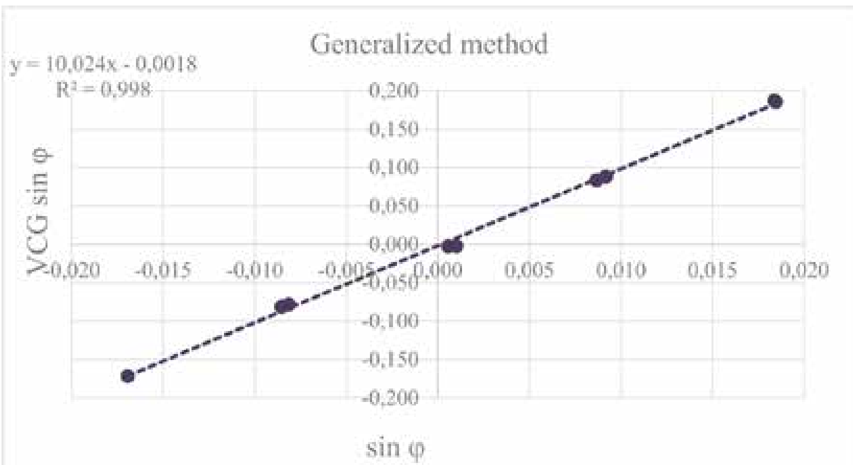

Figure 6. Diagram to determine the center of gravity of a container ship obtained by the generalised method

The graphical method, unlike the other two, uses averaged the *VCG* values from each shift governed by equation (14). A more suitable approach, as is stated in reference [7], would be to use least squares method which is applied here in order to maximize the capability of the graphical method. Strictly speaking, a proper way should be applying a method in its original proposition for testing purposes, as intended by its authors. Table 4 shows the results of the calculation for the container ship by the graphical method. The value of *VCG* calculated by the graphical method for a container ship is 10,013 m.

Table 4. Calculation of the center of gravity of a container ship obtained by the graphical method

	tan φ	φ	Σ φ	φ	HZ	KN	sin φ	VCG sin φ
		°	°	rad	m	m		
0	0.000	0.000	0.042	0.001	0.000	-0.002	0.001	-0.002
1	-0.009	-0.521	-0.480	-0.009	-0.039	-0.110	-0.009	-0.085
2	-0.018	-1,003	-0.961	-0.017	-0.074	-0.239	-0.017	-0.171
3	0.009	0.493	0.535	0.009	0.037	0.135	0.009	0.082
4	0.002	0.115	0.157	0.018	0.000	0.200	0.018	0.181
5	0.008	0.464	0.506	0.009	0.034	0.123	0.009	0.087
6	0.018	1,020	1,062	0.018	0.074	0.275	0.018	0.189
7	-0.009	-0.498	-0.457	-0.008	-0.037	-0.126	-0.008	-0.080
8	-0.017	-0.980	-0.938	-0.017	-0.072	-0.002	-0.017	-0.168

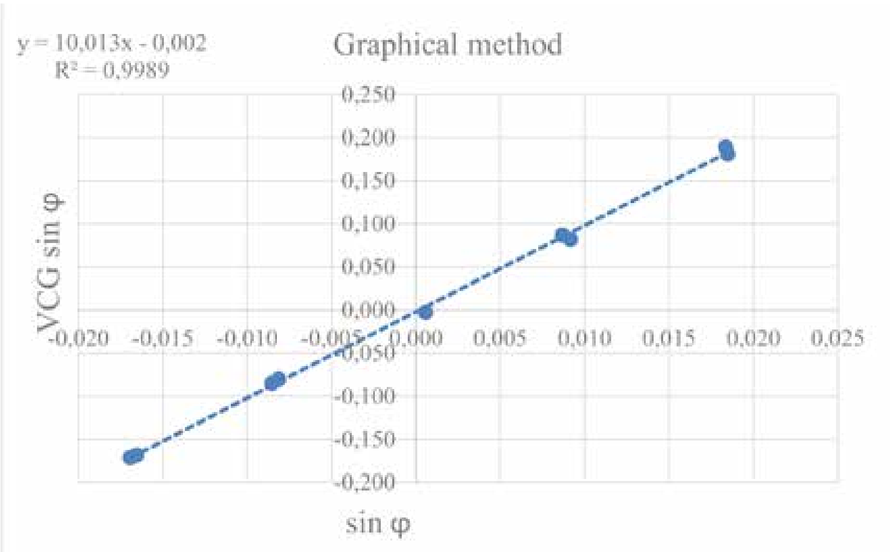

Figure 7. Diagram to determine the center of gravity of a container ship system by the graphical method

Table 5 shows the results of calculations for the container ship obtained by the polar method. The value of *VCG* calculated by the polar method for a container ship is 10,032 m.

Table 5. Calculation of the center of gravity of a container ship obtained by the polar method

	tan ϕ	ϕ	Σϕ	ϕ	HZ	KN	sin ϕ	sin (ϕ_i - ϕ_0)	VCG · sin(ϕ_i - ϕ_0)
		°	°	rad	m	m			
0	0.000	0.000	0.042	0.001	0.000	-0.002	0.001	0.000	-0.002
1	-0.009	-0.521	-0.479	-0.008	-0.039	-0.110	-0.008	-0.009	-0.091
2	-0.018	-1,003	-0.961	-0.017	-0.074	-0.239	-0.017	-0.018	-0.183
3	0.009	0.493	0.535	0.009	0.037	0.135	0.009	0.009	0.085
4	0.002	0.103	0.145	0.003	0.000	0.200	0.003	0.002	0.017
5	0.008	0.464	0.506	0.009	0.034	0.123	0.009	0.008	0.078
6	0.018	1,020	1,062	0.019	0.074	0.275	0.019	0.018	0.178
7	-0.009	-0.498	-0.456	-0.008	-0.037	-0.126	-0.008	-0.009	-0.078
8	0.000	0.000	0.042	0.001	-0.072	-0.002	0.001	0.000	-0.002

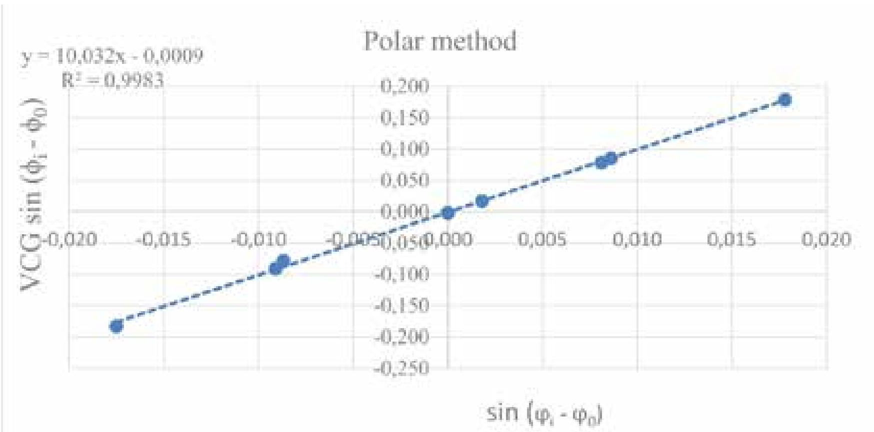

Figure 8. Diagram of the center of gravity of a container ship system obtained by the polar method

Table 6 shows the results of the calculation for the work vessel obtained by the general method. The value of *VC*G calculated by the general method for a work vessel is 2,015 m.

Table 6. Calculation of the center of gravity of the work vessel obtained by the generalized method

	tan φ	φ	Σ φ	φ	HZ	KN	sin φ	VCG sin φ
		°	°	rad	m	m		
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	-0.012	-0.688	-0.667	-0.012	-0.042	-0.059	-0.012	-0.024
2	-0.025	-1,410	-1,389	-0.024	-0.085	-0.113	-0.024	-0.049
3	0.013	0.745	0.766	0.013	0.044	0.065	0.013	0.026
4	0.001	0.057	0.078	0.001	0.000	0.002	0.001	0.005
5	0.012	0.705	0.726	0.013	0.041	0.053	0.013	0.025
6	0.026	1,467	1,488	0.026	0.085	0.112	0.026	0.052
7	-0.013	-0.745	-0.724	-0.013	-0.044	-0.065	-0.013	-0.026
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

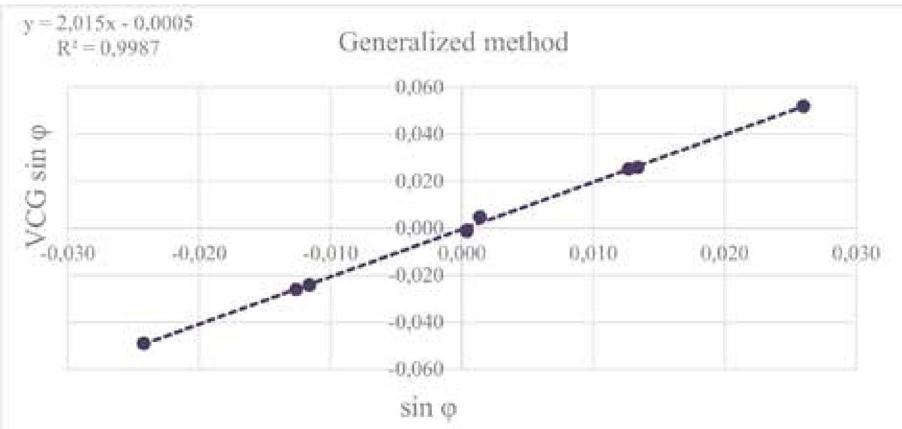

Figure 9. Diagram to determine the center of gravity of the workboat obtained by the generalized method

Table 7 shows the results of the calculation for the tugboat obtained by the graphical method. The value of *VCG* calculated by the graphical method for the tugboat is 3.185 m.

Table 7. Calculation of tugboat center of gravity obtained by the graphical method

	tan ϕ	ϕ	Σ ϕ	ϕ	HZ	KN	sin ϕ	VCG sin ϕ
		°	°	rad	m	m		
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.001
1	-0.010	-0.544	-0.544	-0.010	-0.032	-0.063	-0.010	-0.031
2	-0.021	-1,175	-1,175	-0.021	-0.063	-0.131	-0.021	-0.068
3	0.010	0.584	0.584	0.010	0.031	0.062	0.010	0.031
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.010	0.544	0.544	0.010	0.033	0.065	0.010	0.032
6	0.023	1,318	1,318	0.023	0.063	0.133	0.023	0.070
7	-0.011	-0.630	-0.630	-0.011	-0.036	-0.072	-0.011	-0.036
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

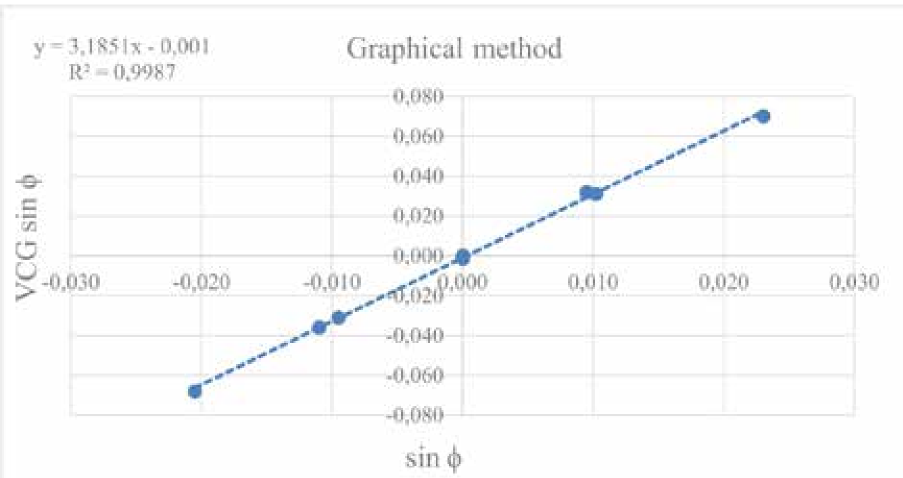

Figure 10. Diagram to determine the center of gravity of the tugboat obtained by the graphical method

Table 8 shows the results of the calculation for a passenger ship obtained by the polar method. The value of the *VCG* calculated by the polar method for a passenger ship is 0.83 m.

Table 8. Calculation of the center of gravity of a passenger ship obtained by the polar method

	tan ϕ	ϕ	Σ ϕ	ϕ	HZ	KN	sin ϕ	sin (ϕ$_i$ - ϕ$_0$)	VCG · sin (ϕ$_i$ - ϕ$_0$)
		°	°	rad	m				
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	-0.023	-1,331	-1,331	-0.023	-0.049	-0.068	-0.023	-0.023	-0.019
2	-0.046	-2,632	-2,632	-0.046	-0.092	-0.130	-0.046	-0.046	-0.038
3	0.022	1,272	1,272	0.022	0.048	0.067	0.022	0.022	0.019
4	0.002	0.115	0.115	0.002	0.000	0.000	0.002	0.002	0.000
5	0.022	1,238	1,238	0.022	0.049	0.068	0.022	0.022	0.019
6	0.046	2,637	2,637	0.046	0.092	0.130	0.046	0.046	0.038
7	-0.023	-1,318	-1,318	-0.023	-0.044	-0.063	-0.023	-0.023	-0.019
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

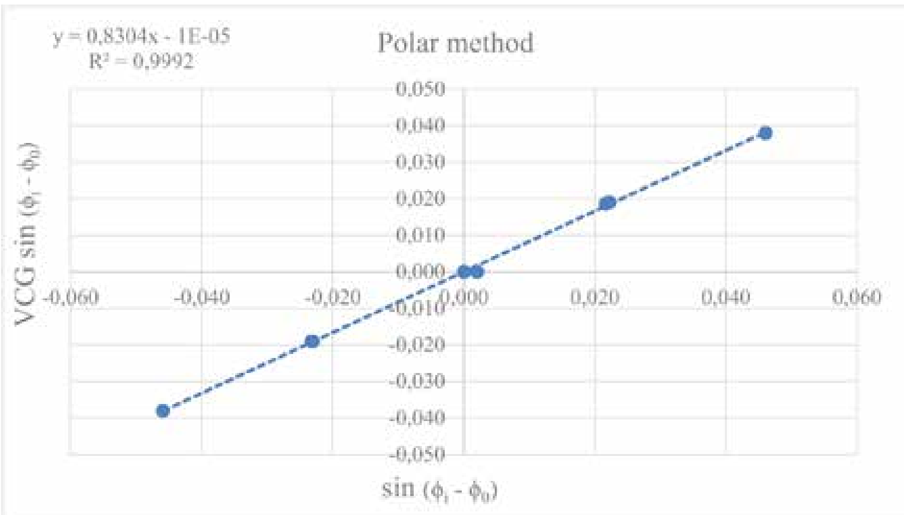

Figure 11. Diagram of the center of gravity of a passenger ship obtained by the polar method

5. Comparison of results

Table 9 shows the summary of the vertical center of gravity of the ships for each type of ship and for each method. The difference between the obtained position of the center of gravity by the classical method and alternative methods was calculated. The difference is shown graphically in Figure 12.

Table 9. Comparison of results

	Classical method	Generalized method			Graphical method			Polar method		
	VCG	VCG	Diff.	Diff.	VCG	Diff.	Diff.	VCG	Diff.	Diff.
Ship type	(m)	(m)	(mm)	%	(m)	(mm)	%	(m)	(mm)	%
Container ship	9,661	10,024	363	-3.75	10,013	352	-3.6	10,032	371	-3.8
Work vessel	2	2,014	14	-0.7	2,014	14	-0.7	2,014	14	-0.7
Passenger ship	0.805	0.83	25	-3.1	0.83	25	-3.1	0.83	25	-3.1
Tugboat	3.25	3.18	-70	2.1	3.18	-70	2.1	3.18	-70	2.1

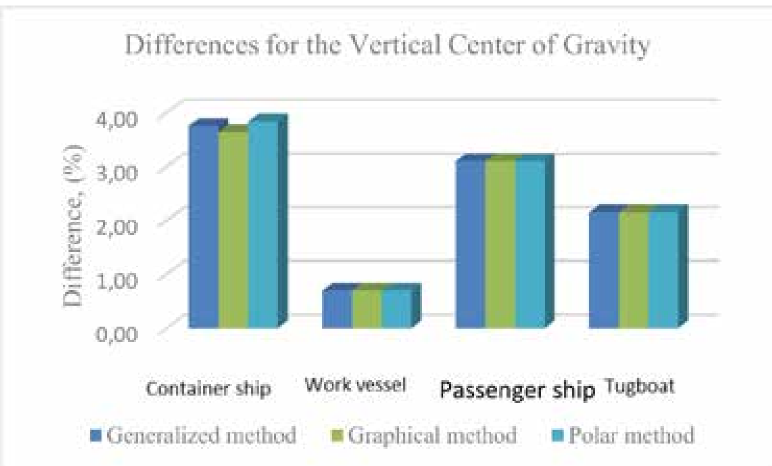

Figure 12. Comparison diagram for three novel methods

The results are presented by the absolute value of the percentage error, regardless of over or underestimation in order to compare the methods against each other.

By comparing the new methods, it can be deduced that all three methods yield virtually the same results for the the work vessel, passenger ship and tugboat. The difference is more subtle for the container ship. It comes as no surprise as one would expect that due to their more unconventional hull form with higher fore and aft flare and subsequent higher change in waterplane area.

All methods have been compared with results obtained from the classical method as shown in Figure 13.

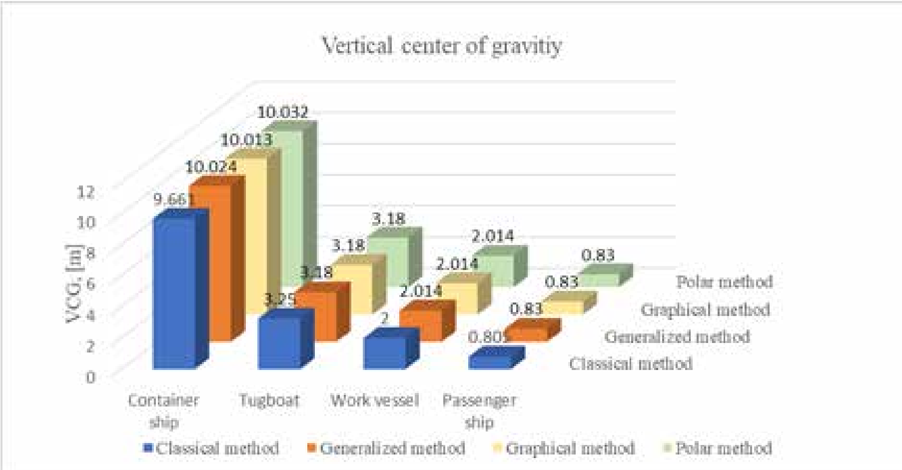

Figure 13. VCG values from all four methods

The difference between the vertical positions of the center of gravity for a container ship is 3.6% and this is the largest difference, while the lowest difference for the work vessel is less than 1%. The results demonstrate only the difference between methods, but not the methods difference from the actual VCG. Given that the results for three novel methods are similar if not the same, it certainly favours the statement that those three methods may replace the classical method as a convenient and more flexible alternative.

Furthermore, by not knowing the actual VCG it is difficult to use the results to conclude which method is more accurate or optimal than the others. In fact, based on the results in this paper, it is not possible to conclude that any calculation method is more accurate than the other, only their respective differences from each other, rather than the vessels' true *VCG*. However, in [10], it is proved that the polar method produces zero errors in a fully technical inclining experiment, and may, with correct assumptions, be used as the true *VCG* and baseline for the industry to know that there are other and more reliable alternatives to the classical method and this should be accounted for in the regulations and guidelines in use today.

6. Conclusion

In this paper, the results of the inclining experiment for four different ships are processed, where the calculation of the position of the center of gravity of the ship is determined by the classical method and three alternative methods.

The classical method is a simple, practical, and fast method based on the starting position of a metacenter. The location of the metacenter changes when the ship is heeled, but in the classical method this is neglected and the calculation of the position of the center of gravity of the system by height is inaccurate.

The calculation by alternative methods is not complicated, but it is more time-consuming because for each angle of inclination one needs to find the transverse position of the center of gravity, which prolongs the calculation process.

The general method is the first proposed one. It is a rather simple method, however precise because it takes into account the initial transverse position of the center of gravity. The graphical method is actually a general method converted into graphical form. The difference is that it does not take into account the initial transverse position of the center of gravity and therefore in ships with a transverse angle of more than half a degree it gives inaccurate results, which is not an improvement over the classical method. The polar method is the last proposed method that takes into account the initial transverse position of the center of gravity of the ship, the initial angle of inclination and the change of the transverse position of the center of gravity when moving cargo during the experiment, therefore the method is applicable to all angles.

The differences between the results of alternative methods are negligible. The differences between the positions of the center of gravity obtained by the classical method and the alternative methods are more profound.

Some additional research namely on the uncertainty and sensitivity analysis and certainly the reference studies should provide the International Maritime Organization an insight to consider alternative methods in its own regulations as relevant for determining the ship´s center of gravity.

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