Bringing the Naval Inclining Experiment into the 21st Century

George Payne MEng AMRINA[1], Rick Goddard MSc MEng CEng CMarEng MIMarEST MRINA[2], Paul Gliddon MEng CEng MRINA[3], Steve Marshall MSc CEng RCNC FRINA[4]

[1] *Lead Author, Steller Systems Ltd, Nailsworth, UK*
[2] *Steller Systems Ltd, Nailsworth, UK*
[3] *Steller Systems Ltd, Nailsworth, UK*
[4] *UK Ministry of Defence*

Synopsis

The concept of using inclining experiments to calculate the Vertical and Transverse Centre of Gravity (VCG and TCG) of a ship has been in place since the late 1700s. Whilst the form of current inclining experiments differ greatly from these early conceptual approaches; they still rely on a long-standing classical method to calculate the results. The classical method assumes that the ship is wall sided - an assumption that, in the modern day, does not need to be made.
This paper utilises new, more accurate methods formulated by (Karolius, 2018) and (Dunworth, 2015) and compares them to the classical method. In order to understand their reliability and practical advantages and their applicability to the naval vessel hull form, a large number of past naval vessel inclining experiments have been reassessed utilising the two new methods. The results have then been compared to the classical results that were originally calculated at the time of inclining. This paper discusses the differences and practical benefits of these new methods alongside their potential to simplify the inclining experiment process. The work considers these factors for a range of naval platforms and makes recommendations as to how the methodologies are best applied to different types of naval vessel.
Further work and future possibilities to improve the inclining experiment result accuracy further are also outlined.

Keywords: Ship Stability, Inclining Experiment, Calculation Methods

1. Introduction

An inclining experiment measures the location of a ships centre of gravity, most crucially its vertical location or VCG, a vital measure used to calculate a ship's stability. Split into two stages, the inclining experiment has sensitivities both in the initial experimental conduct and in the latter final calculation. This paper considers two new calculation approaches and suggests how the new methods may offer practical benefits in the experiment stage of the inclining experiment.

Using previous naval vessel inclining experiments as the basis, this paper uses the new calculation methods to recalculate past inclining experiment results to quantify the difference they have on the results. The differences are discussed and recommendations made on how they could be applied to help simplify and improve the experimental process.

2. What are the New and Classical Methods?

At the time of hand calculations, with planimeters used to determine transverse areas, the generation of stability data was a time consuming affair. The classical method circumnavigates this, using a series of assumptions to simplify the calculations needed to assess the results of an inclining experiment from a simple upright set of hydrostatic data. With modern computational methods and computer power, the calculation of hydrostatic data at varying heels and trims is both efficient and quick, opening the door to more fundamental approaches to inclining experiment assessments. The two recent calculation methods which make use of these

Author's Biographies

George Payne is a Senior Naval Architect with experience in both surface and sub-surface vessels, design and analysis. He has performed numerous ship stability assessments to UK Naval Rules and spent time working in the Naval Authority Group. George is no longer an employee of Steller Systems, he is now an employee of Thales UK.

Rick Goddard is a chartered engineer, he has a background in stability certification, derivation of standards and advanced intact and damaged seakeeping analysis. Rick has experience of working on in-service support projects as well as concept designs. In his earlier employment Rick worked in the Naval Authority stability section. Rick is no longer an employee of Steller Systems.

Paul Gliddon is a Principal Naval Architect and Chartered Engineer with experience in stability assessments of both naval and commercial vessels from concept through to build and in service support.

Steve Marshall is the Head of Ship Hydromechanics in the Naval Authority Group, UK MoD. He has over thirty years of experience in Warship and Naval Auxiliary design and, as the Naval Authority for Ship Stability, their Safety Certification.

opportunities are the Dunworth and Polar methods, full details of which can be found in (Dunworth, 2015) and (Karolius, 2018) respectively.

Traditionally the classical method relies on understanding the upright hydrostatics and using these to calculate the position of the metacentre relative to the keel (KM). The fundamental input that both of the new methods rely on is KN, the righting lever through which the buoyancy force acts, with centre of gravity assumed to be at the keel. KN is sensitive to displacement, heel and trim, the adoption of stability models for most modern naval and commercial ships has made this data readily available. The definitions of KN and KM are illustrated in Figure 1.

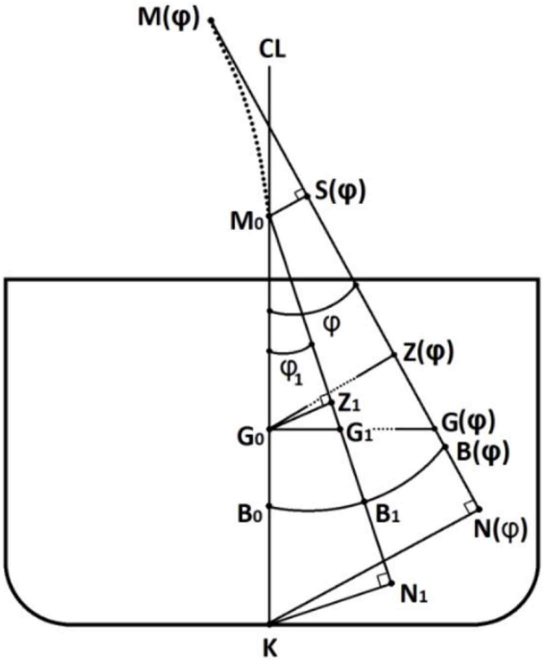

Figure 1: Ship cross section illustrating the locations of key variables (Karolius, 2018).

Using KN to calculate KG negates the need to perform calculations with reference to the ships metacentre which moves relative to the change in Water Plane Area (WPA) as a ship heels. The classical inclining experiment calculation method assumes that the metacentre is a fixed point, maintaining its position from the upright condition throughout the incline. In contrast the KN values are driven entirely by the shape of the submerged hull form and calculated for every heel angle reached in the inclining experiment. This means the new methods remove any errors caused by a change in metacentric height (KM) when heeling over in the inclining experiment.

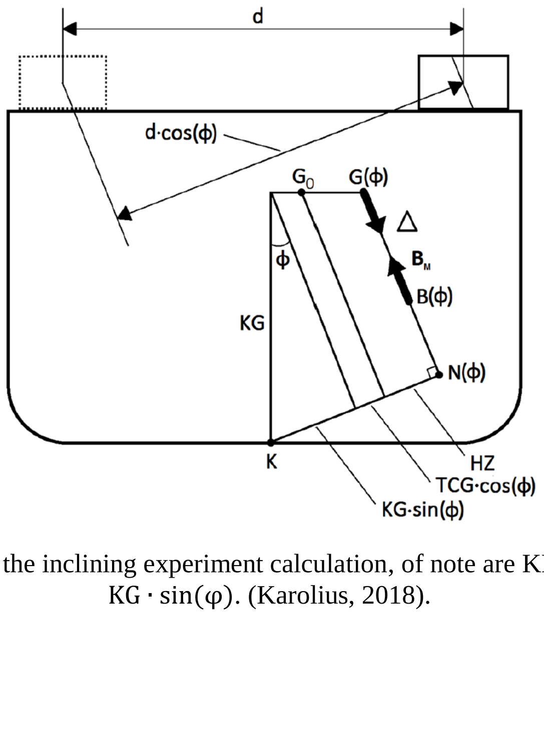

Figure 2: Variables used in the inclining experiment calculation, of note are KN, HZ, $\mathrm{TCG}_0 \cdot \cos(\varphi)$, and $\mathrm{KG} \cdot \sin(\varphi)$. (Karolius, 2018).

The final equations used to calculate VCG and TCG using each method are displayed below, all variables used are illustrated in Figure 1 and Figure 2. Subscript ‘0’ denotes the value when the ship is in the upright position, and ‘i’ when the ship is inclined to an angle of φ_i. The isolation of metacentric height from both the Dunworth and Polar methods are clearly seen.

Classical

$$VCG = KM_t - GM_t$$

$$TCG_0 = GM_t \cdot \tan \varphi_0$$

Dunworth

$$VCG = \frac{KN_i - HZ_i - TCG_0 \cdot \cos \varphi_i}{\sin \varphi_i}$$

$$TCG_0 = KN_0 - HZ_0$$

Polar

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

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

3. Current Naval Incline Guidance

Naval guidance stipulates that the classical method should be used to calculate the result of an inclining experiment whereas commercial guidance does not dictate the method to be used.

All naval ships are inclined at start of life and again at regular intervals throughout their life. Current guidance on how to perform an experiment and the method to calculate the results has been largely unchanged for centuries. Guidance on how to complete a naval inclining experiment is contained within the Maritime Acquisition Publication (MAP) 01-024 (MOD, 2010), this states some key conditions – and the reasons behind them – that the ship to be inclined must meet to ensure that the calculation method remains valid:

- The inclining ballast “should be sufficient to give a 2° heel. A 2° heel has been taken as the generally accepted best compromise between retaining the validity of an approximation made to the ‘wall sided formula’ in the stability analysis, whilst achieving pendulum readings that are large enough to be insensitive to ‘reading errors’ and reasonable quantities of inclining ballast.”
- “The ship is to be brought upright to within 0.5° prior to the start of the experiment to minimise any differences between the immersed/emerged wedges as the ship heels to port and starboard.”
- “The ship is to be brought as near as possible to the design trim, or to a trim agreed with the yard/Ship Staff/MCA/MOD project using the minimum quantity of fluids. This is to be at a draught and trim combination such that the waterplane inertia remains constant as the ship heels i.e. chines and flats do not emerge or submerge.”

All of these three points are orientated around keeping the WPA, and by proxy the metacentric height, as constant as possible throughout the experiment. Time and resources are used to ensure that these requirements are met at the beginning of an inclining experiment.

4. Methodology

For this paper 36 past naval inclining experiments, comprising 4 different naval vessels, have had their VCG and TCG results recalculated using the Dunworth and Polar methods. The results have then been compared to the original results (calculated using the classical method).

Using a dataset of this size allows for a good quality comparison of the results obtained by each method, and since each of the inclining experiments are real it gives a practical insight into the use of the new calculation methods. Table 1 presents the average prismatic and block coefficients for the four ships used along with the number of inclining experiments assessed for each.

Table 1: Ship Parameters

Ship	Mean Block Coefficient	Mean Prismatic Coefficient	No. of Inclining Experiments Assessed
Ship 1	0.505	0.637	7
Ship 2	0.475	0.546	3
Ship 3	0.496	0.653	9
Ship 4	0.479	0.597	17

This paper focuses on a comparison between calculation methods, the accuracy to which the original experiment itself was carried out has not been considered as there was insufficient data to make a reasonable assessment of likely errors in each experiment. As a result of typically occurring errors in the experiments there is no true datum and so the results can only be compared to each other.

VCGs and TCGs have been recalculated for the vessels in the as-inclined condition, not the lightship. Extra calculations are performed to account for deadweight items and tank fluids from the as-inclined condition to reach the lightship condition, these estimations of vessel state are subject to further experimental error. To avoid the potential for unnecessary errors to accumulate from the lightship correction and deadweight the as-inclined condition was used. It is worth noting this approach when considering the magnitude of errors between results; the difference in a lightship value such as KG once solid and fluid deadweight have been added will be reduced as a result of the simple moment calculation conducted. To this end, the lightship errors associated with each calculation will in actuality be greater than those seen in the as-inclined condition.

Hydrostatic models of the ships have been used to obtain KN values, at the stated displacement, LCG, and water density specified in the incline report. The weight shift data and pendulum readings from the incline report have been used to calculate the applied moment and angle of heel for each shift.

The free surface moment correction factor (calculated in each inclining experiment report) has been subtracted from the fluid VCG (VCG_f) to give the solid VCG (VCG_s). This is the value that has then been compared to the as inclined VCG_s in the incline report.

In all cases the input data taken from inclining reports was considered to be of sufficient precision for rounding errors to be deemed negligible.

In all cases Paramarine has been used as the hydrostatic modeller. Balancing and faceting tolerances were set to tenths of a mm. KN values were calculated in meters, taken to 5 decimal places, and intervals of 0.5 deg from -5 to +5 deg. Linear interpolation was then used to calculate the KN values at the required angles of heel.

5. Presentation of the Results

5.1. Vertical Centre of Gravity

The Polar and Dunworth methods produced very similar VCG results with an average difference of 0.1mm and maximum deviation of 0.5mm, they were therefore grouped together for the purpose of comparison to the classical method. Figure 3 shows the difference between as-inclined VCG results using the classical and Polar methods plotted against the year of the incline to show the spread of results. Each marker type represents a different naval vessel.

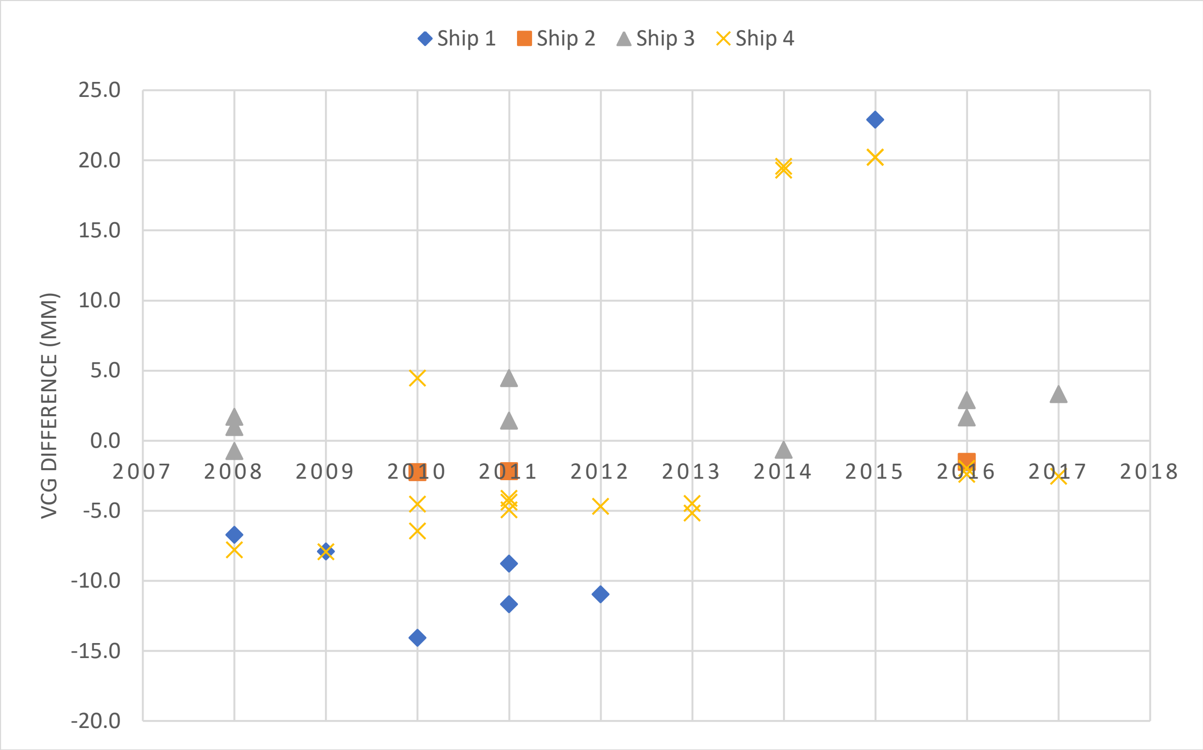

Figure 3: VCG difference between the classical and Polar / Dunworth methods plotted against the inclining experiment year.

With the exception of the result in 2015, Ship 1 consistently has a lower VCG when calculated with the Polar than the classical method (averaging a reduction in VCG of 10mm). This is a significant reduction and shows the classical method to generally be conservative in its VCG calculation.

Ship 2 displayed the most consistent VCG difference, but as it only contains 3 instances, also has the smallest sample size. It averages a -2mm difference, showing the Polar method to produce a consistently lower VCG result than the classical method.

Ship 3 also displayed a relatively consistent difference, averaging +1.7mm difference.

Ship 4 showed the least consistent VCG difference of the ships assessed here, with 4 points positive and 13 negative points.

Overall these results generally show a trend between the results for each ship type with some outliers to each result. As with any experimental process, variance in the trends seen are potentially a result of experimental errors either in the conduct of the inclining experiment, mistakes in the calculation or in the accompanying report. On average ships 1, 2, and 4 show a reduction in VCG using the new methods whereas ship 3 shows an increase. Of note in many of the cases is the magnitude of the difference in calculated result, errors in excess of 5mm are not uncommon, translated to the lightship, these differences become even more significant.

5.2. *Transverse Centre of Gravity*

The TCG results have been displayed in the same manor, but on separate plots for the Dunworth and Polar methods as there was some variation in the results, they are shown in Figure 4 and Figure 5 respectively.

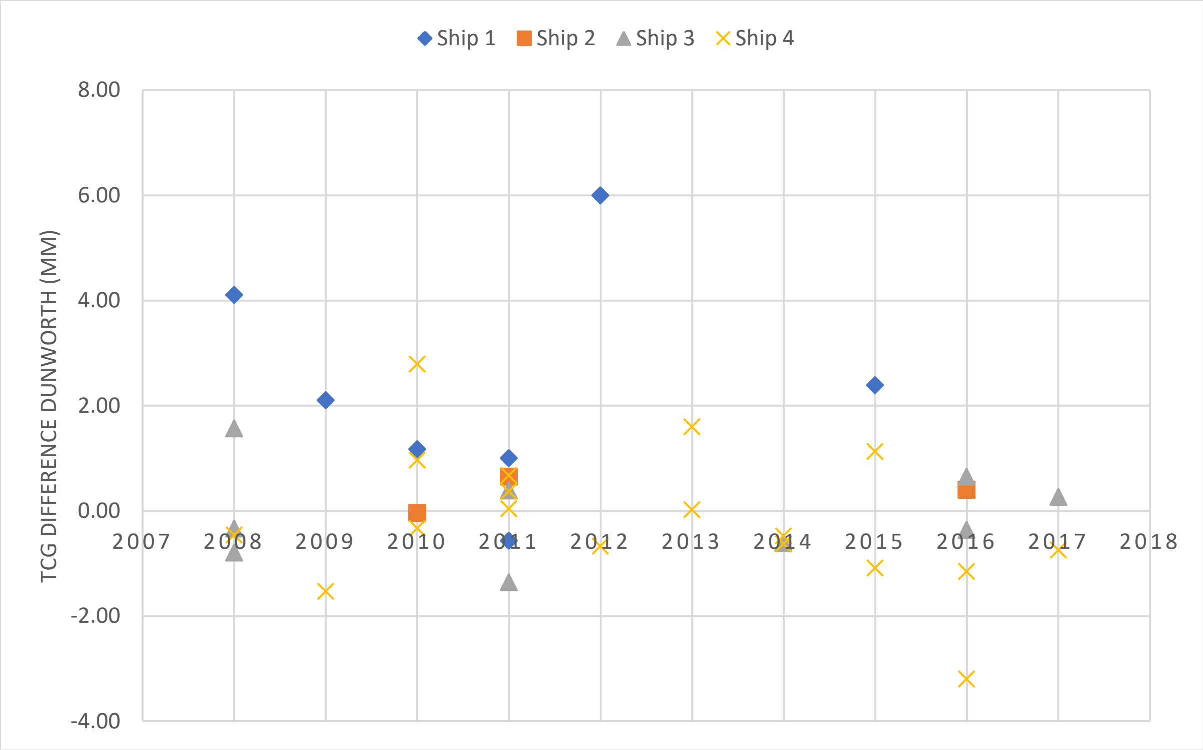

Figure 4: TCG difference between the classical and Dunworth methods plotted against the inclining experiment year.

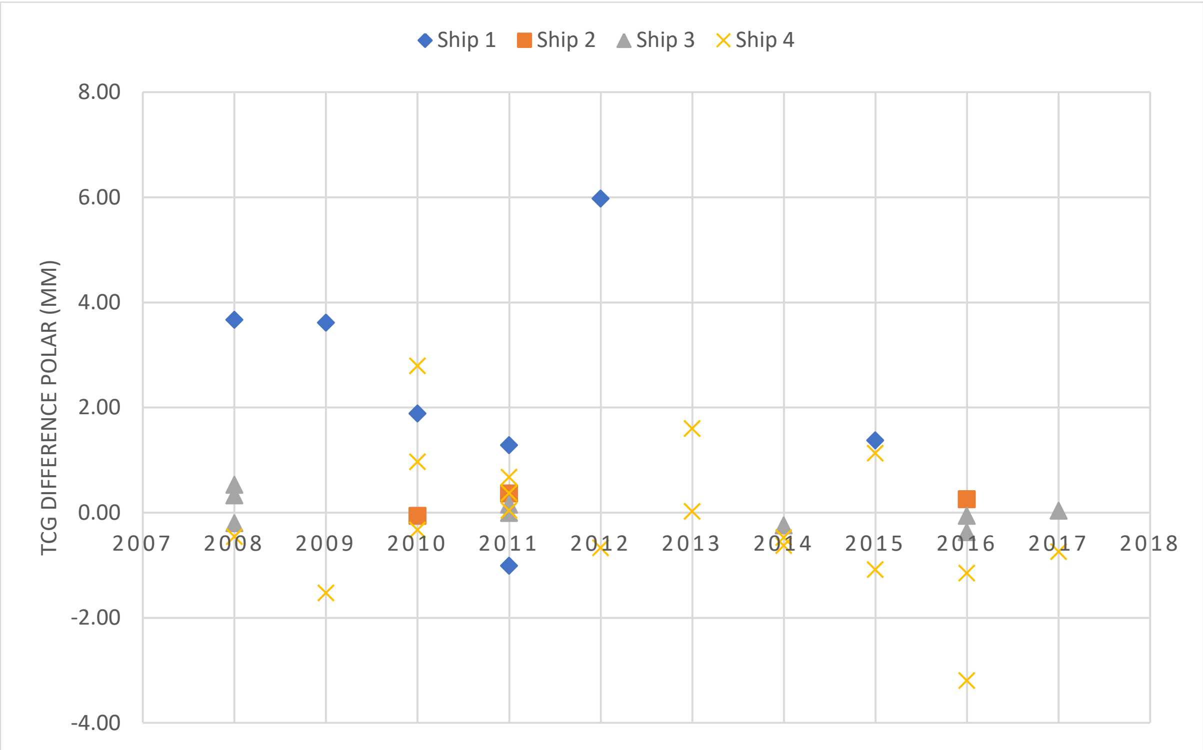

Figure 5: TCG difference between the classical and Polar methods plotted against the inclining experiment year.

Figure 4 and Figure 5 show TCG errors are of a smaller magnitude than those seen in VCG, however as a percentage error of the original classical values they show far greater variance. The direct proportionality of TCG to GM using the classical method is the likely cause of potential differences.

6. Discussion of the Results

The new methods have been theoretically shown to be more accurate than the classical method in their respective papers when baselined against a mathematically absolute datum, but they also increase the criticality of some experimental readings, such as the draught mark readings. In the classical method draught mark readings are used to calculate the displacement and initial list and trim which in turn allow KM to be estimated. The new methods calculate the KN values based on these same inputs, which, if erroneous have a large impact on estimated KN values and so lightship centroids. For example, the draught mark readings are used to calculate the initial heel, then from this initial heel and the pendulum readings the subsequent heel angles are calculated, this means that any error in the initial heel value will skew the KN values for all heel angles.

Balancing out this sensitivity to what is a notoriously difficult input to assess (the draught mark), the adoption of the new calculation methods offers up a couple of practical benefits pertaining to the conduct of an inclining experiment:

6.1. The Need to Bring the Ship to an Upright Condition in Heel and Trim

Currently time and money are spent at the beginning of an inclining experiment ensuring that the vessel is as close to upright as possible, both transversely and longitudinally. This is usually achieved by placing weights on the ship or arranging fluid in tanks to correct for any list or trim present. This process can lead to fluids being outside of recommended ranges in terms of number of slack tanks or tank waterplane relative to tank geometry. It can also lead to delays in the experiment as the condition is reached. In extreme cases, the failure to bring a vessel into an acceptable heel or trim has led to the cancellation of experiments at great cost. Adoption of the new methods removes this constraint. The conditioning of the ship can instead focus on the optimisation of tank levels in terms of free surface moment, leading to the potential for considerable time, effort and cost savings.

6.2. Maximum Heel Angle

It is stated in the naval guidelines that during each weight shift of an inclining experiment the vessel should not heel to more than 2 deg. This is considered as large as possible to minimise experimental errors reading the pendulum whilst minimising the risk of breaking wall sided assumptions of constant WPA. MAP 01-024 recommends a pendulum length no less than that required to achieve 60mm of deflection per degree. In practicality, this is hard to achieve on many smaller vessels. Of particular concern are open boats such as landing craft, on these vessels the pendulum is often swung externally to achieve the required length, leading to susceptibility to wind disturbances. Adopting the new calculation methods, it is possible to heel to angles far in excess of 2°, reducing angular calculation errors and making it practical to use far shorter pendulums which are additionally easier to site. For example, using a 3m pendulum with a 2° heel angle and a typical reading tolerance of ±2mm gives an accuracy of ±1.9% on the heel angle, whereas using a 2m pendulum with a heel angle of 6° reduces this error to ±0.9%.

If implemented both of these points would reduce the time and cost involved in the preparation of an inclining experiment, as well as increase the accuracy of the result in smaller vessels where larger pendulums are not practical. Notwithstanding any practical benefits, the new methods offer ship yards and naval architects a simple calculation with which to verify an inclining experiment calculation.

7. Conclusions

From the perspective of absolutes, and in a perfect world where all experimentally read values in an inclining experiment are of absolute accuracy, the new methods of calculating lightship centroids are of a higher degree of accuracy than the classical method. In the realities of experimental conduct, where draught mark readings are commonly read to an accuracy of ±1cm, pendulum readings impacted by passing vessels, wind or merely the way in which a reader sits in front of the pendulum and where tanks readings are dictated by the accuracy of a modelled sounding tube, the difference between the methods is somewhat clouded. Of particular consideration is the fact that the higher accuracy of the new methods is predicated upon the accuracy of the most difficult experimental reading – the draught mark.

The advantages of the new methods are most tangible in smaller vessels where the wall sided assumptions of constant waterplane area are least likely to hold true and where the practicalities of long pendulums are a hindrance. In these cases, the most limiting factor of the new approaches, draught mark accuracy, is mitigated by the fact it is common to weigh the vessel using a load cell.

In larger ships, the methods offer practical advantages in terms of achieving an acceptable initial condition and in terms of including the effect of key features such as bulbous bows, sonar domes, waterjets, chines etc., which are increasingly more common in modern naval platforms.

In all cases, the data presented in this paper demonstrates the potential variance in VCG results which is possible as a result of using the more evolved approach of the new methods, these variances are not trivial and have the potential to impact the through life stability management of naval platforms.

For these benefits to be taken advantage of, accurate KN data is required. With the availability of hydrostatic models for naval vessels this is not an issue, but there is scope for the accuracy of these models to be further validated using 3D scanning. There are numerous other areas of the inclining experiment where a more accurate reading has the potential to improve the accuracy of the results and hence our understanding of the ships stability, these are detailed in the next section.

It is recommended that the new methods be adopted on a trial basis for small vessels where the benefits of shorter pendulums and greater heel angles and the mitigation of low block and prismatic coefficient hullforms can be most realised. It is also recommended that the method be used as a second calculation for all inclining experiment assessments on larger vessels in order to build a better picture of the impact on lightship and to ensure that the most conservative value is used. A final recommendation is that the new calculations be used in any instances where lightship TCG corrections are planned in order to ensure an accurate baseline of lightship TCG is obtained.

7.1. Further work to Improve the Accuracy of Inclining Experiments

Critical to the accuracy of the new methods is confidence in the hydrostatic data used to generate KN curves which accurately represent the physical ship. Differences between computer models and in service platforms are common, arising from alterations and additions, repairs, variance in a class of ship between shipyards and simply errors in the creation of the initial computer model. Similarly, large errors in draught mark placement are not uncommon and these would have a significant impact on any inclining experiment, but especially one where the result is calculated using the new methods. The leveraging of technology is the solution to these issues; the adoption of 3d scanning during docking periods to create accurate models of each platform is of great potential benefit. The cost of such surveys is now trivial compared to other naval vessel maintenance activities. The inclusion of modern photometry as part of this process, common in most 3d scanning approaches, allows draught marks to be accurately assessed and confirmed against the baseline, minimising errors in this regard.

Future studies should seek to quantify the potential for this approach, baselining existing computer models against 3d scan data and calculating updated KN curves from the results. This study would highlight not only what effect age has on a ships hull, but also the difference between models based on design data and those generated post build. Updated KN values and displacement taken from the validated hull form could subsequently be used to update the incline results and compare any differences in the results.

The accuracy of draught mark readings is accepted as the greatest driver of inclining experiment accuracy, regardless of the method used to conduct the calculations. An electronic draught gauge, allowing the time averaging of surface disturbances would greatly assist in improving the accuracy of this element of the experiment particularly when combined with a 3d scanned verification of draught mark locations. The development of technology to achieve a ‘digital draughtboard’ is not a particularly complex challenge and when considering the potential benefits, should be targeted more keenly.

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