ITTC Quality System Manual
Recommended Procedures and Guidelines

Procedure

Inclining Tests

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Disclaimer

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Inclining Tests

1. PURPOSE OF PROCEDURE

1.1 Historical background.

The historical background is essential to understand inclining tests procedure. It is very well explained by Nowacki and Ferreiro (2003). They show that the first theoretical written base came from Archimedes (ca. 287-212 B.C.) who explain stability for a homogeneous floating solid made of simple geometrical shapes (in those case the centre of gravity of the immersed part of the body is also the centre of volume). It was necessary to wait until the 17th century to found mentioning procedures to estimate loads (which was needed to estimates taxes) and then displacement of the ship, by draft measurement and waterplane estimation (Anthony Deane in UK or Johannes Hudde in Netherlands). Those measurements were made at full scale and not using drawings or plans. Notable theoretical improvement from Archimedes theory came simultaneously and independently from Bouguer and Euler, the first introduce the metacentre and the second the restoring moment, both around 1746-1749. Only few years later, in 1748, the first inclining test (referenced by Nowacki and Ferreiro) was performed in Brest (France) by Clairin des Lauriers in order to test the new theory.

1.2 Objectives

The objective of this procedure is to determine the effective displacement and position of centre of gravity of a ship with experiments at the current loading condition. “Effective” means that the vertical position of the centre of gravity is obtained, taking into account the effect of free surface of fluids in tanks, which are necessary for stability evaluation or needed for operational reasons. In particular, that means that no extrapolation at another displacement is considered (except for inclining weight and gear). As per the ASTM Standard Guide (2014), this procedure is not applicable to vessels such as tension-leg platforms, semisubmersibles, rigid hull inflatable boats and so on. More generally, this procedure is only applicable for conventional vessels. For a non-conventional ship, applicability of this procedures should be validated. While the methodology for a full-scale ship and a model, intended for a tank test, can be the same, its applicability for a model should be considered. For example, if a model is small, techniques using only the weight measurement in air can be more precise.

1.3 Inclining Tests.

In this procedure, inclining tests is decomposed in four parts:

- Survey of the ship,
- The determination of displacements,
- The inclining experiment itself, which is based on a transverse shift of weight,
- Post-processing.

The first parts should be done in the smallest delays between them in order to reduce change in mass and position. The order of two middle parts can be swapped. It should be specified in the report, where the test has been performed, as well as the time and the duration of the test.

2. REQUIREMENTS

2.1 Environmental conditions

During test, environmental conditions should be as favourable as possible and documented in the report. The following information should be clearly specified:

- Wave conditions during draft measurements (as a general rule, wave height should be less than 0.05 m. The allowable wave height depends on the used measurement technique and ship response of the waves),
- Wind conditions (should be less than 10 knots in gust (usually defined as the average of the wind velocity over a duration of 5 s) including relative heading (continuous wind measurement is encouraged),
- A current if any, including tide,
- Other meteorological phenomenon, as rain (potential water accumulation on deck) or environmental phenomenon (wake of others ships) which can have an effect on the results have to be mentioned,

For estimation of displacement by draft or freeboard measurements, seawater density should be measured.

2.1.1 Wave effects

In order to evaluate wave effects, it is recommended to record heel time history and compare it to natural roll period of the ship. Effect of a relatively large resonant roll motion can be limited by computation of the average of the signal during a large period but it should be checked that other frequencies do not disturbed too much the results.

2.1.2 Wind effects

In order to evaluate the effects of wind, it is suggested to determine the heel angle due to the wind. For this purpose, the windage area and others ship parameters from booklet can be used. Calculations may be done analogously to the weather criterion of 2008 IMO IS Code (IMO, 2008) with a rough approximation for the vertical position of the centre of gravity. More data can be found in Blendermann (1996) for the drag coefficient. To be conservative, it should be taken into account the wind velocity in gust (average over 5 seconds of duration). If the gust velocity is unknown, it can be estimated from the nominal wind velocity (average over 10 minutes at an elevation of 10 m) usually given by measurements or hindcast. Another reason to select only the gust condition is that the effect of a constant wind velocity can be accounted for (Figure 1). A gust factor of 1.5 in terms of heeling moment is used by this 2008 IMO IS Code for the evaluation of the Weather Criteria. The gust factor in term of wind velocity is defined as the ratio from maximum velocity in a gust to the nominal wind velocity, it is equal to $\sqrt{1.5} = 1.225$. As mentioned in the IS Code, it is not a maximum value. The maximum should in terms of velocity be around 1.7, according to Watanabe et al. (1956), referenced in the IS Code, but with others definition of nominal velocity. Recent analysis converges towards a ratio in term of velocities of $\sqrt{2}$ Renilson (2015). A demonstration of using the ratio, is given by Durst (1960) with nominal wind speed values from 10 to 36 kt. According Deacon (1965), the same ratio for all speeds below 18 kt can be used, which may too large.

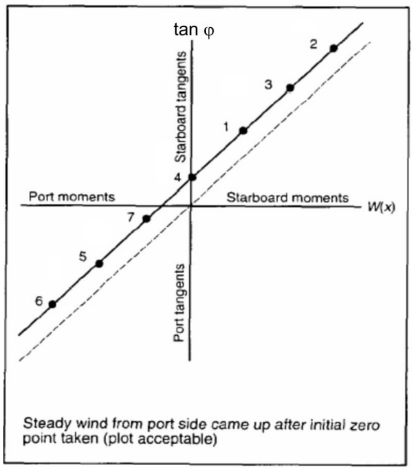

Figure 1 Moment under constant wind velocity (figure A1-4.3.2-4 of explanatory notes of the 2008 IMO IS Code)

A relative reduction of the velocity can be obtained by taking into account the relative heading and /or perform the test in a wind-protected area.

Regarding the wind, there is a maximum nominal wind speed acceptable for a given ship, see (Leguen et al. 2023). Some conclusions are, for a particular ship:

- At each inclination, the heel angle due to the wind gust should be well below the heel inclination due to the shift mass;
- For the same precision of measured *GM*, increasing the recording time, increases the maximum nominal wind speed acceptable.
- It is necessary to increase the measurement time to keep the same uncertainty on the *GM*, at a constant nominal wind and heel angle.
- To reduce the uncertainty on the measured *GM*, at a constant wind and recording time, it is necessary to increase the heel angle due to shifted masses; the use of advanced methods (*KN* type) is necessary.

2.1.3 Effect of a current

Because effect of current is difficult to estimate, it is recommended to avoid this situation whenever it is possible, for example by conducting the experiment around slack tide (if any).

2.1.4 Sea water density

If necessary, seawater density should be evaluated in one or more places around the ship depending of the conditions (for instance: suspicion of non-uniform density due to mixing of seawater and freshwater after rain or near a river). The sample of water used should be taken at a depth representative to the draft of the ship. In some cases, depending on density evaluation techniques used, temperature of the water has to be measured too.

2.1.5 Other effects

In order to avoid any external perturbation a continuous visual observation outside the ship is recommended and should be noted in the report.

2.2 Ship conditions

The ship should be at a distance form a quay or any other objects floatable or not. Any changes or transfer of mass of the ship should be avoided during the entire test. Precautions should be taken to prevent both deliberate and accidental liquid transfer (Moore 2010).

It should be verified that there is enough water under the keel in order to be sure that the ship can move freely for entire duration of the experiment.

All gears should be secured in order to prevent their shifting during the experiment.

Draft at which abrupt changes in the water plane are to be avoid as possible (Moore, 2010).

In order to check it, it is suggested to plot expected trajectory of the metacentre with changing heel angle, as shown in Figure 1c of (Dunworth 2014) or figure 2. The non-linearity in the heeling moment vs. angle of heel can imply different solutions for post processing.

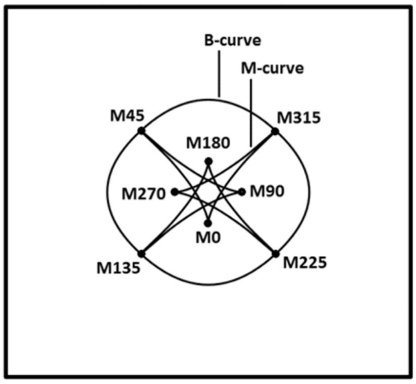

Figure 2 Box-shaped vessel with movement of B and M (Karolius (2018))

2.2.1 Tanks

The results of inclining tests produce the effective position of centre of gravity. That means that the effect of fluid moving in tanks will be included in the results. To avoid this influence, it is preferable to empty as many tanks as possible including the cases of with relatively small amount of fluid that may cause disturbances that are difficult to quantify (corner effects in particular). Emptying almost full tank is also preferable to avoid influence of air pocket and venting.

Emptying all tanks is the preferable. Slack tank can contain small quantity of fluid inducing a large free surface effect, leading to non-expected nonlinearity and hysteresis phenomenon. Full tank can induce non-predictable free surface effect. In pressed tank, it can be observed air trap, dependent on location, which also may produce inaccuracy in the results.

In the case of non-empty tank, free surface effect have to be included. If this effect remains during the experiment, usual correction is obtained from moment of inertia of the free surface in the tank. If not, the shift of centre of gravity of the fluid have to be calculated for each inclinations and considered for the evaluation of the heeling moment.

Anti-rolling tanks, using fluid, produce a large free surface effect. Those tanks have to be fully emptied.

Pipe between tanks should be preferably closed.

For all cases where a fluid is used, its density should be indicated (specifying whether it is a default value or a measurement).

2.2.2 Machinery

All unnecessary machinery should be shut down or isolated to prevent fluid transfer. Fluid consumption are to be minimised and be drawn preferably by centreline tanks. Estimation of transfer of fluid during the experiments should be reported (MAP, 2010).

2.3 Numerical model and numerical tools

The hull geometry should be precisely described in order to estimate the level of uncertainty. Unless modern numerical tools are utilized, hydrostatic pre-calculated tables can be used. The following elements should be specified:

- The sign convention for roll angle and heeling moment;
- The reference of the numerical hull file used as input data, and the name of the numerical tools used;
- The uncertainty expected of the numerical hull definition (2D or 3D representation);

- The representation of the numerical hull file (out frame size or the overall size of the hull) and keel thickness if available,
- The list of appendices (including bow thruster, added keel etc…) taken into account and those, which are not.

3. PROCEDURES

3.1 Preliminary

The motion of the ship should be simulated before the inclining test with estimated value of the displacement and the centre of gravity (from sister ships results or of from the design office) in order to check:

- If the expected weight and their location are acceptable,
- Possible safety problems due to excessive heel angle,
- Possible excessive change in the surface of flotation (it can induce the used of different numerical tools post-processing),
- The influence of wind; to estimate if the maximum wind velocity is acceptable for experiments.

3.2 Survey

Survey of a ship is important in order to check if everything is in an acceptable state for the experiment (inventory, and if necessary remove any weight, including fluid, that can shift). The survey also should note loading condition of a ship: light operational or full displacement. All tanks have to be checked (sounding, filling rate, density) and adequate measures should be taken to exclude air pockets in almost-full tanks (IACS, 2004). It is also preferable to check all compartments and void spaces.

3.3 Displacement measurements

Displacement estimation can be done by many different ways depending on the size of a ship, the availability of hull geometry description and required level of uncertainty. Because, at an early stage, this procedure is more focused on the determination of the centre of gravity where displacement is only an input data, this part will not be developed so much. Only a list of solutions with advantages and disadvantages is proposed for the moment.

Even if it should be the more accurate solution, direct mass measurement is possible only for small ship, then the basic theory used is to estimate the volume of water displaced. By water density multiplication, the displacement is directly accessible.

The usual solution to determine the displacement of a ship by measuring drafts or freeboard figures (at least one, preferably in four to six locations). Draft measurement on official draft mark are preferable for a better accuracy of the results. The position of these marks should have been verified and formalized in ship documentation, which should be referenced in the experiment report. Depending of number of draft measurements, it may be necessary also to evaluate heel and trim. The six draft measurements (at the bow, amidships, and aft end for both sides) can allow to account for a potential hull deformation. Different approximations can be used for hull deformation, but they have to be referenced in the experiment report. The default approximation can be taken from (Lewis, 1988), theoretically justified for a rectangular barge with homogeneous weight distribution. In this case, parabolic deformation is expected and can be evaluated with three points available. A more rigorous methodology of modern tools utilize moment of inertia of main section in order to find a more realistic hull deformation (Grinnaert and Billard, 2021).

The drafts measurements, complemented by angles, determine the exact position of the underwater geometry of the ship, while the water surface considered flat (water surface can be lightly deformed in order to simulate hull deformation –it is easier than "deforming" the hull geometry). Once the hull geometry is known, the volume of displaced water can be obtained. Application of a numerical model to obtain the best fit between all measurements is preferable than using only equivalent draft and a hydrostatic table. Methodology applied should be specified in the report.

With adequate post-processing, the volume of the water displaced, the mass of the ship, the position of the centre of gravity (longitudinal, transversal and vertical) can be determined. The centre of gravity is located along the vertical line from the centre of buoyancy which is determined by numerical tools.

3.4 Inclining tests

The methodology is to shift a weight on the ship and measure precisely induced motion. Any kind of weight shift can be used, even ballast water transfer. However, as the objective is to minimize the uncertainty, some techniques may be preferable over other from the precision standpoint. For example, a carriage carrying weights and rolling in transverse rails gives excellent results because little rolling of the ship it induces and the movement of the weights can be and measured and adjusted accurately (Moore 2010). Calibrated weight shifted transversely on horizontal deck close to the midship section should be preferable. In any case, the shifted weight has to be shaped in a way so its centre of gravity can be accurately determined (IACS, 2004).The weight should be on board for the draft measurement. In case of using ballast water, heel and trim have to be taken into account. In case, the weight are shifted in open spaces (e.g. weather deck), the weights have to be watertight (MAP, 2010).

For all weight shifting (including the reference situation), the motion of the ship should be recorded. There are no specific requirements what measurement techniques have to be used, however proper documentation is important for further evaluation of the uncertainty of the motions measurements.

The effect from transient motion, usually observed after shifting weights, should be removed from the final results.

The zero point is the reference attitude of the ship, where final position of centre of gravity will be determined by the inclining test. Heeling points should be symmetrical (in number and in values) from this reference point.

Several tests are needed; more test are conducted, more accurate the final results will be. At least one test (the zero point) should be done twice.

During experiments, any observation of change in the surface of flotation due to heel should be reported, using the zero point as reference (e.g. emergence of transom, bulbous bow, bilge keels, etc.)

3.5 Post-processing

It is recommended to reproduce all the experiments with numerical tools and not limiting with traditional formulas and hydrostatic table:

- The real displacement of the metacentre,
- The real location of the centre of buoyancy,
- The real free surface effect of tanks,
- The real initial attitude of the ship (trim and heel),

More accurate methodologies are available from Wilczynski and Diehl (1995), Dunworth (2013, 2014 and 2015) Smith et al (2016) and Karolius and Vassalos (2018), recently examined by Ozayan and Taylan (2019). These methods allow more attitudes of the ship, even with drastic change of the waterplane area with heel, compare to traditional methods, ASTM F1321-14 (ASTM 2014).

The end result usually comes as the slope from regression, while the intercept does not have to be zero. Maximum likelihood method is preferable, in order to not minimize the uncertainty, propagated from one axe to another, as occurs in a linear regression.

This graph (tangent of the heel angle vs heeling moment) should be plotted during the test in order to find potential error before the end of the experiments (Moore 2010). Different types of errors could be made visible by examination of the graph, see IMO IS Code 2008.

4. UNCERTAINTY

Uncertainty quantification is based on work of Shakshober and Montgomery (1967), Whitrow (2003), Hansen (1985), Woodward et al, (2016) Woodward and Hutchison (2016). Whitrow (2003) includes results of a questionnaire collected from a sample of naval architects, surveyors and the Royal Navy personnel. The first step should be the evaluation of input errors. Whitrow (2003) proposes a summary of input errors estimation, used in (MAP, 2010), summarized in Table 1.

Most of the items in Table 1 depend on measuring device (for example, draft measurement can be improved by a device such as draft tube) and numerical tools (using numerical tools allows not to use the hypothesis of fixed metacentre which improve the final results).

Table 1: Inputs errors, mainly from Whitrow (2003) and Hansen (1985)

Input parameter	Error applied	Source
Visual draught reading (depending of the weather)	0.005 m	ASTM / MAP
Draft mark vertical position	0.006 m	Whitrow
Seawater density	0.00045 t/m^3	Withrow
Tank content dip tape reading	0.003 m	Whitrow / ASTM
Tank content gauge readings	3.2 %	Whitrow
Density of liquids in tanks	0.00045 t/m^3	Whitrow
Free surface moment of inertia of tanks	1.50 %	Hansen
Solid deadweight estimates	1 %	MAP
KG of deadweight estimates	0.150 m	Hansen
Weight of personnel	5.0 %	Hansen
KG of personnel	0.150 m	Hansen
Inclining gear weight	4.15%	Hansen
KG of inclining gear	0.050 m	Hansen
Longitudinal distance between forward marks and aft marks	0.100 m	Hansen
Longitudinal distance between aft marks and midships marks	0.100 m	Hansen
Longitudinal distance between aft marks and midships marks	0.100 m	Hansen
Hull deflection parameter	10.0 %	Hansen
Calculated volume	0.1 %	Hansen
Volume due to appendages	1.0 %	-
Difference of centre of buoyancy due to appendages	1.0 %	-
Difference between design and build dimensions	0.06 m / 100 m	Hansen
Vertical moment of displaced volume	0.05 %	Hansen
Water line moment of inertia	0.09 %	Hansen
Visual pendulum defection	0.002 m	-
Hell angle measurement	0.01°	ASTM
Metacentre position, KM	1.0 %	-
Pendulum lengths and reading	0.002 m	Whitrow / ASTM
Pendulum lengths and reading	0.002 m	Whitrow / ASTM

It should be noticed that using a single weight for all inclinations implies that an error in the value of this weight will be present in all points and will not be visually detectable on the slope of the plot of tangent of the heel angle vs. heeling moment, (Moore 2010). To estimate the slope, a linear regression is often performed.

The usual correlation coefficient of the fit:

$$R^2 = \frac{\sum(\hat{y}-\bar{y})^2}{\sum(y-\bar{y})^2}.$$

The R^2 value is not enough to quantify the uncertainty; it only serves as a quality indicator. Several weight shift (or similar heeling moment) are needed. It is assumed that inclining are measurement are independent (which it is not exactly true, e.g. use of same weight for all the points). Uncertainty is quantified with the standard deviation of the slope or as the standard deviation of results at all the inclinations.

$$GM = \frac{1}{N}\sum_{i=1}^{N}\frac{M_i}{\mathrm{W}\tan(\varphi_i)}$$

The uncertainty of GM should be added the uncertainty of KN or KM (depending of the post-processing used). The use of a numerical tool is recommended.

5. FINAL CHECK

In order to check the quality of the experiments and the results, the following questions are to be addressed:

- Were the mooring lines checked?
- Were the meteorological conditions good enough?
- Was the wind speed measured and recorded?
- Was clearance under the keel measured or evaluated?
- Were the redundant heel measurements used?
- If any, have all visual measurements been done properly?
- Were the measurements systems properly calibrated?
- Were the weights properly calibrated?
- How many natural periods were used in the heel angle inclination method?
- Were any metrological tools used?
- Were measuring systems for draft or freeboard measurements adequate?
- Was the metacentre assumed fixed?
- Were the numerical tools used in the particular experiment? Were these numerical tools accurate?
- Where there enough points measured? Were they symmetric?
- Was the personnel on board minimized, limited to the crew, and informed of the requirements of an inclining test in order to not disturb the measurements?
- Was there more than one measurement for one inclination? There should be at least two measurements for the initial zero angle, preferably three.

6. REPORT

Report should be consistent in its form and its content in order to give the possibility to repeat the calculations. The report should use ITTC symbols and ISO units. Taking photographs of draft marks, weight and location of measurements are recommended. Drawings of positions for the draft/freeboard measurements should be included in the report. If the draft mark was used, the draft mark plan should be t referenced, including a report of the verification of position of these draft marks.

In addition, in order to estimate the uncertainty, some measurements details should be specified:

- Techniques used to measure draft (visual, pressure, etc.) and the number of independent readings,

- Techniques used to estimate the water density (and if necessary the water temperature) and number of the independent estimations,
- How the zero point was determined (on board value, reference place in the ship, etc.),
- Details of numerical output used for the post-processing (hydrostatic tables, equilibrium at each point, etc.), and the numerical tools used (including reference of the input data),
- Calibration certificate of all measurements systems used.

A list of all tanks with the levels and density of fluids is required. Additional information such as the positions of centre of gravity, free surface effect and variation of this effect with heel and tank levels should also be included. The list should show how the filling level has been measured (by hand, electric gauges, etc.).

A list of all compartments and void spaces showing that they have been checked for the experiments.

Comprehensive description of the weight location of the ship during the experiments (reference of the loading plan used is needed).

Transfer of fluid during the experiments should be included in the report.

The report should contain basic data, such as the weight of each inclining weight, the distance the weight was moved, the lengths and displacement of each pendulum, rather than only the moments and tangents, in order to permit further checking in case any data appear later to be questionable (Moore, 2010). Including photographs of pendulums, weights, etc. are recommended.

A chapter with of the uncertainty quantification should be included in the report. For example, for slope coefficient of the regression line the mean value and variance estimate of results from all the inclinations.

The report should contain a conclusion from the personnel in charge of the experiments and some comparisons against similar ships results.

7. RECOMMENDATIONS

Final recommendations are:

- Use of modern tools for hydrostatic calculations is preferable;
- Use numerical model as precise as possible;
- Environmental condition should be as favourable as possible, recording time history of wind velocity and direction is encouraged;
- Ship conditions should be the nearest to the loading conditions expected for the rest of trials in order to reduce extrapolations;
- Modern and adequate metrological instrumentation should be used;
- Measurement of roll period, complemented with uncertainty quantification is recommended during the tests in order to track any changes after the tests. The relation between the roll period and the metacentric height can be applied (Grin et al. 2016, Park et al. 2016, 2017).

8. LIST OF SYMBOLS

GM	Metacentric height,	m
KM	Distance to metacentre from a keel,	m
KN	Righting arm, measured from the keel,	m
M	Heeling moment,	N·m
N	Number of inclining test	
R^2	Correlation coefficient for regression	
W	Weight displacement of a ship,	N
y	Measured value	
$\bar{y}$	Averaged value	
$\hat{y}$	Fitted value	

φ Angle of heel, rad

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