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 mention of procedures to estimate loads (which was needed to estimates taxes) and then displacement of the ship, by draught measurement and waterplane estimation (Anthony Deane in UK or Johannes Hudde in Netherlands). It must be noticed that those measurements were made at full scale and not using drawing 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 on a new-built 74-gun ship *Intrépide* specifically made in order to test the new theory.

1.2 Objectives

The objectives of these procedures are to determine the effective displacement and position of centre of gravity of a ship in the situation during the experiments. Effective, means that the vertical position of the centre of gravity obtained, take into account the effect of free surface in tank, necessary for the stability evaluation. In particular, that means that no extrapolation at another displacement is considered (except for inclining weight and gear). As for the ATM standard guide (2014), this procedure is not applicable to vessels such as tension-leg platforms, semisubmersibles, rigid hull inflatable boats and so on.

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-treatments.

The three first parts can be done in any order but must be done in the smallest delays between them in order to reduce change in mass and position. It must be specified in the report where the test have been performed, time and duration of the test.

2. MANDATORY CONDITIONS

2.1 Environmental conditions

During test, environmental conditions must be as favourable as possible and very well documented in the report of the experiments. It must be clearly specified in the report of the experiment:

- Wave conditions during draft measurements (should be less than 5 cm high but can be depend of the technical solution used),

- Wind conditions (should be less than 10 knots in gust but the limit can depend of the ship) including relative heading (temporal wind measurement is encouraged),
- 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 must be measured.

2.1.1 Wave effects

In order to evaluate waves effects it is recommended to record temporal trace of measurements and to compare it to natural roll period of the ship. Effect of a relatively large roll resonance motion can be limited by computation of the average of the signal during a large period but it must be checked that other frequencies do not disturbed too much the motions.

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 wind surface and others ship parameters can be the ones chosen in the stability booklet for the verification of the IMO's meteorological criteria with a raw approximated value for the vertical position of the centre of gravity. More data can be found in Blendermann (1996) for the draft coefficient. The wind velocity is the gust value (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 10 meters high) usely given by measurements or hindcast. A gust factor of $\sqrt{2}$ has to be used from the nominal wind velocity and gust velocity. A relative reduction of the velocity can be obtained by taking into account the relative heading. The heel angle due to this gust wind velocity should be very small and in all case much smaller than the first heel inclination observed during the inclining experiments.

2.1.3 Current effects

Because effects 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 must 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 mandatory and must be reported.

2.2 Ship conditions

The ship must be as less linked as possible to the quay or other part, floatable or not, non-include in the ship definition. Mass modification and mass transfer should be avoid during the whole tests. Precautions should be taken to prevent both deliberate and accidental liquid transfer (Moore 2010).

It must be verified that there is enough water under the keel in order to be sure that the ship is entirely free in all experiment situation and during the entire duration of the experiment.

All gear should be secure in order to not shift 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 draught the metacentre movement with heel angle on a figure as the figure 1c of Dunworth (2014) or figure 2 of Karolius (2016). The non-linearity in the heeling moment vs. angle of heel can imply different solutions for postreatment.

2.2.1 Tanks

The results of those tests will gave the effective position of centre of gravity. That means that the effect of liquid in tanks shifting with heel will be included in the results. To avoid this phenomenon, it is preferable to fully empty as many tanks as possible and exclude the cases of reservoir or decks containing relatively small amount of liquid that could cause disturbances difficult to quantify (corner effects in particular). Excluding almost full tank is also preferable to avoid air pocket and venting problems.

Empty tank is the preferable situation. Slack tank can contain small quantity of fluid inducing a large free surface effect, non-expected linearity with heel angle and hysteresis phenomenon. Full tank can induce non-predictable free surface effect. In pressed tank, it can be observed air trap dependant to location of events which also induce inaccuracy in the results.

In the case of non-empty tank, free surface effect have to be include. If this effect can be remain constant during the experiment, usual correction obtain from surface inertia o the free surface in the tank can be used. 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-roll tanks using liquid have, by definition, a large free surface effect. Those tanks have to be fully empty.

Pipe between tanks should be preferably closed.

2.2.2 Machinery

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

2.3 Numerical model and numerical tools

The hull geometry must be very precisely described in order to estimate the level of uncertainty obtained. Using numerical model of the ship and modern numerical tools is necessary and have not only to be used through hydrostatic pre-calculated tables. The following elements must be specified:

- The sign convention for roll, heel and moment must be fixed,
- 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 must 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,
- The possible security problems due to excessive heel angle,
- The possible excessive change in the surface of flotation (it can induce the used of different numerical tools post-treatments),
- The influence of wind to estimate the maximum wind velocity acceptable for experiments.

3.2 Survey

Survey of the ships is important in order to check if everything is in an acceptable situation for the experiment (inventory, and if necessary limit, any weight, including liquid, with possible shift) and to be able to describe precisely the conditions of the ship during the experiments (conditions for light operational or full displacement). All tanks have to be verified (sounding, filling rate, density) and adequate measures have to be taken to preclude air pockets in about full tanks (IACS, 2004). It is also preferable to check all compartments and voids.

3.3 Displacement measurements

Displacement estimation can be done by many different ways depending on the size of ship, the knowledge of the geometry of the ship and the incertitude wanted. 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 at sea is to measure drafts or freeboard (at least one, preferably four and usually six). Draft measurement on official draft mark are preferable for a better accuracy of the results. Depending of number of drafts measurements, it can be necessary to also measure heel and trim. The usual combinations is six draft measurements and one density measurement. The six draft measurements (at front, middle, and fore end for both side) can allow to take into account a potential hull deformation. For hull deformation, different approximations can be used and have to be well referenced in the final report of the experiment. The default one can be the one described in Principle of Naval Architecture (1988), and theoretically strictly justified for a rectangular barge with homogeneous weight repartition. In this case, parabolic deformation is expected and cannot be discarded because there is always a parabolic lines passing through three points. A more rigorous methodology could be obtained with modern tools using, for example, the mechanical inertia of the main section in order to find a more realistic hull deformation.

Those drafts measurements, eventually completed by angles, determine the exact position of the theoretical geometry of the ship beside the water surface considered as flat (water surface can be lightly deformed in order to simulate hull deformation because it can be easier than deforming the hull geometry). Then it is necessary to use a hull geometry to obtain volume of displaced water. Using the numerical model to obtain the best fit between all measurements if preferable than using only equivalent draft and hydrostatic tank table.

With adequate post treatments, it could be possible to estimate the volume of the water displaced, the mass of the ship, the position of the centre of gravity (longitudinal, transversal and vertical) located somewhere along the vertical from the centre of buoyancy which is determined by numerical tools.

3.4 Inclining tests

The methodology is to shift mass in the ship and measure precisely the induce motions of the ship. Any kind of mass shift can be used (even water transfer in ballast) but it must be kept in mind the objective of uncertainty because some of the solutions can be less precise than others. For example, a car carrying the 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 accurately (Moore 200) and adjusted. Calibrated mass transversely shifted on horizontal deck nearest the middle of the ship should be preferable. In any case, the shifted mass should be shaped so that its centre of gravity may be accurately determined (IACS, 2004) and already inboard for the draft measurement. In case of using water ballast heel and trim have to be taken into account. In case of outside location during storage and/or experiments impervious to water is needed (MAP, 2010).

For all shift mass (including the reference situation), the motion of the ship must be recorded. Measurement techniques is free but must be well documented in order to estimate the uncertainty of the motions measurements.

The final results should avoid effect of resonance roll usually observed after shifting weight.

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

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

During experiments, it must be report any observation of change in the surface of flotation due to heel from the zero point as reference (transom, bulbous, bilge keel, ..).

3.5 Post-treatments

It is strongly recommended to reproduce all the experiments with adequate numerical tools and not only using traditional formulas and hydrostatic table in order to take into account at all angles:

- 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),

Those more accurate methodologies where re-demonstrated recently by Wilezynski (2015), Dunworth (2013, 2014 and 2015) Smith et al (2016) and Karolius et al (2018). Those methods allow more attitudes of the ship even with drastic change of the waterplane area with heel than traditional methods as mentioned by ASTM F1321-14 (2014).

At the end, results came usually from the slope of a graph (it is not mandatory that the regression line pass through the origin). The evaluation of this value should preferably use likelihood method in order to not minimize the incertitude along one axe from the other, as linear regression do. For each point the uncertainty of heeling moment and heel angle can be evaluate using following table and taken into account.

This graph (tangent of the heel angle vs heeling moment) should be draught during the test in order to found potential error before the end of the experiments (Moore 2010). Different typical error visible by examination of the slope of the graph is commented, for example, in IMO IS 2008.

4. UNCERTAINTY

Uncertainty study can be based on Whitrow (2003) and Hansen (1985) work. Whitrow include results of a questionnaire sent to a sample of naval architects, surveyors and Royal Navy personnel. The first step must be the evaluation of input errors. Whitrow propose a summary of input errors estimation, used in (MAP, 2010), and resumed and lightly completed in the following table.

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

Input parameter	**Error applied**	**Source**
visual draught reading (depending of the weather)	0.005 m	ASTM / MAP
draught 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 defelection 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
KM Metacentre postion	1.0 %	-

pendulum lengths and reading	0.002 m	

Most of the items in the previous table depend on measuring device (for example, draught measurement can be improved by adequate device as draft tube) and numerical tools (using numerical tools allow to not use the hypothesis of a fixe metacentre which improve the final results).

It must be noticed that using a single weight for all inclinations imply that and error in the mass of this weight will be present in all points and will not be visually detectable on the slope of the graph, tangent of the heel angle vs heeling moment (Moore 2010).

5. FINAL CHECK

In order to check the quality of the experiments and the results it can be reported those questions:

- Were the mooring lines checked?
- Was the meteorological condition good enough?
- Was the wind speed measured?
- Was water under the hull measured/evaluated?
- Were redundant heel measurements used?
- If any, have all visual measurements been done properly?
- Are all measurements systems properly calibrated?
- Are weights properly calibrated?
- How many natural periods were used in the heel angle inclination method?
- Were metrological tools used?
- Were adequate systems used for draught or freeboard measurements?
- Is the Metacentre assumed fixe or not?
- Were numerical tools accurate?
- Are there enough measuring points? Are they symmetric?
- Personnel on board is minimized, limited to the crew, and informed of the requirements of an inclining test in order to not disturb the measurements?
- Is there more than one measurement for one inclination situation? At least two measurements for the initial zero angle, preferably three.

6. REPORT

Report must be consistent in form and in content in order to give the possibility to redo the calculation. Report have to use ITTC symbols and ISO units. Photographs of draft marks weight and location of measurements are strongly recommended.

Drawing of reading position of the draft/freeboard measurements must be given in the report. If the draft mark was used, the draft mark plan should be at least referenced.

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

- Technical solutions used to measure draft (visual, pressure, …) and the number of independent catch,
- Number positions and technical solutions used to estimate the water density (and if necessary the water temperature),
- How was determine the zero point (on board value, reference place in the ship, …),
- Details of numerical output used for the post-treatment (hydrostatic tables, equilibrium at each point, …), and the numerical tools used (including reference of the input data),
- Calibration certificate of all measurements systems used.

A list of all tank with levels and density is require. Additional information as position of centre of gravity, free surface effect and variation of this effect with heel and tank level have to be also given. The list must show how the filling level have been measured (by hand, electric gauges, …).

A list of all compartments and voids showing those which have been checked for the experiments.

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

Estimation of transfer of fluid during the experiments have to be reported.

The report must contain basic data, such as the weight of each inclining weight, the distance it was moved and the lengths and deflections 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).

A chapter with evaluation of the uncertainty must be include in the report. For example, regression coefficient of the slope of the graph if used, or average value and variance of results from all inclinations.

The report must 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,
- Ship conditions should be the nearest to the loading conditions expected for the rest of trials in order to reduce extrapolations,
- Use modern and adequate metrological instrumentation,
- Roll period measurement is recommended during the tests in order to follow the change after the tests as suggested by IMO, using the link between the roll period and the metacentric high.

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