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Uncertainty Analysis for free running manoeuvring model tests

1. OVERVIEW

The purpose of the guideline is to provide guidance for ITTC members to perform uncertainty analysis (UA) of a model scale free running model test following the ITTC Procedures 7.5-02-06-01, 'Free running model tests'. It is a guideline until it has proved itself for at least one 3-year period of the ITTC so that more institutes can elaborate this and become familiar with the concept of uncertainty analysis for free running model tests.

The present UA guideline is based on ISO GUM. The procedure 7.5-02-01-01 is referenced by this guideline, but the present guideline is different, because it describes the way to perform an uncertainty analysis for free running manoeuvring tests, which is completely different from static measurement such as a for example a resistance test as referenced by 7.5-02-01-01. Free running manoeuvring tests are typical transient tests from which deterministic parameters are derived. Therefore, the entire chain of the process has to be considered in detail, because each link introduces uncertainties.

The guideline outlined below is focussed at obtaining the values for the final outcome of the free running manoeuvres. This outcome is for example an overshoot angle or a tactical diameter, as measured by free model tests on model scale. Possible scale effects of free running model tests are not considered. At the time of writing the guideline, only one publication was written on a complete Uncertainty Analysis for Free Running Manoeuvring Model tests (see Quadvlieg and Brouwer, 2011). This publication discusses the uncertainty analysis for model tests on "KVLCC2", one of the proposed benchmark ships. The UA concept proposed in this paper is embraced as example for this guideline. The essence of this paper is that from all individual causes of uncertainty, the effect of these causes on the end result (such as a tactical diameter) is quantified. This quantification can be captured using repeat tests or through simulations that quantify the sensitivity of the end result to a change in input parameter. Examples on uncertainty analysis based on repeat tests are given by Toxopeus (2011) on the benchmark ship "Hamburg Test Case (HTC)" and Toxopeus, van Walree and Hallmann (2011) on the benchmark vessel "5415M".

The proposed methodology takes into account the uncertainties, arising from the stochastic variation in measured parameters (Type-A), and uncertainties related to all other parameters included in the Data Reduction Equations (Type-B). In addition, the methodology takes into account many parameters that do not appear in the data reduction equations but that are considered to have a possible influence on the results. These parameters are based on uncertainty propagation analysis.

2. DESCRIPTION OF FREE RUNNING MANOEUVRING MODEL TESTS

During free running manoeuvring model tests, a ship model is free to move in all 6 degrees of freedom. The manoeuvre is in general actuated by one or more steering devices (further always referred to as rudder), propulsors and/or thrusters (further always referred to as propeller). Performing free model tests consists of a number of steps, as explained in 7-5-02-06-

01 (free running manoeuvring tests). Each of these steps has possible sources of uncertainties. The guideline for determining the uncertainty starts by treating all the typical steps in free running model tests. In Chapter 3, a list of sources of uncertainty in every step is given. The typical steps of free running manoeuvring model tests are:

- Model manufacturing
- Model set up (the draught marks, the mounting of the propeller(s) and rudder(s), the engines, rudder servos and their steering mechanism, the loading condition and stability)
- The measurement system and the calibration. The measurement will often be made through an optical measurement system, which is calibrated and will have calibration uncertainties. This will be the key measurement equipment.
- The performing of the tests, meaning that the model is brought to speed, there is a release of the model, rudder(s) and propeller(s) movements initiated in some way, and the measurement of motions during the manoeuvre.
- The analysis of the measured data, which consists of the digitising, sometimes the filtering, the data reduction from the measured time traces towards parameters such as an overshoot angle or a tactical diameter.

3. LISTING AND DISCUSSION OF THE SOURCES OF UNCERTAINTY

- The accuracy of test results is influenced by the following imperfections of the experimental technique:
- Inaccuracy of ship model characteristics
- Undesired facility related hydrodynamic effects
- Unsteady approach conditions
- Errors on ship model control equipment parameters (e.g. propeller rate of rotations, rudder angle, rudder turning rate and delays in rudder control)
- Disturbance from test arrangement on model (e.g. power and signal cables)
- Measurement inaccuracies

The objective of this chapter is to list parameters of which its uncertainty will have an influence on the uncertainty of the final result.

3.1 Uncertainty of model characteristics.

A model should be manufactured in accordance with ITTC “recommended procedures & guidelines model manufacture ship models (7.5.-1-01-01). The uncertainty in the model principal dimensions can then be obtained assuming the model fabrication error to be no more than +/- 1 mm in all coordinates. The influence of some factors (e.g. errors on main dimensions, offsets, loading condition, moments of inertia) on the accuracy of test results is hard to estimate, because that would need repeats of model manufacture, model installation, appendage manufacturing etcetera.

Related to the model characteristics, the following list of uncertainties are to be considered.

- Model manufacturing
- Model length, breadth, draught
- Model geometry (obliqueness)
- Rudder accuracy (effect of area, chord, span, profile)
- Rudder mounting (under a small angle, oblique behind the propeller)
- Propeller accuracy
- Propeller mounting (tilt angle, offset)

A characteristic of all these model-related uncertainties is that they will cause a bias in the final outcome. When performing repeat tests, this bias will not become visible, because it is model related and not test related. It may become visible when multiple models are made, but even then, it is questionable whether this bias may be visible, because it may be compensated by other aspects. Practical reasons will impede that many models will be made to quantify this uncertainty. However, it will be possible to quantify an uncertainty interval for model and appendage manufacturing accuracy.

3.2 Uncertainty of model set-up

This set-up has to do with the individual accuracies of the model set-up:

- GM
- Displacement and ballasting
- Initial roll angle
- Initial trim angle
- Longitudinal radius of inertia

A characteristic of all these model set-up uncertainties is that they will cause a bias in the final outcome. In repeat tests, this bias will not be visible. Only when the model is repeatedly ballasted and de-ballasted, the effect will become quantified. It will be possible to quantify an uncertainty interval for these model set-up uncertainties.

3.3 Uncertainty due to experimental procedures

The experimental procedures may have the largest effect on the uncertainties. For this uncertainty analysis, these experimental procedures are divided in groups of uncertainties related to:

1.1.1 Uncertainties with respect to pre-test settings.

Prior to the model tests, the RPM and the neutral rudder angle(s) are set to certain values, or an autopilot steers the vessel. The RPM is selected on RPM-speed tests carried out before the real manoeuvring tests, and the selected RPM will be a source of uncertainty. Again, this is a bias, which is an uncertainty.

3.3.1 Uncertainties related to the release of the model and the state at the start of the manoeuvre

For turning circle and zigzag tests, the manoeuvre starts at the time when the first rudder action takes place. The history of motions before this first rudder action is not taken into account in the analysis: it is assumed that the model is ‘steady’ and in ‘equilibrium’. The amount of steadiness is a source of uncertainty, which could be bias and/or random.

The equilibrium at the start of the manoeuvre is indicated by the procedures in the model test basin (which should be focussed on having these initial conditions as close as possible to the target values). The following variables will show a bias or a random uncertainty which will affect the final outcome to some extent.

- Drift angle
- Rate of turn
- Rudder angle
- Heel angle
- Ship speed
- RPM
- Accelerations caused by the autopilot
- A bias in release condition or acceleration phase

Part of these phenomena will show up while performing repeat tests, but not all of these aspects, because the release could be biased. For example, when the release mechanism always shows a movement in a lateral direction, this may affect the initial condition always in the same way, which makes it a systematic bias which is not covered by repeat tests.

3.3.2 Uncertainties related to the measurement set-up.

There will be a disturbance from test arrangement on model (e.g. an umbilical for power cables and signal cables, or the fact that tests are performed in open air facilities). These uncertainties may lead to bias and random uncertainties on the final result.

3.3.3 Undesired facility related hydrodynamic effects.

A ship model's dynamics and, therefore, test results may be affected by several influences caused by the limitations of the experimental facility, so that tests are not performed in unrestricted still water. Some examples are:

Residual motion of the water in the basin may affect the model's dynamics if the waiting time between two runs is too short.

Non-stationary phenomena occurring during transition between acceleration and the real test may also affect the model's dynamics. In particular, the achievement of steady state running condition prior to the start of the manoeuvre can have large consequences on the results of free running manoeuvring tests. Basin width and length limitations induce undesired additional forces and modify the trajectory, e.g. wall effects.

In shallow water tests, bottom profile variations will affect the dynamics of the model.

The influence of these effects on the accuracy of test results generally increases with decreasing water depth. Although complete prevention is principally impossible, the effects can be reduced by an adequate selection of test parameters.

3.3.4 Uncertainties on ship control equipment parameters.

During a test run, a number of control equipment parameters (propeller rpm, steering device angle, etc...) are controlled; setting or control errors have a direct influence on the motions of the model.

- Accuracy of the heading measurement leading to the "laying of the rudder" (is it a 10/10 or a 10/11 zigzag manoeuvre?);
- Accuracy of the rudder angle (is it a 10/10 or a 11/10 zigzag manoeuvre?);
- The way in which the torque control operates (for manoeuvres carried out with a constant torque strategy);

These uncertainties may lead to bias and random uncertainties on the final result.

3.4 Measurement uncertainty

The position and heading of the model are the most important information obtained from the free model tests; hence the accuracy of these measurements should be documented.

The following values are measured and are hence subject to measurement uncertainty:

- Position and heading
- Speed

- Yaw rate
- Rudder angle
- Propeller rate

3.5 Uncertainty in analysis

In the analysis, the measured time series of the path and heading are analysed and data reduction is performed. The values of for instance overshoot angles, advance or tactical diameter are derived using an analysis procedure.

- The type and amount of filtering of the raw time traces data;
- Eventual correction of the results for any discrepancies. These corrections may be based on the measured variations or biases of earlier measured phenomena, such as the 'rudder reversal' phenomenon from section 3.3.4.

As an example: for the determination of the tactical diameter, the lateral deviation of the model with respect to the original lateral position is taken. This should be taken at a heading which differs from the starting heading by 180 degrees. The measurement of the heading will influence the results in two ways: at the beginning of the manoeuvre, because it determines the initial offset. At the end of the manoeuvre, because the lateral distance at 180° of heading determines the tactical diameter.

3.6 Grouping of the individual uncertainty sources

All individual uncertainty contributions from this chapter are grouped in a table, shown in Figure 1. Six groups of individual uncertainty sources can be observed.

In this table, all sources of uncertainties can be estimated. Some can be assigned to the classical type A uncertainty analysis (namely box number (6)). Some values should be (partly) obtained from repeat tests (boxes number (1), (2), (4) and (6). Other values can be obtained through uncertainty propagation analysis (boxes number (1) and (3)). Box (5) is the classical measurement uncertainty, for which values can be obtained using the well-defined methods of calibration uncertainty. These different ways of treating these boxes is explained in Chapter 4.

		Uncertainties of deterministic nature	Uncertainties of stochastic nature
Related to the performing of the model test	Random	(1) "error is constant during 1 run" • Initial drift angle • No steady state at start of run • …	(2) Inherent hydrodynamic uncertainty • Turbulence • …
	Systematic	(3) "error is constant during a set of tests" • Draught uncertainty • GM uncertainty • Permanent bias in the initial conditions	(4) Facility bias • Influence of umbilical • …
Measurement related	Measurement accuracy	(5) • Calibration offset • Analysis method • …	(6) • Noise on sensor • …

Figure 1: Grouping of the individual uncertainties in different groups

4. QUANTIFICATION OF THE UNCERTAINTIES TOWARDS THE FINAL RESULT

Obtaining the uncertainty interval for the final result is the combination of three types of approaches. This is different from the approach presented for a captive test in ITTC 7.5-02-02, General Guidelines for Uncertainty Analysis in Resistance Towing Tank Tests . The three types of approaches available are:

(1) Measurement uncertainty analysis, determines the uncertainty of measuring equipment, as carried out many times in UA analysis (Coleman & Steele, 2009). This should also include data reduction and data analysis.

(2) Repeatability analysis, giving the scatter in data due to a number of tests. This reveals stochastic uncertainties which are otherwise unidentifiable.

(3) Uncertainty propagation analysis. With the aid of uncertainty magnification factors, UMF's, uncertainty of the results can be determined from uncertainties in input variables, i.e. draught and trim. Characteristic is that these uncertainties are the same for repeat runs, so that repeatability tests do not reveal a spreading in results due to these input variables.

These three approaches do not contain mutely exclusive contributions to the total combined uncertainty. Care has to be taken when deciding which factors are overlapping and which are exclusive. First the three approach types are elaborated separately in the following three sections. These three approaches are then combined to determine the combined uncertainty.

4.1 Measurement uncertainty analysis

The first type of uncertainties is related to the measurement uncertainty of the used sensors. Sensors of any type typically have a random standard uncertainty (or Type A) and may contain systematic standard uncertainty components (or Type B).

As an example the position measurements and one of its derivatives, forward velocity, are considered. The example is taken from free running model tests with the KVLCC2 as reported by Quadvlieg and Brouwer (2011). These free running model tests use a Krypton position measurement system.

The Krypton position measurement typically exhibits a 1 mm uncertainty interval (U95) for translations and a 0.1 deg U95 for rotations (model scale values). These are random components. The rotations may contain a systematic error, caused by oblique mounting of the camera, which is corrected using a steady turning circle measurement. When this correction would not be carried out, the combined standard uncertainty of the rotations would be higher, namely 0.3 deg.

The position of the carriage on which the Krypton camera's are mounted is measured through rulers with an U95 of 0.1 mm. The combined measurements from the carriage and Krypton system gives the positions of the model. Important to assess the velocities of the model is the accuracy of the time at which a measurements is taken. Due to the combination of various systems, this time of measurement has an U95 of 0.002 s for position signals. Due to this uncertainty, derivative signals like velocity and drift angle contain scatter if no signal conditioning is applied. Low pass filters can be used to suppress this scatter. However, care has to be taken not to delete useful information by filtering too stringent.

Uncertainty intervals established by analysis of the measurement uncertainty are limited to a single test. No information is obtained for uncertainty regarding the repeatability and reproducibility of the test.

4.2 Repeatability tests

The second type of uncertainties is resulting from stochastic scatter that would be visualised through repeat tests. Repeat tests are several tests performed with the same conditions and set points. The results of these tests will however not be the same. The resulting distribution of these results are said to be the parent population of the repeatability uncertainty. The example is taken from free running model tests on KVLCC2 as reported by Quadvlieg and Brouwer (2011), the free running manoeuvring tests on Hamburg Test Case (HTC) as reported by Toxopeus (2011), and the free running manoeuvring tests on 5415M as reported by Toxopeus, van Walree and Hallmann (2011).

The differences between the results are related to various random uncertainty sources:

Randomness in the state at the moment the manoeuvre begins (initial condition). Since the model is brought up to speed using external aids and its own controller, the initial conditions will not always exactly be on the target conditions, i.e. zero drift angle and zero rate of turn.

Any deviation in the initial conditions will have a systematic influence on the end result of a manoeuvre. The following initial conditions are considered to influence the results: Heading ψ_0 at the time that the manoeuvre starts t_0, rate of turn r_0, drift angle β_0, heel angle φ_0, speed V_0, rpm (the speed and rpm may not be in equilibrium), rudder angle δ_0, and rudder history before t_0. Also the corresponding accelerations may not be zero. In the towing tank, the automated manoeuvre only begins when all these parameters are within set margins. The word *randomness* in the release conditions is deliberately chosen. A systematic bias could also occur, but cannot be obtained through repeat tests.

Another source of randomness is the stochastic behaviour of lift and drag forces of the hull and appendages due to the variable point of flow separation and turbulent effects. This source of uncertainty can only be observed by means of repeatability tests.

A third source of uncertainty within the repeatability results is the stochastic influence of any umbilical cables in the measurement set-up. The carriage is programmed to keep the umbilical cables strictly vertical with as little side force influencing the model as possible, however some side forces may still be present, which may be random.

Small deviations from the target position lead to a random force component which eventually may lead to small deviations of the model position.

The true mean is the value that would be found only when an infinite number of samples is acquired. A higher number of realisations will lead to a smaller repeatability uncertainty although the parent population is assumed the same. This is explained by the following equation, see Coleman & Steele (2009) and Toxopeus (2011):

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{N}} \qquad (1)$$

In which N is the number of realisations, σ is the standard deviation of the parent population and $\sigma_{\bar{x}}$ is the standard deviation of the mean. For example, when we have four realisations from a parent population with standard deviation 2.0, the resulting mean is assumed to have only a standard deviation of 1.0. This lower number indicates the mean value is closer to the true mean.

When the model is symmetrical (i.e. a twin screw model), the starboard (SB) and portside (PS) results might be taken together in the estimation of the repeatability uncertainty. When the model is a single screw model (which makes it an asymmetrical model with asymmetrical results), the SB results and PS results are not to be combined. In any case, the uncertainty interval of the SB turning circle may be applied to the PS turning circle assuming a similar behaviour to both sides (and vice versa).

The maximum number of repeat tests for the KVLCC2 tests reported by Quadvlieg & Brouwer (2011) was four, which only gives a degree of freedom of 3 which can be considered low. The number of repeat tests for the HTC tests reported by Toxopeus (2011) was 8 for tests at 10 knots, which gives a degree of freedom of 7, and 4 for tests at 18 knots. For 5415M, reported by Toxopeus, van Walree and Hallmann (2011), 4 or 5 repeat tests were carried out. In hindsight a number of ten repeat tests is recommended despite the high costs involved. Due to the low degree of freedom, a student distribution was assumed for all U95 values rather than multiplying the standard deviation by two in order to find the confidence intervals. For the KVLCC2 example, the repeatability of the overshoot angle has a U95 of 1 deg and the repeatability of the tactical diameter has a U95 of 30 m full scale.

Uncertainty intervals established by analysis of the repeatability uncertainty are limited to the information that is obtained from a set of tests. No information is obtained for uncertainty regarding systematic uncertainty sources like modelling errors.

Zig-zag 18 kn, with bilge keels								
	$\delta/\psi = 10°/10°$						$\delta/\psi = 20°/20°$	
	1st overshoot angle [deg]		2nd overshoot angle [deg]		Initial turning ability [L_{pp}]		1st overshoot angle [deg]	
	PS	SB	PS	SB	PS	SB	PS	SB
Average $\bar{\phi}$	11.0°	10.2°	23.4°	27.6°	1.68	1.70	21.2°	20.8°
Standard deviation s_ϕ	0.1°	0.2°	1.2°	1.5°	0.01	0.08	0.7°	0.6°
Observations n	3	3	3	3	3	3	3	3
$t_{\alpha/2}(n-1)$	4.30	4.30	4.30	4.30	4.30	4.30	4.30	4.30
$U = t \cdot s_\phi/\sqrt{n}$	0.4°	0.6°	2.9°	3.7°	0.03	0.21	1.8°	1.6°
$U/\bar{\phi}$	3%	6%	12%	13%	2%	12%	8%	8%
$\bar{\phi} - U$	10.6°	9.6°	20.6°	23.9°	1.65	1.49	19.4°	19.2°
$\bar{\phi} + U$	11.3°	10.8°	26.3°	31.3°	1.71	1.91	22.9°	22.4°

Figure 2: Result of uncertainty analysis based on repeat tests for free running model tests on HTC by Toxopeus (2011)

4.3 Uncertainty propagation through sensitivity coefficients

Specifically for free running manoeuvring model tests, the propagation of uncertainties is to be analysed. For example an uncertainty in the starting speed will propagate to an uncertainty at the end of a test. The way in which this uncertainty propagates is expressed in the sensitivity coefficient method. For FRMT, this can be dealt with in a very simple way using sensitivity analysis based on (for example) simulations using an empirical or dedicated mathematical model. In that way, the use of many dedicated model tests to study the uncertainty propagation can be avoided. This is explained in the following:

Uncertainty propagation (see Coleman and Steele, 2009) is used to calculate an uncertainty interval for an output variable as a result from the uncertainty in an input variable. So-called uncertainty magnification factors (UMF's) are key in this process. The uncertainty of an input variable is multiplied by the UMF to obtain the uncertainty contribution of that input variable to an output variable. Uncertainty intervals for input variables have to be established by dedicated measurements or otherwise assumed. For example, the initial yaw rate might be known, but an uncertainty in trim of the model has to be assumed. UMF's can be computed either analytically or by means of CFD or empirical simulations. Since the results of free-sailing manoeuvres come from a rather complex process, an experimentally obtained UMF is unlikely. The use of simulations is therefore recommended, as long as the simulations are adequate, because the simulation model itself induces an uncertainty on the computed UMF. The simulation model does not have to be very accurate, but it is important that the trends are correctly and robustly predicted. This means that for the investigation of the UMF's for a container ship, a mathematical model that is applicable for that container ship must be used, with its particular loading condition etcetera. The deviation of the result predicted by the mathematical simulation model compared to the model test should not be too large, although an exact match is not necessary. In practical terms a small change in an input parameter will not yield meaningful results. It is far more practical to look at the result of a range of larger changes in an input parameter and then obtain the gradient from a linear or appropriate higher-order expansion fitted to the data. In many cases it will not be practical to use the free-running model test to obtain the sensitivity result. Clearly it would not be cost effective to produce two (or more) models to explore the sensitivity of specific manoeuvres to, for example, breadth. In such cases, it is recommended to obtain the sensitivity coefficients from other methods. Possible simulation methods are:

- Numerical simulations based on captive test results;
- Numerical simulations based on CFD;
- Numerical simulations based on derivatives obtained using empirical methods;
- Empirical prediction methods.

Using these time domain simulations, it will be possible to determine the sensitivity to each input parameter. To determine the UMF with respect to one input parameter, at minimum of two simulations is required, one with no initial disturbance, the other with a small initial disturbance of any of the input parameters. However, care has to be taken with two issues. First of all, the physics involved need to be described in enough detail. For example, if a simulation does not contain the influence of roll angles, no UMF's involving initial roll angle can be computed for these will all stay zero while in reality there might be a non-zero contribution to the final result. The second issue involves the discretisation in simulations. When varying input variables by a too small amount in simulations, no change at all or an abrupt change in output variables might be observed. On the other hand a large variation will take you outside the linear trend. Often a large incremental time step or badly chosen data format in which variables are stored causes this behaviour. It is therefore recommended to start computing UMF's with a range of initial disturbances and study the relation between input and output variables. This relation should be a highly linear trend. The slope defines the UMF. A stepped or saw tooth pattern in the relation indicates a discretisation problem which should be solved before continuing calculating various UMF's.

As an example, Figure 3 demonstrates an uncertainty propagation. It shows the effect of the uncertainty in the overshoot angle ψ_{OS} due to the propagation of an uncertainty in the release velocity V_0.

	Example
Individual uncertainty source	Initial velocity of the manoeuvre, V_0
Uncertainty interval	$u95_{V_0} = 0.2[\text{knots}]$
Uncertainty magnification factor (UMF)	0.1 knots difference will result in 0.5 degrees difference in overshoot angle, UMF = 0.5/0.1 = 5 [deg/kn]
Individual uncertainty contribution	$u95_{\psi_{OS}(V_0)} = 0.2 \cdot 5 = 1[\deg]$
Total uncertainty	$u95_{\psi_{OS}} = \sqrt{\left(u95_{\psi_{OS}(V_0)}\right)^2 + \ldots}$

Figure 3: Calculation of uncertainty through uncertainty propagation

The stepwise approach consist of:

- The identification of individual uncertainty sources (for which guidance is given in Chapter 3 of this guideline);
- Measuring and defining individual uncertainties (precisions or bias);
- Identification of the uncertainty propagation coefficients or uncertainty magnification factors (UMF) (for example through simulations);
- Calculation of the individual uncertainty distribution through multiplication of the input uncertainty with the UMF;
- Calculation of total uncertainty using the root summed squared method of all individual uncertainty contributions.

When using simulations, create an UMF by performing a simulation for the situation without initial disturbance. Second, a simulation can be performed with initial disturbance. For the example of Figure 3, this means that the simulation should start with an RPM equal to the original RPM but a speed with a difference of DV from the original speed. After having done the two simulations, an original overshoot angle $\partial\psi_{OS_{original}}$ and an overshoot angle $\partial\psi_{OS_{offset}}$ calculated with the disturbed velocity V_s+DV_s is found. The UMF can then be calculated as:

$$\text{UMF} = \frac{\partial\psi_{OS}}{\partial V_s} = \left| \frac{\partial\psi_{OS_{offset}} - \partial\psi_{OS_{original}}}{\Delta Vs} \right| \quad (2)$$

5. EVALUATION OF THE COMBINED UNCERTAINTY

The combined uncertainty is now calculated as the RSS of the uncertainties due to the "measurement uncertainty", the "repeat tests", and the "uncertainty propagation". For the case of the overshoot angle, this is calculated as:

$$u_c(\psi_{OS}) = \sqrt{\begin{array}{l}\left(u_{c_{Measurement}}(\psi_{OS})\right)^2 \\ +\left(u_{c_{Repeat}}(\psi_{OS})\right)^2 \\ +\left(u_{c_{Propagation}}(\psi_{OS})\right)^2\end{array}} \quad (3)$$

In formula (3), the first contribution on the right hand side is the classical type A measurement accuracy. The second contribution on the right hand side is determined from repeat tests. This is drawn from repeat tests with a parent population of N repeats. The third contribution is determined from the uncertainty propagation analysis of uncertainties which are not quantified by repeat tests.

6. EXPANDED UNCERTAINTY

The expanded uncertainty should be obtained in terms of the combined standard uncertainties in accordance with [7.5-02-01-01].

7. SUMMARISING STATEMENT

This guideline explains how an uncertainty analysis of free running manoeuvring model tests can be carried out. The uncertainty analysis is focussed on the determination of the end result (i.e. a manoeuvring characteristic such as the tactical diameter or an overshoot angle). The method uses classical measurement uncertainty, uncertainty from repeat tests and uncertainty from uncertainty propagation. Especially the uncertainty propagation is important to address, because a free running manoeuvre is a transient manoeuvre, and effects that occur in the beginning of a test may affect the end result.

The method to quantify propagation of the uncertainty based on the initial conditions of a manoeuvre are very useful to investigate the effect of the initial condition (the conditions at the start of the manoeuvre) on the end result. It is recommended to use this method to verify whether deviations from the initial conditions are acceptable or unacceptable.

8. REFERENCES

Coleman, H.W. and W. G. Steele, 2009 “Experimentation, validation and uncertainty analysis for engineers”, 3rd edition, 2009, John Wiley & Sons, Inc., ISBN 978-0-470-16888-2

ISO, 1995, “Guide to the expression of uncertainty in measurement”, International Organisation for Standardisation, Genève, Switzerland.

ITTC – Recommended Procedures and Guidelines 7.5-02-01-01 “Guide to the Expression of Uncertainty in Experimental Hydrodynamics” (2008)

ITTC – Recommended Procedures and Guidelines 7.5-02-01-03 “Fresh Water and Seawater Properties” (2011)

ITTC – Recommended Procedures and Guidelines 7.5-02-02-02 Testing and Extrapolation Methods, “General Guidelines for Uncertainty Analysis in Resistance Towing Tank Tests” (2008)

ITTC - Recommended Procedures and Guidelines 7.5-02-06-01 “Free Running Model Test Procedure” (2014)

Quadvlieg, F.H.H.A. and Brouwer, J., 2011; “KVLCC2 Benchmark Data Including Uncertainty Analysis To Support Manoeuvring Predictions”. IV International Conference on Computational Methods in Marine Engineering (ECCOMAS MARINE), Lisbon, Portugal, 2011

Toxopeus, S.L., 2011, “Practical Application of Viscous-flow Calculations for the Simulation of Manoeuvring Ships”. PhD-thesis Delft University of Technology, 2011

Serge Toxopeus, Frans van Walree and Rink Hallmann, 2011, Manoeuvring and Seakeeping Tests for 5415M. NATO AVT-189 Specialists Meeting on "Assessment of Stability and Control Prediction Methods for NATO Air and Sea Vehicles", Portsdown-West, UK

APPENDIX A: EXPLANATION OF THE UNCERTAINTY PROPAGATION METHOD, APPLIED TO KVLCC2

All component standard uncertainties should be combined in the manner given in the ITTC Guidelines to the expression of uncertainty in experimental hydrodynamics [7.5-02-01-01]. When the input quantities are uncorrelated (independent) the total combined uncertainty is the square root of the sum of the squares of the standard uncertainties; given by equation (4).

$$u^2_{c\text{Propagation}}\left(y_j\right)=\sum_{i=1}^{n}c_{ij}^2\cdot\left(u\left(x_i\right)\right)^2 \qquad (4)$$

In equation (4), $u_{c\text{Propagation}}\left(y_j\right)$ is the uncertainty of the resulting manoeuvring characteristic y_j. $u\left(x_i\right)$ is the uncertainty of the individual uncertainty source x_i. c_{ij} is the uncertainty magnification factor of uncertainty source x_i to the end result y_j.

For example, the advance parameter in a turning test may well be influenced by the metacentric height; which does not appear in any of the data measurements used to process the results. Nevertheless, it is entirely possible to include such terms. The sensitivity of the parameter of interest should be found by an appropriate method (see section 4.3). The combined uncertainty is then obtained in accordance with equation (4). The following gives a list of possible sources of uncertainty that may be included (derived from the description given in Chapter 3). This list is not complete.

x_1 model length;
x_2 model breadth;
x_3 position of the model draught mark and model loading to draught mark with respect to trim;
x_4 position of the model draught mark and model loading to draught mark with respect to draught;
x_5 position of the model draught mark and model loading to draught mark with respect to heel angle;
x_6 mass displacement (as a function of the calibration for individual component masses);
x_7 radius of gyration in yaw;
x_8 radius of gyration in roll;
x_9 vertical position of the mass centroid (thus inferring GM);
x_{10} longitudinal position of the centre of gravity (this may be correlated to x_3);
x_{11} transverse position of the centre of gravity (this may be correlated to x_5);
x_{12} bias in initial model speed (surge velocity);
x_{13} bias in initial sway velocity (and hence drift angle);
x_{14} bias in initial yaw rate;
x_{15} propeller setting for self-propulsion point;
x_{16} propeller alignment;
x_{17} rudder alignment;

It should be noted that, in accordance with ISO GUM, all possible sources of uncertainty should be listed. However, many of these may have only a negligible influence on the resulting expanded uncertainty; and may thus be neglected. The decision to include or disregard parameters can be made using standard 'Design of Experiments' (DoE) techniques. Clear justification of such decisions should be included in the Uncertainty Analysis report.

Sensitivity Coefficients

For all of the above-defined uncertainty sources, the sensitivity coefficients or uncertainty magnification factors (UMF) c_1 to c_{17} should be obtained by an appropriate simulation method.

The case of the zigzag test

In addition to the above, some specific uncertainties exist for zigzag tests. Specifically, the execution of the rudder switch time is dependent on the measured heading angle; which itself includes uncertainties. This results in uncertainty in the overshoot angle as a function of the uncertainty in the heading angle multiplied by the sensitivity of a particular overshoot to any previous rudder switch command. Let's define the first overshoot angle ψ_{OS1} as y_1, and the second overshoot angle ψ_{OS2} as y_2. Then further (correlated) uncertainty exists due to the following:

$c_{18,1}$ sensitivity of the first overshoot to the first heading switch angle;
$c_{19,2}$ sensitivity of the second overshoot to the first heading switch angle;
$c_{20,2}$ sensitivity of the second overshoot to the second heading switch angle;
$c_{21,1}$ sensitivity of the first overshoot to the first rudder set angle;
$c_{22,2}$ sensitivity of the second overshoot to the first rudder set angle;
$c_{23,2}$ sensitivity of the second overshoot to the second rudder set angle;
c_{24} sensitivity of the first overshoot to the zero rate-of-turn point;
$c_{25,2}$ sensitivity of the second overshoot to the zero rate-of-turn point;

As described above, the sensitivity coefficients may be obtained by additional model tests or by alternative appropriate practical methods. This could include performing dedicated zigzag tests (experimentally or by numerical simulation).

To obtain the sensitivity coefficients or UMF's associated with heading switch angles (c_{18} to c_{20}) additional tests or simulations can be performed with alternative heading switch angles for the same rudder setting. For example, the overshoot angles may be obtained for tests including a 10°/9° (9° heading with 10° helm) and an 10°/11° (11° heading with 10° helm) test. The angles of heading sensitivity are chosen here in intervals of 1 degree. Depending on the sensiticity of the measuring equipment, this is an adequate choice. For less sensitive equipment, steps of +/- 2° may be selected. The gradient of the curve obtained by plotting overshoot angle against switch heading angle gives the sensitivity coefficient.

To obtain the sensitivity coefficients or UMF's associated with rudder set angle (c_{21} to c_{23}) an analogous method can be applied.

To obtain the sensitivity coefficients associated with the zero rate-of-turn point (c_{24} and c_{25}) additional tests or simulations can be performed with alternative rate-of-turn set points. For example, the overshoot angles may be obtained by taking the heading when the rate-of-turn is ±1° per second. The gradient of the curve obtained by plotting overshoot angle against the selected turn-rate setting gives the sensitivity coefficient.

However, when in the above described cases the sensitivity coefficient is determined using experiments, the measurement uncertainty should be taken into account, because otherwise, more correlated uncertainties are introduced.

Example of uncertainty propagation method elaborated for the example of the KVLCC2

For all individual input uncertainty sources x_i that are defined, the typical uncertainty intervals and UMF's were determined for manoeuvres performed with the KVLCC2. Individual UMF's can have a negative sign, but this sign is neglected on the conservative assumption that all individual uncertainty sources are uncorrelated and are symmetrically distributed. For the KVLCC2, the combined uncertainty determined by the uncertainty propagation method only, is given in Figure 4. Please note: all individual uncertainty sources which are determined by other means are not included in Figure 4. Figure 4 shows that the uncertainty of the overshoot angle due to the contributions determined by uncertainty propagation amounts to 0.13 degrees.

	$u(x_i)$	UMF	$u(y_{OS})$
Model characteristics			
Uncertainty in propeller offset	0.05 [m]	0.014 [°/m]	0.00 [°]
Uncertainty in rudder offset	0.05 [m]	0.66 [°/m]	0.03 [°]
Model set-up			
Uncertainty in draught	0.05 [m]	0.13 [°/m]	0.01 [°]
Uncertainty in trim	0.05 [m]	0.007 [°/m]	0.00 [°]
Uncertainty in radius of inertia	0.01 [Lpp]	0.001 [°/m]	0.00 [°]
Experimental procedure			
Pre-test settings			
Uncertainty in selected speed	0.2 [kn]	0.0049 [°/kn]	0.00 [°]
Model release			
Heading	0.8 [°]	0.075 [°/°]	0.06 [°]
Drift angle	0.8 [°]	0.11 [°/°]	0.09 [°]
Rate of turn	0.03 [°]	0.59 [°/°]	0.02 [°]
Initial speed equilibrium	0.4 [°]	0.1 [°/°]	0.04 [°]
Rudder angle	0.01 [°]	0.19 [°/°]	0.00 [°]
Yaw check angle	0.2 [°]	0.075 [°/°]	0.02 [°]
Ship control parameters			
Uncertainty in rudder angle	0.3 [°]	0.19 [°/°]	0.06 [°]
Uncertainty in yaw check angle	0.2 [°]	0.075 [°/°]	0.02 [°]
Combined uncertainty of "uncertainty propagation" contributions			0.13 [°]

Figure 4: Table with the combined uncertainties determined through the uncertainty propagation method.

Total combined uncertainty elaborated for the example of the KVLCC2

For the KVLCC2, it was determined that the uncertainty of the measurements was 0.02 degrees. The uncertainty determined from 4 repeat tests was 1°. The uncertainty determined by the uncertainty propagation (see Figure 4) amounted to 0.13°. Consequently, the uncertainty of the overshoot angle ψ_{OS} would amount to:

$$u_c(\psi_{OS}) = \sqrt{(0.02)^2 + \left(\frac{1}{\sqrt{4}}\right)^2 + (0.13)^2} = 0.52° \tag{5}$$

Observe that in this case the number of repeat tests is the decisive factor.