ITTC Quality System Manual

Recommended Procedures and Guidelines

Procedure

Seakeeping Experiments

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Seakeeping Experiments

1. PURPOSE OF PROCEDURE

This procedure outlines the recommended state-of-the-art practice of model seakeeping experiments for the evaluation of ship hull performance in predefined operational and environmental conditions.

The procedure describes requirements relevant to the selection of model size, completeness of its geometry, ballasting and mass distribution and possible model configurations. It provides recommendations for model response data measurements, and operational and environment parameters that should be included in the test plan.

The procedure also outlines the recommended approach to data analysis and presentation formats as well as the preferred approach to uncertainty analysis including theoretical background and practical examples.

2. SEAKEEPING EXPERIMENTS

2.1 Model Size

The size of the model should be such that tank wall interference is avoided for the range of wave frequencies and model speeds to be tested. Figure 1 and Table 1 give, in dimensionless form, a relationship between model length L_M, tank breadth B_T, Froude number Fr and the highest wave frequency ω at which interference effects may occur in head waves.

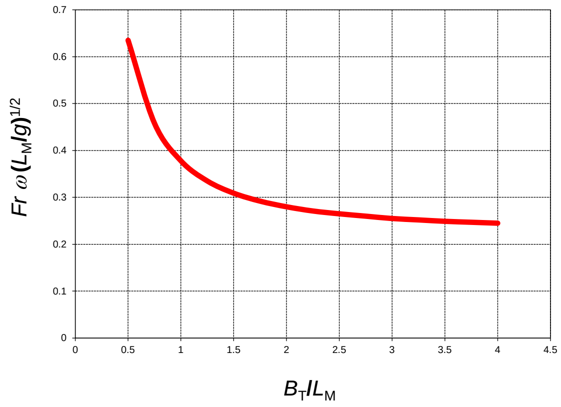

Figure 1. Maximum frequency at which tank interference occurs in head waves

B_T/L_M	$Fr \cdot \omega\sqrt{L_M / g}$
0.50	0.635
0.75	0.458
1.00	0.378
1.25	0.335
1.50	0.309
1.75	0.292
2.00	0.280
2.25	0.271
2.50	0.265
2.75	0.260
3.00	0.255
3.25	0.252
3.50	0.249
3.75	0.247
4.00	0.245

Table 1. Maximum frequency at which tank interference occurs in head waves

Those calculations are made by estimating the potential generated by a source with harmonic strength. Calculations using the unified-slender ship theory were made by Kashiwagi & Ohkusu (1991).

Figure 2 shows where tank-wall effects are expected for a prolate spheroid of beam - length ratio 1/8 with $K = \omega^2/g$. The dotted lines in Figure 2 show the results of Figure 1.

Non published work of Fernandez shows that the finite depth must be taken into account in tank-wall effects for:

$$Fr \cdot \omega_e \sqrt{L_M / g} \le 1/2$$

with ω_e, the encounter circular frequency.

These estimations use calculations of the potential generated by a source with harmonic strength in finite depth. Figure 3 shows results in the same format as Figure 1.

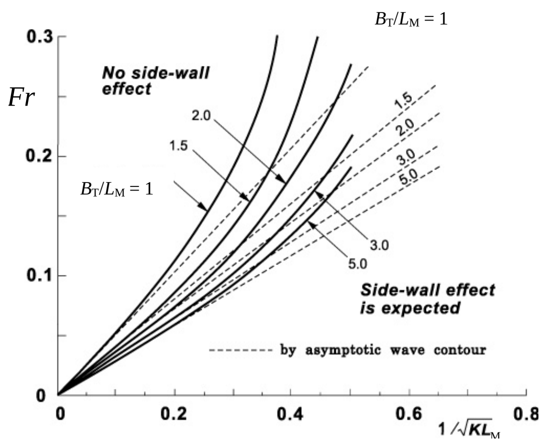

Figure 2. Estimation of tank-wall effects using unified slender theory (Kashiwagi & Ohkusu 1991).

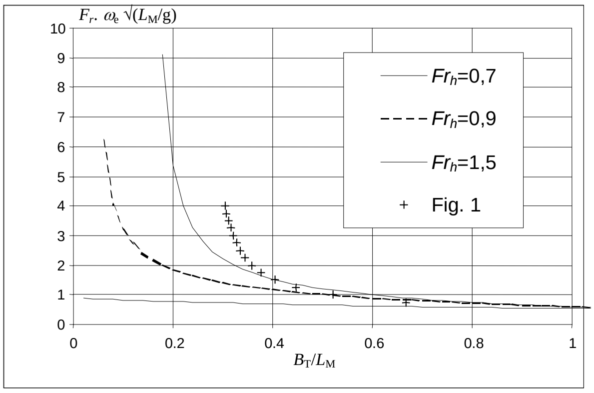

Figure 3. Maximum frequency at which tank interference occurs in head waves and finite depth.

2.2 Model Completeness

It is desirable that the model is complete up to the uppermost weather deck, including forecastle and bulwarks. A more complete modelling of deck fittings, deck houses and freeing ports may be necessary if parameters such as deck wetness are to be measured.

All appendages should be fitted, and the report should state which appendages were fitted during the experiments.

2.3 Model Weight Distribution

If bending moments, shears, and torsion experienced by the model in waves are to be measured, the longitudinal and transverse distributions of mass must be reproduced as correct as possible, and must be correctly reported. In other cases, only the radii of gyration need to be simulated. For tests in head or following waves with a model restrained in rolling, it is not necessary to simulate the transverse weight distribution.

If the longitudinal radii of gyration for pitch or yaw are unknown, a value of 0.25 L_{PP} should be used. If the transverse radius of gyration is unknown, a value between 0.35B

and 0.40*B*, depending on the ship type, should be used. (These values are those without including the effect of added mass).

For experiments during which rolling is not restrained, the metacentric height should be simulated. If the vertical position of the centre of gravity is unknown, it should be established and reported. As an alternative to ballasting the model to a specified transverse radius of gyration, the natural period of rolling of the full-scale ship may be simulated.

When measuring loads on catamarans, cross products of inertia have to be taken into account.

2.4 Guidance System

The guidance system should be such as to impose the minimum restraint on the motions of the model. It is desirable that even in head or following waves the model should have the freedom to roll. In oblique waves, care also must be taken to minimize restraint on sway and yaw motions.

The report should describe in detail the characteristics of the guidance system used. Should the guidance system be a soft mooring arrangement with springs, the natural frequency of the system for each heading should be far from the wave frequency range. The recommended ratio of natural mooring frequency to wave (peak) frequency is 1/6.

Model control systems used in seakeeping experiments, particularly with respect to autopilot and roll stabilization, usually serve two objectives:

- To assess the sea-keeping capabilities of a vessel in a reliable and repeatable manner, and/or,
- To assess the efficacy of a full-scale design for a particular control system or set of control surfaces.

The approach taken in the first one is to replace the need for a human pilot in sea-keeping experiments. Automatic control eliminates differences seen in sea-keeping experiments caused by differences in operation between human pilots. Care must be taken, however, to ensure that the control system dynamics of the automatic steering do not interfere with the vessel dynamics being measured in a seaway.

The second item above applies to scenarios in which a full-scale control design is to be evaluated. In this case, care must be taken to ensure that the dynamics of the full-scale control system are preserved. Note that such control systems will likely influence the open-loop dynamics of the vessel and impact the vessel's natural sea-keeping performance.

In Appendix B of this document and in the 28^{th} ITTC Proceedings, more details are given for the theory behind the tuning procedures for control systems in model scale particularly for heading control, tracking control, roll stabilization through active fins and roll stabilization through rudder. High-level tuning procedures themselves (for both seakeeping experiments as well as scaled control assessment experiments) are detailed.

2.5 Free Running Tests

Testing with a free running self-propelled model is preferred method for seakeeping experiments. Experiments are usually run at predefined speeds. Preliminary tests can be necessary to adjust the rpm in order to reach the desired speed in waves. Alternatively, the rpm can be automatically controlled to obtain the desired mean speed in waves.

The autopilot parameters should be chosen to reflect a realistic full-scale response of the model. Care should be taken in selecting a realistic rudder rate during model tests. These parameters should be reported.

Care has to be taken to reduce any influence of cables or safety lines on the model's motions to a minimum.

It is recommended that rpm and rudder action are continuously recorded.

2.6 Measurement of Wave Loads

Segmented models for measuring global loads should have natural frequencies far from the wave frequency range. These frequencies have to be measured and documented.

The mass, CG and inertias of each separate segment have to be known (measured or calculated) and reported. Preferably, the loads due to the mass and inertia of the segments should be separated from the total loads during analysis to get the wave-induced loads.

For global bending moment, sagging and hogging loads should be reported.

2.7 Measurement of Added Resistance

The power increase in waves can be measured directly with free running models or determined indirectly from measurements of added resistance on captive models (refer to ITTC recommended procedure 7.5-02-06-0.1 and the new recommended procedure "Calculation of the weather factor f_w for decrease of ship speed in waves").

2.8 Measurement of Impact Loads

The guidelines for the measurement of impact loads are presented in procedure 7.5-02-07-02.3 Loads and Responses Seakeeping, Experiments on Rarely Occurring Events.

2.9 Parameters to be Measured

The hull motions, motion rates and accelerations in the desired degrees of freedom should be measured.

Wave height measurements should be made with a probe mounted close to the model, but not causing interference. The probe should preferably be fixed to the carriage, but measurements may be made at a fixed point in the tank. In the latter case, the measuring point should be selected in the position where waves are fully formed without being affected by the waves reflected at the wave maker and the tank walls & beaches.

Non-contact probes are preferable for wave measurements moving with the model, especially at high speeds. There are reliable wave tape sensors available that are flush with the hull at a specific station and cause no interference. Alternatively, such sensors can also be considered.

The capability to measure the following additional parameters should be provided:

- Relative motion. Measurements of the relative motion between the model and the water surface at points that allow correlation with wave and other motion data.
- Rudder angle. In cases where active rudder control is employed, the rudder control signal and actual rudder angle should be continuously monitored.
- Impact pressures on the hull or on deck at selected locations.
- Still water resistance and added resistance in waves (if not freely running).
- Water on deck.

- Propeller revolutions. Whenever a self-propelled model is used, the shaft revolutions should be recorded.
- Visual records. Tests should be recorded visually, preferably in a way allowing scaling of time.

Additionally, the following parameters may be measured depending on the test requirements:

- It is recommended that propeller torque and thrust be also continuously recorded.
- Encounter (heading) angle. The angle between the mean model heading and the wave direction.
- Leeway (or drift) angle. The angle between the mean model heading and the tangent to the path of *CG*.

2.10 Headings

When performing tests in oblique seas, the range of encounter angles between zero and 180 degrees should be selected in accordance with the stated test objectives. The 180 degrees heading represents head seas.

2.11 Regular Waves

For conventional ship forms, a sufficient number of tests should be carried out at each speed to provide adequate data for a minimum range of wavelengths from at least 0.5 L_{PP} to 2.0 L_{PP}. More tests with closely spaced wavelengths can be necessary to ensure a good definition in the resonance region. Either the ratio of the wave height to L_{PP} or the ratio of wave height to wavelength should be maintained constant. (The recommended value of the ratio of wave height to wavelength is around 1/50).

For new or unconventional hull forms and to investigate inception of large or extreme responses (around resonance frequencies, parametric roll) experiments in wave frequencies equivalent to a wavelength of 4.0 L_{PP} or higher should be considered. For similar reasons wave height to wavelength ratios of 1/30 to 1/20 or less, depending on model facilities limits should be taken into account.

In determining the motions, it is recommended that the average amplitude and period of at least 10 cycles be obtained. Alternatively, a spectral analysis following the procedures for irregular waves outlined below could be followed to obtain the mean amplitude and period of waves and responses. Guidelines for regular wave data analysis are given in the ITTC Recommended Procedure 7.5-02-07-03.2 “Analysis Procedure for Model Tests in Regular Waves”.

2.12 Transient Waves

The transient wave technique is an experimental technique in which a wave train that contains wave components of all the relevant frequencies is produced in such a way that the component waves reach a certain place in the test tank simultaneously so that a single large wave packet is formed. If a model structure is positioned at the place where the single large wave packet accumulates, response characteristics to regular waves of all the frequencies contained in the wave packet are obtained in one single experiment (provided the linear superposition assumption holds).

This technique proves to be very efficient as a standard tool for evaluating RAO’s of stationary offshore structures or towed/self-propelled ships. Due to the short time duration of the wave packet possible reflections in the testing basin are avoided. Clauss (1999) gives an overview of the technique and its application to seakeeping tests for evaluating RAOs and its application the simulation of design storm waves.

A related technique to efficiently obtain the linear response characteristics is the use of a broad banded spectrum of a specific shape to obtain RAOs. A typical spectrum used for this application is pink noise (ITTC, 2002).

2.13 Irregular Waves

Tests should be carried out in waves corresponding to the sea conditions in which the vessel may be required to operate. In the absence of specific wave spectrum data the ITTC spectrum should be used for open ocean and JONSWAP spectrum should be used for fetch-limited seas. When generating irregular waves in a tank, the input signal to the wave maker should be produced such that the generated waves are not repeated within the generated wave train.

Irregular wave generation in experimental tanks is subjected to voluntary or involuntary truncation of idealized spectrum as a result of mechanical limits of wave making facilities. The truncation frequency is facility specific and depends on characteristics of the wave maker and model scale selected for the experiment. Selection of too low cut-off frequency affects properties of resultant spectrum and values of target significant wave height $H_{W1/3}$ and modal period T_P. If $n=f_T/f_P$: f_T is truncated frequency and f_P is peak frequency of idealized spectra, the recommended ratio n for cut-off frequency for most facilities is greater than 2, and preferably approaching 3.

Data should preferably be digitised before analysis, using sample rates appropriate for the avoidance of aliasing with the individual measured parameters. Care must be taken for the duration of the data acquisition so that enough data are recorded for the objective of the test.

The test duration is represented by total number of waves (encounters) N. The N=50 should be taken as a lower limit. Larger values are to be preferred and it is more usual to take N=100 as the standard; N=200 or above is considered excellent practice. For the following sea case, 30 minutes of equivalent full scale is considered sufficient.

The time interval between test runs is also important and can be tank specific. In most cases 20 minutes between runs is acceptable for a typical facility. The residuary tank disturbance of less than 1% of the next target wave height is a valid alternative.

The sample rate in the data acquisition needs to be fast enough in order to achieve sufficient resolution. A sampling rate corresponding to about 4 Hz at full scale is enough for most measurements but much higher rates (in the order of kHz) are necessary to detect peaks of slamming loads.

Energy spectra of waves and relevant responses should be produced through spectral analysis using either the indirect method of Fourier transformation of the autocorrelation function, or the direct method of splitting the record into suitable blocks and subjecting these to a Fast Fourier Transform. A comparison of the spectrum of the generated waves with the target spectrum should be carried out, since resulting vessel responses may be sensitive to particular parts of the spectrum (ITTC, 2002).

In addition to the spectral analysis, statistical analysis should be performed to produce at least the mean, maximum, minimum, and the mean of 1/3 highest values. In the presentation of the results the techniques utilised to smoothen spectral shapes, such as block overlapping, should be documented. When reporting statistics, the number of events and number of encounters should also be reported together with the overall statistics.

When non-linear effects and extremes are of importance, attention should be paid to more detailed wave characteristics (ITTC, 2002) and the response characteristics. Considering the probability distributions of the wave elevation and the individual crest and troughs as well as the probability distributions of the individual peaks in the response can be helpful in this respect.

For the measurement and analysis of rarely occurring events such as slamming or wetness refer to ITTC recommended procedure 7.5-02-07-02.3.

2.14 Data Presentation

The coordinate system in which data are presented should be defined. Motion components should also be defined. Linear translations and rotations may be presented in non-dimensional form as being divided by wave elevation and wave slope respectively. Rudder angles may be non-dimensionalized by wave slope or be presented in other appropriate non-dimensional form.

Translations	$\frac{x_{1,2,3}}{\varsigma_A}$
Rotations	$\frac{x_{4,5,6}}{\kappa\varsigma_A}$

Dimensional presentations can sometimes be more appropriate depending on the objectives of the experiment. Phase angles should be given in degrees and increases in resistance and propulsion parameters should be presented in the non-dimensional form. Accelerations should be made non-dimensional by $L_{PP}/(g\zeta_A)$. It is recommended that the results are plotted to a base of $\omega(L_{PP}/g)^{1/2}$ or $\omega_e(L_{PP}/g)^{1/2}$, although, depending on the objectives of the experiment, other bases such as wavelength - ship length ratio or wavelength may be appropriate. The limit of tank wall interference effects should be indicated on the plots.

For tests in irregular waves, the corresponding wave-energy spectrum should be defined.

When appropriate, performance in irregular waves should be presented in non-dimensional form involving a characteristic wave period or frequency and a characteristic wave height.

The results of statistical analyses may be presented to depict probability of exceedance and as cumulative probability distribution for selected responses.

Tabular presentation of results is recommended in addition to plots.

3. PARAMETERS

3.1 Parameters to be Considered

The following parameters defining the tests are to be taken into account (as applicable):

- Scale
- Model dimensions
- Ratios of model to tank dimensions
- Hull configuration (lines, appendages, superstructures, ...)
- Loading conditions (displacement and draft)

- Mass distribution (CG, inertias, ...)
- Towing and/or restraining device characteristics (specially DOF)
- Speeds and headings
- Wave characteristics (heights, periods, spectra, dispersions, ...)
- Autopilot control law and gains
- Speed control characteristics
- Run duration
- Number of runs per test condition
- Positions of sensors (accelerometers, relative motion, encountered wave, ...)
- Resonance frequencies for segmented models
- Sampling frequency
- Sensor calibrations and accuracy

3.2 Recommendations of ITTC for Parameters

1975 Performance in irregular waves should be presented in non-dimensional form involving wave characteristic period and characteristic wave height.

1978 Recommendation for open ocean spectral formulation:

$$S(\omega) = \frac{A}{\omega^5} e^{-B/\omega^4} \quad (1)$$

where

$$A = 173\left(\tilde{\zeta}_W\right)_{1/3}^2 / T_1^4$$
$$B = 691 / T_1^4$$
$$T_1 = 2\pi m_0 / m_1$$

1984 Recommendation for long crested limited fetch sea spectral formulation:

$$S_J(\omega) = 155 \frac{\left(\tilde{\zeta}_W\right)_{1/3}^2}{T_1^4 \omega^5} \exp\left(-\frac{944}{T_1^4 \omega^4}\right) 3.3^{\gamma} \quad (2)$$

where:

$$\gamma = \exp\left[-\frac{(0.191\omega T_1 - 1)^2}{2\sigma^2}\right]$$
$$\sigma = \begin{cases} 0.07 & \omega < 5.24 / T_1 \\ 0.09 & \omega > 5.24 / T_1 \end{cases} \quad (3)$$

This formulation can be used with other characteristic periods by use of the following approximate relations:

$$T_1 = 0.924 T_{-1} = 0.834 T_0 = 1.073 T_2$$

where T_{-1} is the energy average period ($2\pi m_{-1} / m_0$), T_0 is the spectral peak period, T_1 is the average period ($2\pi m_0 / m_1$) and T_2 is the average zero crossing period estimated from the spectrum ($2\pi \sqrt{m_0 / m_2}$).

4. VALIDATION

4.1 Uncertainty Analysis

The detailed procedure of uncertainty analysis following the principles behind the ISO-GUM is shown in the Appendix A.

4.2 Benchmark Tests

1) Seagoing Quality of Ships. (7th ITTC, 1955, pp.247-293). A model of the Todd-Forest Series 60 with C_B=0.60. Results from 7 tanks are presented.
   Fr = 0, 0.18 ,0.21 ,0.24 ,0.27 and 0.30
   L_{PP} / H = 36, 48, 60, 72
   $\lambda / _{pp}$ = 0.75, 1.0, 1.25, 1.5

2) Comparative Tests at Three Experimental Establishments with the Same Model. (11th ITTC, 1966, pp.332-342)
British Towing Tank Panel: A 10 ft. Fibre-glass model of the S.S. Cairndhu.
A series of experiments on a ship model in regular waves using different test techniques.
Data obtained in irregular and transient waves and some result predicted by the theory (based on Korvin Kroukovsky's work and employing the added mass and damping coefficients calculated by Grim).

3) Full Scale Destroyer Motion Tests in Head Seas (11th ITTC, l966, pp.342-350).
Comparison among motion responses obtained from full scale tests, model experiments and computer calculations for destroyer H.M. "Groningen" of the Royal Netherlands Navy

4) Experiments in Head Seas For Series 60.

4-1) Comparative Tests of a Series 60 Ship Model in Regular Waves (11th ITTC, 1966, pp.411-415). Series 60 with C_B=0.60.

4-2) Experiments on Heaving and Pitching Motions of a Ship Model in Regular Longitudinal Waves (11th ITTC, 1966, pp.415-418). Series 60 with C_B=0.60.

4-3) Experiments on the Series 60 with C_B=0.60 and 0.70 Ship Models in Regular Head Waves (11th ITTC, 1966, pp.418-420)

4-4) Comparison of Measured Ship Motions and Thrust Increase of Series 60 Ship Models in Regular Head Waves (11th ITTC, 1966, pp. 420-426).

4-5) Estimation of Ship Behaviour at Sea from Limited Observation (11th ITTC, 1966, pp.426-428)

5) Analysis of the S-175 Comparative Study (17th ITTC, 1984, pp.503-511).

6) S-175 Comparative Model Experiments (18th ITTC, 1987, pp.415-427)

7) Rare Events (19th ITTC, 1990, pp.434-442).
Comparison of results from tests at 12 establishments in irregular waves. Absolute and relative motions. S-175 at *Fr* =0.275.

8) The ITTC Database of Seakeeping Experiments (20th ITTC,1993, pp.449-451).

8-1) Tests of Two Dimensional Models. Added mass, damping and wave exciting forces

8-2) Tests of a Wigley hull form. Added masses, damping, exciting forces and seakeeping motions and loads.

8-3) Tests for S-175.

9) The ITTC Database of Seakeeping Experiments (21st ITTC, 1996, pp.43). S-175, high speed marine vehicle

10) Numerical and Experimental Investigation to Evaluate Wave-Induced Global Design Loads for Fast Ships (Schellin et al, 2003). Two segmented models of fast ships (*Fr* up to 0.63) were tested in head seas. Motions and global loads are reported. The results are compared with several non-linear codes.

5. REFERENCES

Kashiwagi, N. and Ohkusu, M., 1991, "A new theory for side-wall interference effects on forward-speed radiation and diffraction forces", Schiffstechnik, vol. 38.

Clauss, G.F., 1999, "Task-related wave groups for seakeeping tests or simulation of design storm waves", Applied Ocean Research, vol. 21, pp. 219-234.

ITTC, 2002, "The Specialist Committee on Waves – Final Report and Recommendations to the 23rd ITTC", Proceedings of the 23rd International Towing Tank Conference, vol. 2, pp. 505-736.

Schellin, T.E. et al, 2003, "Numerical and Experimental Investigation to Evaluate Wave-Induced Global Design Loads for Fast Ships", Transactions SNAME, vol. 111, pp. 437-461.

ISO/IEC 2008, "Guide 98-3, Uncertainty of measurements – Part 3: Guide to the expression of uncertainty in measurements (GUM: 1995)", 2008 Switzerland.

ITTC (2008), "Discussion to the 25th ITTC Seakeeping Committee by Joe Longo, Claus Simonsen, Fred Stern", Proceeding of 25th ITTC-Volume III, September 2008, Fukuoka, Japan, pp. 697-701.

Kishev, R., (1998), "Uncertainty Analysis of Dynamic Model tests and Its Application to Capsizing Simulation in Waves", Proceedings of International Workshop on Modeling of Ocean Environments in Waves & Current Basin, February, 1998, Taejon, Korea.

Yum, D.J., Lee, H.Y. and Lee, C.M., 1993. Uncertainty Analysis for Seakeeping Model Tests. *Journal of the Society of Naval Architects of Korea*, 30 (3): 75-89.

Appendix A

A.1. Background to ISO-GUM

The recommendation of the ITTC 2008 was to adopt the ISO-GUM (International Organization for Standardization, Guide to the Expression of Uncertainty in Measurements, ISO 1995) approach to conducting uncertainty analysis of experimental results. The ISO GUM recognises two groups of uncertainty, type A and type B, which are based on way in which the uncertainty is evaluated. Type A represents the random category of uncertainty evaluated by using statistical analysis of repeated measurements of, nominally, the same observation; type B components are estimated by means other than repeated observations. The "other means" may include previous measurements, past experience or general knowledge, handbook information, manufacturer specification or data provided as a certificate. A detailed approach to uncertainty analysis in experimental hydrodynamics can be found in ITTC procedure 7.5-02-01-01.

A.1.1. Type A uncertainty

The fundamental form of uncertainty associated with a measurement is type A, $u_A(x_i)$, which can be expressed as a standard deviation. Type A uncertainty is typically based upon the analysis of repeated measurements which characterizes the randomness of the experimental process. The most common approach to estimating type A uncertainty is by undertaking end-to-end multiple repeated runs; care should be taken to ensure that as many factors as possible that affect repeatability of experiment are accounted for. Numbers of repeats should be as large as practicable in order to minimize type A uncertainty; however 10 repeats indicates good experimental practice. However, in most seakeeping tests it is not practicable to carry out multiple repeats for all experimental conditions. It may be more feasible to select only characteristic or unique test conditions (due to environment and/or operations) for which repeat runs should be undertaken and reported. Historic database of information on Type A uncertainty could be created (occasionally confirmed) and used to report uncertainty for routine experiments.

A.1.2. Type B uncertainty

Type B uncertainty, $u_B(x_i)$, may be considered as an approximation to the experimental variance or standard deviation respectively. In the same way as type A uncertainty, type B is assumed to be equal to the standard deviation $u_S(x_i)$. Typically type B uncertainty can be estimated from quoted values of uncertainty, assumed statistical distribution of the parameters and factors depending on a level of confidence in the measurement. Generally, the experimenter can assume that the type B uncertainty is normally distributed around some mean, however, in some specific cases is may be pertinent to consider alternatives such as triangular or rectangular distributions. For type B uncertainty that is assumed to be normally distributed Table A1 shows the factors that need to be applied for some examples of confidence.

Confidence Level [%]	Factor
50	0.6757
68.27	1.
90	1.645
95	1.96
99	2.576
99.73	3

Table A1. Confidence factors for normally distributed type B uncertainties

For example, this means that, statistically, one can have 95% confidence that a measurement lies within a value of $\pm 1.96\,u(x_i)$.

A.1.3. Standard uncertainty

The standard uncertainty, $u_S(x_i)$, in a measured value is the summation of type A and all of the type B uncertainties and can be calculated using the uncertainty propagation formula:

$$u_S(x_i) = \left(\sum_{i=1}^{N} u_A{}^2(x_i) + \sum_{j=1}^{K} u_B^2(x_i) \right)^{\frac{1}{2}} \qquad \text{(A1)}$$

A.1.4. Combined uncertainty

A further step is required when result of an experiment is derived from values of a number of other measurement variables (x_i). The most common situation where this is undertaken in seakeeping experiments is when the results are non-dimensionalised. In this case, the combined uncertainty $u_C(y)$ is applied to express uncertainty in the derived result.

$$u_C(y) = \left(\begin{array}{l} \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u_S{}^2(x_i) + \\ +2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u_S(x_i, x_j) \end{array} \right)^{\frac{1}{2}} \qquad \text{(A2)}$$

The second term in the combined uncertainty formula represents the cross correlation between two or more variables. These terms are zero when variables are considered to be independent. The $\frac{\partial f}{\partial x_i}$ term is the partial derivative with respect to variable x_i, also known as the sensitivity coefficient and $u_S(x_i)$ is the standard uncertainty of variable x_i.

A.1.5. Expanded uncertainty

When presenting the results of experiments along with interval expressing some level of confidence in that measurement then the expanded uncertainty U is applied.

$$U = k u_C(y) \qquad \text{(A3)}$$

where, k represents the confidence or coverage factor, and the result of the measurement can be interpreted as $y\text{-}U \leq Y \leq y+U$.

So, Y can be interpreted as the best estimate that the resultant measurement lies within the range $y\text{-}U$ and $y+U$; the value of U is defined by k. For cases where the uncertainty can be assumed to be normally distributed the confidence factors presented in Table 1 can be used. For example, a value k=2.576 value gives confidence level of 99%.

A.2. Sources of uncertainty

A typical requirement from a seakeeping experiment is to obtain the basic rigid body motions (surge, sway, heave, roll, pitch and yaw), accelerations and relative motions at specific locations, waves, model speed, and propulsion and steering systems characteristics (propeller revolutions, rudder angle). All of these measured parameters are subjected to type A and type B uncertainties that need to be estimated as a part of the experimentation procedure.

A.2.1. Type A uncertainty

As indicated in section A.1.1 type A uncertainty is evaluated by taking repeated measurements of the same experimental condition (recommended number of repeated runs is 10). Since repeating the entire set of test runs in a seakeeping experiment makes the programme prohibitively long (and hence expensive) it is recommended that only a few selected representative test conditions should be repeated to obtain some understanding of the type A uncertainty.

A.2.2. Type B uncertainty

There are elemental type B uncertainties that are an inherent part of each sensor, its calibration, the data acquisition system, processing and analysis.

All of these elemental type B uncertainties should be accounted for, using in equation A2, to determine the type B uncertainty for each measured parameter.

Sensors

Measurements of the rigid body motions of the model, accelerations and relative motions, propulsion and control parameters are usually primary requirements of seakeeping experiments. Specifications provided by the manufacturers of the sensors used in experiments, coupled with past experience in the use of such sensors, allows an estimation of the relevant type B uncertainty to be made. The manufacturer may present sensor uncertainty information as standard deviations (or multiples of) or as an expanded uncertainty with a specified confidence level. This information can be translated to a standard deviation and can be used to obtain the standard type B uncertainty for that particular element. For example, a sensor specification stating that roll and pitch angles are measured to a dynamic accuracy of 0.5 degrees rms can be interpreted as a 0.5 degree standard uncertainty in roll and pitch. In most cases individual sources of uncertainty need to be identified from available specification documents and the uncertainty propagation formula should be used to obtain the standard uncertainty given in (A1).

Elemental sources of uncertainty that are usually identified from manufacturer's specification may include: non-linearity, hysteresis, non-repeatability, zero offset drift, spam temperature coefficient, and resolution.

Calibrations

Before used in experiments, all instruments need to be calibrated; either bench or in-situ calibration or else factory calibration constants are applied.

Calibration characterises an instrument's uncertainty but does not eliminate it; indeed, the calibration process itself is subject to uncertainties. Generally, a system level, in-situ end-to-end calibration is advisable that includes as many of the possible elemental sources of uncertainty in the calibration procedure. A few, additional, elemental sources of uncertainty need to be considered when estimating uncertainty: calibration standards (quality of calibration specimens or injection source), calibration curve fitting, calibration set up (misalignments) and A/D conversion.

The uncertainty associated with the quality of the calibration standard and calibration device/jig set-up misalignments can be estimated from the manufacturer's specification. Uncertainty due to calibration standards B_{CS} can be estimated using:

$$u_{BCS} = \sqrt{\sum \left(A_{CG} \cdot W_i \right)^2} \quad \text{(A4)}$$

A_{CG} accuracy of calibration specimens; e.g., weight, distance, angle…

W_i physical values of calibration points; weight, distance, angle…

The uncertainty associated with misalignment in the calibration set-up u_{BCM} can be evaluated from:

$$u_{BCM} = \sum (W(1-\cos\alpha_j) \qquad (A5)$$

W nominal measurement value

α angle of misalignment in relevant plane.

The curve fitting uncertainty can be estimated using the standard error of estimation (SEE) formula:

$$\mathrm{SEE} = \left[\frac{1}{n(n-1)}\sum_{1}^{n}\left(y_n - y_{LS,k}\right)^2\right]^{1/2} \qquad (A6)$$

In the formula n is the number of calibration samples, y_n is calibration data point, and $y_{LS,n}$ is fitted value. In most cases n ≥ 7 is recommended. It can be assumed that the SEE value is approximately equal to the standard uncertainty.

Generally, the majority of data acquisition systems that are currently in use employ a 16-bit (or better) analogue to digital (A/D) converters. However, some specific equipment may still use 12-bit A/Ds to acquire model data.

The type B uncertainty associated with the A/D conversion u_{BCAD} is equivalent to ½ the resultant resolution and can be estimated from:

$$u_{BCAD} = \frac{1}{2}\frac{TotalVoltageRange}{A/Dbits}\cdot CalibrationFactor \qquad (A7)$$

The *TotalVoltageRange* is typically equal to either ±10 Volts or ±5 Volts; the *A/Dbits* value is 2^{16} or 2^{12} for 16 and 12 bit convertors respectively, the *CalibrationFactor* is a calibration constant that translates voltage to physical units. Typically, uncertainty due to resolution of 16-bit system would be negligible, but for 12-bit system it could be significant for higher precision instrument.

In the case of measuring instruments that are provided with manufacturer calibration data (most modern digital instruments) calibration standards are reflecting standards of high precision source (voltage) that, normally, is expected to be considerably more accurate than accuracy that can be achieved in a physical bench calibration.

It is advisable, if practical, to conduct in-situ end-to-end (with all model systems being active) calibration of the sensors that are to be used in the experiment. In such a situation, the calibration process should include all or most elemental type B uncertainty sources, which are difficult to estimate individually. However, for in-situ calibration they don't have to be individually identified and estimated.

This approach does not exclude the need for uncertainty analyses due to calibration standards, set up, curve fitting and other related sources of uncertainty but hopefully overall simplifies the procedure.

Data Acquisition System.

In case when in-situ end-to-end calibration procedure is applied all data acquisition system elemental error sources are included in the process except for noise due to variation in surrounding external environment (temperature, humidly) and other used devices (propulsion motor). Good testing practice requires screening of all noise sources, but when this appears to be difficult those effects should be estimated.

Data processing.

Type B uncertainty due to data reduction and analysis should include any uncertainty related to data integration, differentiation, filtering and other methods of data manipulation. It can be evaluated based on previous experience of working with data processing systems. Uncertainty due to any data reduction associated with the calculation of basic statistics (mean, standard deviation) should be considered negligible, however, for more complex data manipulations resultant uncertainty may need to be considered. These uncertainties can be estimated by using the same data manipulation process with a known signal with known analytical solution (sin or cosine) comparing the processed and analytic outputs.

Data analysis.

Model speed and heading. - Model speed uncertainty is subjected to both type A and type B uncertainties. The type A component is calculated using equation for the standard uncertainty (the uncertainty propagation formulae A1) and the combined uncertainty (A2). The Type B uncertainty component is dependent upon the method in which the model speed is obtained. If, during the experiments, the model is attached to or follows the carriage and speed of the model can be assumed to be equal to the speed of the carriage, then the method presented in ITTC 2008 7.5-02.07-02.1 and that suggested by Fogash (1992) can be used.

Under the assumption that model speed, v, through the water is equal to the speed of towing carriage, the model speed is determined from

$$v = \frac{n/5000\pi D}{t} = \frac{f\pi D}{5000} \tag{A8}$$

where D (m) is the diameter of carriage wheel and n is the number of light pulses sensed by the photo coupler during the time period t. The 5000 number is facility specific and indicates number of pulses per single turn of carriage wheel. The measured quantities and error sources for the estimation of model speed and error limit are the diameter of carriage wheel and the pulse frequency f $(=n/t)$.

The combined uncertainty becomes, in this case:

$$u_C(v) = \left[\left(\frac{\partial v}{\partial f}\right)^2 u^2(f) + \left(\frac{\partial v}{\partial D}\right)^2 u^2(D)\right]^{\frac{1}{2}} \tag{A9}$$

$$u_C(v) = \left[\left(\frac{\pi D}{5000}\right)^2 u^2(f) + \left(\frac{\pi f}{5000}\right)^2 u^2(D)\right]^{\frac{1}{2}} \tag{A10}$$

If a free running model is used in the experiments and, for example, an optical tracking system is used for to determine model position, then v=s/t should be applied, and the instantaneous and/or mean speed can be calculated (s is distance between two consecutive sampled positions, and t is time between two consecutive samples). In this case, the combined uncertainty formula can be used to obtain model speed uncertainty:

$$u_C(v) = \left[\left(\frac{\partial v}{\partial s}\right)^2 u^2(s) + \left(\frac{\partial v}{\partial t}\right)^2 u^2(t)\right]^{\frac{1}{2}} \tag{A11}$$

$$u_C(v) = \left[\left(\frac{1}{t} \right)^2 u^2(s) + \left(-\frac{s}{t^2} \right)^2 u^2(t) \right]^{\frac{1}{2}} \quad \text{(A12)}$$

Standard (or combined) uncertainties $u(s)$ and $u(t)$ need to be estimated based on information provided on model positions and accuracy of sample time. Nominal values of s and t should be applied to obtain combined uncertainty.

Similarly if a captive model is used or free running model follows the carriage the heading angle is assumed to be equal to the heading of the carriage with respect to the oncoming waves. For free running, self-propelled models when an optical system is used to obtain model positions the instantaneous (and mean) heading angle can be estimated from consecutive longitudinal and lateral positions of the model. The estimate of combined uncertainty in heading is then based on the uncertainty in the lateral and longitudinal position of the previous and next location of the model, and the nominal longitudinal and lateral distance between those two points. The arctangent is applied to estimate the uncertainty in the angle based on the uncertainty in the ratio of the lateral (ΔY) and longitudinal (ΔX) consecutive positions. Uncertainty in the ratio can be calculated from:

$$u\left(\frac{\Delta Y}{\Delta X}\right) = \left[\left(\frac{\partial\left(\frac{\Delta Y}{\Delta X}\right)}{\partial(\Delta Y)} \right)^2 u^2(\Delta Y) + \left(\frac{\partial\left(\frac{\Delta Y}{\Delta X}\right)}{\partial(\Delta X)} \right)^2 u^2(\Delta X) \right]^{\frac{1}{2}} \quad \text{(A13)}$$

$$u\left(\frac{\Delta Y}{\Delta X}\right) = \left[\left(\frac{1}{\Delta X} \right)^2 u^2(\Delta Y) + \left(-\frac{\Delta Y}{(\Delta X)^2} \right)^2 u^2(\Delta X) \right]^{\frac{1}{2}} \quad \text{(A14)}$$

Nominal ΔX and ΔY values are calculated from the mean heading angle, and the appropriate uncertainty can be used to calculate uncertainty in the ratio.

In case when model heading is obtained after double integration of yaw rate measurement, both uncertainty of yaw rate measurement and accuracy of integration procedure need to be included in combined uncertainty estimate.

Model geometry and mass distribution - sources of uncertainty in model geometry are model length (L_{PP}), width (B) and draft (T). For seakeeping experiments the position of centre of gravity ($\overline{KG}$) and longitudinal radius of gyration (k_{yy}) are also important and their respective uncertainties need to be determined.

Typical suggested tolerances on the principal parameters associated with model geometry are +/-0.05% on linear dimensions larger than 2m, and +/-1mm on dimensions less than 2 m, and +/-1% on model displacement. In all cases they are the type B uncertainties that are constant for the duration of experiment. Examples of achieved and/or suggested uncertainties of model main parameters and mass properties as well as presented results are shown in Kishev (1998) and ITTC (2008).

Uncertainties in model geometry can be determined using past experience in model construction. For instance, if a model manufacturer states that a 5-metre long model is accurate to within +/-2.5 mm with 90%

confidence, then one can assume that the expanded uncertainty of the model length is +/- 2.5 mm. The standard uncertainty can be estimated, using the confidence factor in Table 1, from expression 2.5/1.645=1.52 assuming that a normal distribution can be applied to represent the stated value. So, the resultant standard uncertainty of the length is ~1.5 mm.

To estimate the uncertainty in the model $\overline{KG}$ and k_{yy},, the propagation of uncertainty needs to be applied to the formula used to calculate these respective values. For example if $\overline{KG}$ of a model is estimated based on inclining experiments and the following formula is employed: $\overline{KG}=\overline{KB}+\overline{BM}-\overline{GM}$. The vertical centre of buoyancy ($\overline{KB}$) and transverse metacenter ($\overline{BM}$) are geometry dependent, when metacentric height ($\overline{\mathrm{GM}}$) can be obtained from inclining experiment. The combined uncertainty in $\overline{KG}$ can be evaluated from:

$$u_C(\overline{KG})=\left[\left(\frac{\partial\overline{KG}}{\partial\overline{KB}}\right)^2 u^2(\overline{KB})+\left(\frac{\partial\overline{KG}}{\partial\overline{BM}}\right)^2 u^2(\overline{BM})+\left(\frac{\partial\overline{KG}}{\partial\overline{GM}}\right)^2 u^2(\overline{GM})\right]^{\frac{1}{2}} \quad \text{(A15)}$$

The standard uncertainty of $\overline{\mathrm{GM}}$ can be estimated by applying combined uncertainty formula to:

$$\overline{GM}=\frac{\mathrm{w}\cdot\mathrm{d}}{\mathrm{W}\cdot\tan(\varphi)} \quad \text{(A16)}$$

where, *w* is inclining weight, *d* is distance the inclining weight is moved, *W* model displacement, φ is heel angle when inclined.

The combined uncertainty of $\overline{\mathrm{GM}}$ can be presented as:

$$u_C(\overline{GM})=\left[\left(\frac{\partial\overline{GM}}{\partial w}\right)^2 u^2(w)+\left(\frac{\partial\overline{GM}}{\partial d}\right)^2 u^2(d)+\left(\frac{\partial\overline{GM}}{\partial W}\right)^2 u^2(W)+\left(\frac{\partial\overline{GM}}{\partial\varphi}\right)^2 u^2(\varphi)\right]^{\frac{1}{2}} \quad \text{(A17)}$$

$$u_C(\overline{GM})=\left[\left(\frac{d}{W\cdot tg\varphi}\right)^2 u^2(w)+\left(\frac{w}{W\cdot tg\varphi}\right)^2 u^2(d)+\left(-\frac{w\cdot d}{W^2 tg\varphi}\right)^2 u^2(W)+\left(-\frac{w\cdot d}{W\cdot\sin^2\varphi}\right)^2 u^2(\varphi)\right]^{\frac{1}{2}} \quad \text{(A18)}$$

Standard uncertainty of $\overline{KB}$ and $\overline{BM}$ can be evaluated by assuming a simplified geometry of hull form and using known standard uncertainties of main parameters.

For example, the transverse $\overline{BM}$ for a triangle-prism shaped vessel with a rectangular water plane area can be calculated from:

$$\overline{BM} = \frac{I}{V} = \frac{LB^3}{12\nabla} = \frac{LB^3}{12 \cdot \frac{1}{2} LBT} = \frac{B^2}{6T} \qquad \text{(A19)}$$

Where, I is second moment of rectangular water plane area about its centreline, ∇ volume of displacement, and L, B and T are length and breadth of water plane respectively and T is draft of the vessel.

The combined uncertainty of BM is:

$$u_C(\overline{BM}) = \left[\left(\frac{\partial \overline{BM}}{\partial B} \right)^2 u^2(B) + \left(\frac{\partial \overline{BM}}{\partial T} \right)^2 u^2(T) \right]^{\frac{1}{2}} \qquad \text{(A20)}$$

$$u_C(\overline{BM}) = \left[\left(\frac{B}{3T} \right)^2 u^2(B) + \left(-\frac{B^2}{6T^2} \right)^2 u^2(T) \right]^{\frac{1}{2}} \qquad \text{(A21)}$$

Nominal B and T values, and their respective uncertainties need to be applied to calculate combined uncertainty in transverse $\overline{BM}$.

A similar procedure can be used to evaluate the combined uncertainty in the vertical location of centre of gravity and longitudinal radius of gyration k_{yy} that could be obtained a pendulum experiment.

Wave parameters – the uncertainty in wave measurements (regular and irregular) is one of major sources of uncertainty in experiments. Limitations of wave generators, the deterioration of wave properties propagating forward of experimental facilities and reflections from beach devices contribute to uncertainty in the wave environmental. Those uncertainties are difficult to estimate and are usually neglected. Target irregular wave properties are normally defined as significant wave height, modal period and type of spectrum. Target regular wave properties are described by wave amplitude and frequency. Wave matching is normally conducted based on a measurement in one selected-representative location, and supported by measurements in a few other locations to check for consistency. Two sources of error for which uncertainty could be estimated are difference between the target and matched wave(s) and uncertainty due to measuring and processing errors.

Either regular or irregular wave properties are generally obtained from measurements of wave displacement using devices such as a sonic wave probe and/or capacitance wave probes. Basic statistics from measurements provide rms that can be used as a first estimate of the amplitude of regular waves ($\zeta_A = \sqrt{2} \cdot rms$) and significant height of irregular waves ($H_{W1/3} = 4 \cdot rms$). Spectral analysis can be also be employed to determine significant height of irregular waves $H_{W1/3} = 4\sqrt{m_0}$, where m_0 is area under the energy spectrum curve.

Total standard uncertainty in wave amplitude or height measurements should be evaluated using the uncertainty propagation formula. Type A uncertainty can be evaluated from repeated observations, although this can be impracticable for seakeeping experiments, and type B uncertainty established from properties of measuring device and data process.

Wave direction is also a significant parameter when undertaking experiments in oblique waves. Verification of waves propagation direction can be carried out using many instruments. One possible choice for the validation of wave direction with respect to the tank could be by using a 3D acoustic Doppler velocimeter. Periodic repeated wave measurements for selected wave directions can be carried out to determine standard deviation and standard uncertainty. The direction can be verified during wave matching for a specific experiment.

Data presentation

It is customary to present the final experimental results in a standardized format - usually non-dimensionalised. The linear translations from regular waves tests are typically non-dimensionalised by wave amplitude; rotations by wave slope and amplitude, and accelerations by $L_{PP}/(g\cdot\zeta_A)$. Generally these non-dimensional responses are presented to a base of the non-dimensional encounter wave frequency given as $\omega_e\sqrt{L_{PP}/g}$

Therefore, the combined uncertainty u_c of the non-dimensional heave displacement $z' = z/\zeta_A$ can be calculated from the following:

$$u_C(z') = \left[\left(\frac{\partial z'}{\partial z}\right)^2 u^2(z) + \left(\frac{\partial z'}{\partial \zeta_A}\right)^2 u^2(\zeta_A)\right]^{1/2} \tag{A22}$$

$$u_C(z') = \left[\left(\frac{1}{\zeta_A}\right)^2 u^2(z) + \left(-\frac{z}{\zeta_A^2}\right)^2 u^2(\zeta_A)\right]^{1/2} \tag{A23}$$

Where, z and ζ_A are heave displacement and regular wave amplitude, $u(z)$ and $u(\zeta_A)$ are respective total standard uncertainties of measured heave displacement and wave amplitude including all type A and type B elemental error sources.

Similarly, combined uncertainty of non-dimensional encounter frequency $\omega_e' = \omega_e\sqrt{L_{PP}/g}$ can be evaluated from:

$$u_C(\omega_e') = \left[\left(\frac{\omega_e'}{\omega_e}\right)^2 u^2(\omega_e) + \left(\frac{\omega_e'}{L_{PP}}\right)^2 u^2(L_{PP})\right]^{1/2} \tag{A24}$$

$$u_C(\omega_e') = \left[\left(\frac{L_{PP}}{g}\right) u^2(\omega_e) + \left(-\frac{\omega_e}{2\left(L_{PP}\cdot g\right)^{1/2}}\right)^2 u^2(L_{PP})\right]^{1/2} \tag{A25}$$

Again, ω_e, L_{PP} and g are respective nominal values, and $u(\omega_e)$ and $u(L_{PP})$ are respective standard uncertainties.

Motions in irregular seas are typically presented as plots of non-dimensional or significant values versus velocity, Froude number or sea state.

For example, formulae for non-dimensional pitch motion and the resulting combined uncertainty are as follow:

$$C_\theta = \frac{\theta \cdot L_{pp}}{2\pi \cdot H_{W1/3}} \tag{A26}$$

$$u_C(c_\theta)=\begin{bmatrix}\left(\dfrac{\partial C_\theta}{\partial \theta}\right)^2 u^2(\theta)+\\ +\left(\dfrac{\partial C_\theta}{\partial H_{W1/3}}\right)^2 u^2(H_{W1/3})+\\ +\left(\dfrac{\partial C_\vartheta}{\partial L_{PP}}\right)^2 u^2(L_{PP})\end{bmatrix}^{\frac{1}{2}}$$

where:

$$\frac{\partial C_\theta}{\partial \theta}=\frac{L_{PP}}{2\pi\cdot H_{W1/3}}$$

$$\frac{\partial C_\theta}{\partial H_{W1/3}}=-\frac{\theta L_{PP}}{2\pi\cdot H_{W1/3}^2}$$

$$\frac{\partial C_\theta}{\partial L_{pp}}=\frac{\theta}{2\pi\cdot H_{W1/3}}$$

θ is the significant pitch angle response in irregular wave.

Combined uncertainty in estimation of Froude number ($Fr=V/\sqrt{gL_{PP}}$) can be expressed as follow:

$$u_C(Fr)=\sqrt{\left(\frac{\partial Fr}{\partial V}\right)^2 u^2(V)+\left(\frac{\partial Fr}{\partial L_{PP}}\right)^2 u^2(L_{PP})} \quad \text{(A27)}$$

where,

$$\frac{\partial Fr}{\partial V}=\frac{1}{\sqrt{gL_{PP}}}$$

$$\frac{\partial Fr}{\partial L_{PP}}=-\frac{V}{2\sqrt{gL_{PP}^3}}$$

Once the experimental data have been collected and reduced to non-dimensional format for a particular wave encounter frequency and/or Froude number, they can be presented in a tabular format or we may want to obtain a mathematical expression to represent the data. In this case regression can be performed on the experimental data (after data reduction) and a polynomial equation fit to represent the data. The type B uncertainty associated with the regression should be included in the analysis.

A.2.3. Example

Table A2 and Figure A1 present examples of total standard and combined uncertainty calculations of model parameters and responses from submarine model seakeeping surface experiments in irregular seas.

From the table one can conclude that the uncertainty in the model main parameter is contained below 1%, and that the type B uncertainty is dominating model motions measurements.

A.2.4. Summary

The above presented procedure outlines ITTC recommended ISO GUM approach to uncertainty analysis in seakeeping experiment measurements. Intention of the procedure is to emphasize details unique for seakeeping experiment measurements and data presentation. Background information for ISO GUM approach and assumptions are discussed in ITTC Specialists Committee on Uncertainty Analysis procedure 7.5-02-01-01. The methodologies presented here are relevant to uncertainties in measurements only. Subject of uncertainty in predictions is not included in the above discussions.

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Source of uncertainty	Nominal Value	Units	Description of accuracy	Type A uncertainty	Type B uncertainty	Standard uncertainty
Model Lpp	4.70	m	+/- 3 mm, 90% confidence		0.0018	0.002
Model B	0.51	m	+/- 2 mm, 90% confidence		0.0012	0.001
Model T	0.52	m	+/- 2 mm, 90% confidence		0.0012	0.001
Model D	671.14	m^3	resultant		0.0042	0.004
Model KB	0.29	m	resultant		0.0012	0.001
Model BM	0.302	m	resultant		0.0004	0.000
Model KG	0.264	m	inclining experiment		0.0015	0.002
Model kxx	0.213	m	swing frame		0.0024	0.002
Model GMt	0.038	m	resultant		0.0008	0.001
Speed 1	3.4	knots	Optical tracking Qualisys	0.057	0.012	0.059
Speed 2	6.2	knots	Optical tracking Qualisys	0.042	0.016	0.063
Speed 3	12.9	knots	Optical tracking Qualisys	0.052	0.028	0.108
Roll Angle 1	13.8	deg	FOG	0.190	2	2.009
Roll Angle 2	17.5	deg	FOG	0.169	2	2.007
Roll Angle 3	1.7	deg	FOG	0.054	2	2.001
Pitch Angle 1	3.5	deg	FOG	0.063	2	2.001
Pitch Angle 2	1.1	deg	FOG	0.028	2	2.000
Pitch Angle 3	0.7	deg	FOG	0.041	2	2.000
Heave Displ. 1	2.12	m	Motion Pack	0.030		0.030
Heave Displ. 2	2.14	m	Motion Pack	0.020		0.020
Heave Displ. 3	0.38	m	Motion Pack	0.017		0.017
Vert. Accel. 1	0.16	g	Honeywell, QA 1400	0.001	0.0031	0.003
Vert. Accel. 2	0.14	g	Honeywell, QA 1401	0.002	0.0031	0.004
Vert. Accel. 3	0.04	g	Honeywell, QA 1402	0.001	0.0031	0.003
Relative Mot. 1	1.33	m	ULS, USS 635	0.018	0.0013	0.018
Relative Mot. 2	1.43	m	ULS, USS 635	0.008	0.0013	0.008
Relative Mot. 3	0.69	m	ULS, USS 635	0.010	0.0013	0.010
Wave Elev. 1	2.62	m	Capacitance probe	0.004	0.004	0.005
Wave Elev. 2	1.84	m	Capacitance probe	0.005	0.004	0.007
Wave Elev. 3	0.64	m	Capacitance probe	0.006	0.004	0.007
						Combined Uncertainty
Froude no. 1	0.07					0.0022
Froude no. 2	0.12					0.0024
Froude no. 3	0.25					0.0041

Table A2. Estimate of uncertainty for responses during seakeeping experiments

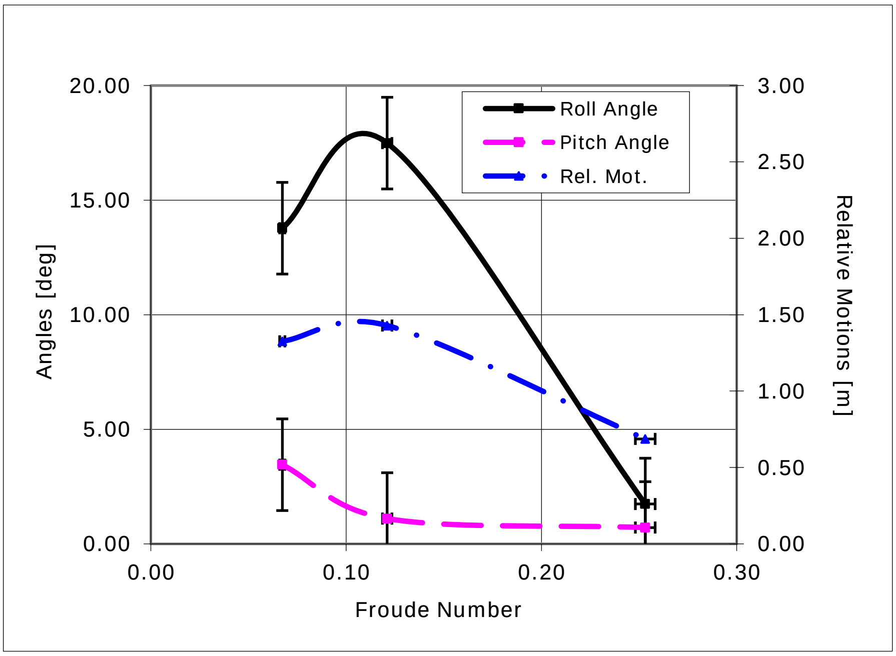

Figure A1. Example of responses and range of uncertainty

Appendix B

B.1. Model control systems tuning

The following outlines the tuning of steering controllers and roll stabilizers using PD / PID-based tunings for standard monohull displacement-hull vessels with a single rudder control surface (or multiple rudder surfaces controlled together). In this process it is assumed that either

- All lifting surfaces are modelled using Froude scaling
- Or model scale deflection forces are functionally mapped to full-scale deflection forces.

Note that the tuning method outlined here is for a defined forward speed. For each forward speed, the process must be re-iterated to capture the vessel dynamics at that speed.

B.2. Heading control through steering

B.2.1. Background

Heading control through steering is based on the Nomoto first-order steering model which relates rudder as an input to yaw rate (Fossen, 1994).

The first order Nomoto steering model is given by:

$$\frac{\dot{\psi}}{\delta}(s) = \frac{K_N}{(1+T_N s)}$$

Where $\dot{\psi}$ is yaw rate, δ is the rudder angle K_N is the static yaw rate gain, T_N is time constant and s is the complex variable of the Laplace transform.

To determine the model parameters, execute a standard "zig-zag" manoeuvre (or any large rudder angle to large yaw angle manoeuvre). The resulting data set can be used to identify model parameters by either system identification methods or graphical methods using a response plot. It should be noted that an identified Nomoto parameter pair is valid for one forward speed only. As an example, for a Mariner Class vessel K_N and T_N are given as 0.185 and 107.3 in (Fossen, 1994).

The form of this approximation for the steering dynamics contains a single pole, which defines the system's steering bandwidth. In the above approach, yaw rate is related to the rudder angle. Whereas in practice the aim is to control the heading angle, □ and not the time derivative of □ Therefore, an integrator to the transfer function models needs to be added. With the integrator, there will be two poles in the system. Hence, when a state feedback control is applied, the goal is to move the two poles of the closed loop system into a complex conjugate pair to produce damped, harmonic response. Overshooting is the result of an underdamped system. Also, an over-damped response, where the damping ratio, ζ , is greater than one, is generally not desirable.

In designing a controller, the bandwidth is chosen so that the inherent natural frequency of the vessel is not altered. This way, the model's natural behaviour is not interfered by the control system performance.

The details of the underlying theory for the above discussions can be found in the 28th ITTC Proceedings. A solution satisfying the above mentioned considerations for the controller can be given as follows:

$$k_P = \omega_0^2 T_N / K_N$$

$$k_D = \frac{2\zeta\omega_0 T_N - 1}{K_N}$$

where k_p is proportional gain, k_d is derivative gain, T_N and K_N are as described above, ω_0 is equivalent natural frequency and ζ is damping ratio as mentioned above.

B.2.2. Guidelines for the heading controller design

The steering controller is recommended to be designed as follows:

1. Identify Nomoto model parameters as outlined above for each forward speed.
2. Best-fit the parameters to the linearized Nomoto model using established procedures developed to fit these parameters from zig-zag data. If possible, system identification techniques may be used, reducing the need for "ideal" zig-zag information. (If a prohibitive number of forward speeds are to be tested - such that determining the Nomoto for each speed is practically very difficult – a range of parameters can be estimated including parameters for the minimum and maximum forward speeds, and two or three speeds in between.)
3. Choose, through pole placement techniques, the desired PD or PID tuning for the autopilot.
4. A different tuning will be utilized for each forward speed to preserve the open-loop characteristics. The following procedure is developed for first-order Nomoto approximations and a PD state feedback control system:

A damping ratio ζ is selected based on the desired response. For each calibrated forward speed K_N and T_N parameters will be identified, which also define the system bandwidth and natural frequency ω_0. Given these parameters, proportional gain k_P and derivative gain k_D can be calculated using the equations given above. Integral gain can be conservatively added if it is deemed necessary to eliminate offset.

The gains calculated using this method provide a useful starting point for tuning steering controllers with minimum influence on seakeeping response.

B.3. Track control

Simple autopilot-based track controllers typically function by providing a heading trajectory signal into the input of the autopilot heading controller. There are numerous methods available to generate a suitable path-tracking trajectory.

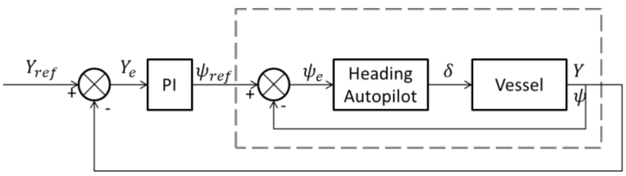

Figure B1. A simple heading autopilot (dashed box) with a simple PI "sway-keeping" outer loop.

Track control is typically implemented in basin seakeeping experiments for the purpose of reducing sway drift-off or "crabbing" events, i.e., to follow a straight path over ground. When used for seakeeping experiments, care must be taken to ensure that any trajectory fed into the autopilot controller does not alter the dynamics of that controller itself.

A simple straight path tracking control scheme can be seen in Figure B1. In this simple case, an outer PI control loop is used to generate the reference signal for the simple heading autopilot to hold a track (with a global Y set-point). When tuning this controller, the overall bandwidth of the control scheme must follow the open-loop bandwidth of the vessel. Conservatively tuning the outer PI loop to control with slower dynamics than the autopilot inner-loop will suffice to ensure that the vessel can track without influencing seakeeping.

More complicated track controllers and trajectory-generating schemes are not recommended for seakeeping experiments, but may be implemented for other test purposes. Examples of these may be found in "Handbook of marine craft hydrodynamics and motion control" by Thor Fossen and other references.

B.4. Roll motion reduction

B.4.1. Active fin stabilization

Fin stabilization systems are highly effective for roll damping. Using lift generated on these surfaces at speed, fins can provide correcting moments which oppose that of the vessel's roll, thus increasing damping. Fin dynamics do not couple significantly into other axes (assuming that they are placed appropriately near mid-ships) and should not require special control considerations to preserve vessel dynamics. Fin rates must be capable of performing a full fin angle sweep in a roll period to be effective.

The simplest control scheme for a fin stabilizer is to feed the roll rate signal (with proportional gain term) into the fin deflection controller.

B.4.2. Rudder roll stabilization (RRS)

Typically used in conjunction with an autopilot, RRS Systems use high-frequency rudder motions to stabilize a vessel in roll by adding roll damping to a ship. Before modeling this type of controller, the following considerations must be made:

- A significant bandwidth separation must exist between the steering-yaw subsystem and the steering-roll subsystem, that is, the frequencies of effective roll subsystem cannot be low enough to affect the low-frequency bandwidth of the steering subsystem. This will cause degradation in the performance of both controllers.
- The steering gear must be capable of withstanding high frequency motions (both model-scale and full-scale), on the order of the roll frequency. Steering systems are typically designed for low-frequency motions under high loads, and hydraulic pump systems typically have lower duty-cycles, unless specifically designed for RRS. The maximum steering gear slew rate must be:

$$\dot{\alpha}_{max} \geq \omega_{\phi}\alpha_{max}$$

Where α is rudder angle correction and ω_ϕ is natural roll frequency.

- Natural roll frequency / damping must be characterized through the speed envelope of the vessel.

Unlike the seakeeping autopilot, use of active roll stabilization systems in a test-basin setting tests the performance of the roll stabilizer controller itself, and as such, care must be taken to appropriately scale the controller properties to predict full-scale performance.

B.4.2.1. Guidelines for the rudder roll stabilization (RRS)

Design choices made in the scaling of lift surfaces and propellers may induce issues when attempting to model full-scale controllers in model-scale. For autopilot control and stabilization control, dynamic response is predicated mainly upon scaling the full-scale moments (and machinery slew rates) appropriately.

Modelling full-scale rudders and fins is a difficult trade-off: modeling them with the appropriate geometry scaling can result in lift curves that vary from that of the full-scale design curves. Modeling them with the correct Froude lift-scaling can result in different sizes and areas, affecting efficiency, resistance, and flow. Whichever design choices are taken to model the lift surfaces, two important aspects must be considered to achieve the appropriate model-scale response:

- Forces (and thus, moments) applied must be appropriately scaled, and,
- Time to generate these forces (generally, “slew rates”) must be scaled.

Care must be taken on the implementation of the second point: it is not sufficient to scale the machinery rates in time if the lift curves are not scaled appropriately. From a control perspective, it is not the lift surface angle that has to be achieved/limited in a span of time (i.e., a machinery slew rate), but rather the lift force (a force slew rate).

This can be achieved through a functional mapping, that is,

Full-Scale Angle » Full-Scale Force » Model-Scale Force » Model-Scale Angle

and,

Full-Scale Slew Rate » Full-Scale Force Rate » Model-Scale Force Rate » Model-Scale Slew Rate

Control gains are also scaled via Froude scaling laws.

B.5. References

Fossen, T., 1994, "Guidance and control of ocean vehicles", John Wiley & Sons Inc.

Ogata, K., 2001, "Modern control engineering", Prentice Hall PTR.

Fossen, T., 2011, "Handbook of marine craft hydrodynamics and motion control", John Wiley & Sons, Ltd.

Perez, T., 2005, "Ship motion control", Springer-Verlag London Ltd.