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Sea Keeping Experiments

1. PURPOSE OF PROCEDURE

To ensure that sea keeping tests to obtain primarily linear response functions in waves are performed according to the state of the art.

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.

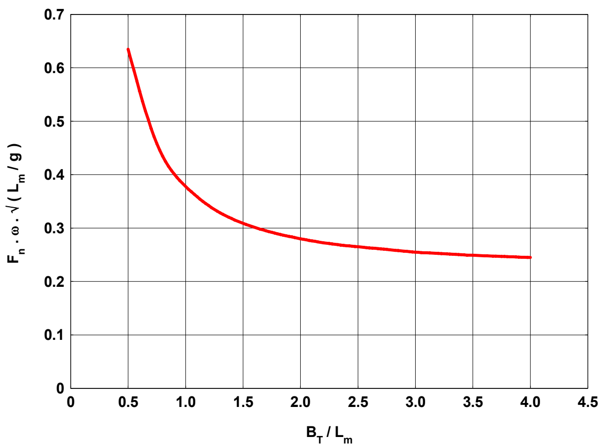

Figure 1. Maximum frequency at which tank interference occurs in head waves

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:

$$Fr \cdot \omega_e \sqrt{L_m / g} \leq 1/2$$

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.

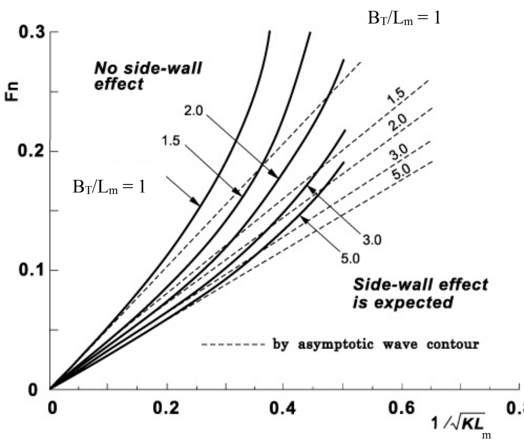

Figure 2. Estimation of tank-wall effects using unified slender theory.

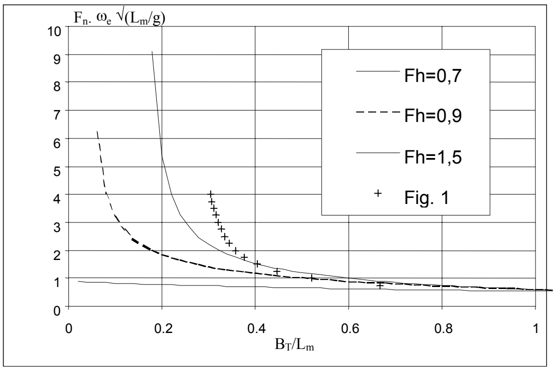

Figure 3. Maximum frequency at which tank interference occurs in head waves and finite depth.

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 0.40B, 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 determined and recorded. 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 in head or following waves the model should have the freedom to roll, that is, to rotate about the longitudinal axis (through the centre of gravity). In oblique waves, care must be taken not to restrain sway and yaw motions.

The report should describe in detail the characteristics of the guidance system.

2.5 Free Running Tests

Tests with self propelled models are normally carried out at or around the model self propulsion point of the design or a certain speed speed?. 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.

The autopilot parameters should be carefully chosen to obtain a realistic response of the model. 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, COG 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 bending, sagging and hogging loads have to be reported.

2.7 Measurement of Added Resistance

The power increase in waves can be measured directly with free running models (refer to ITTC recommended procedure 7.5-02-06-0.1) or determined indirectly from measurements of added resistance on captive models.

In this case often, the duration of the tests has to be longer because of the large fluctuations in the instantaneous resistance.

2.8 Measurement of Impact Load

Two methods are being used to measure impact loads: pressure gauges and force plates.

Pressure gauges measure local loads and therefore their statistical variability is large. Their frequency responses as well as their sampling frequencies have to be very high (in the order of kHz). It is not clear how these measurements are affected by scale effects.

Force plates measure the mean pressure over a bigger area (typically a structural panel) and therefore they are statistically more stable. Their frequency responses have to be sufficiently high or the effects of the frequency responses are corrected by means of accelerometers.

2.9 Parameters to be Measured

The amplitudes and phases of hull motions in the desired degrees of freedom (as defined in Reference 6) should be measured as appropriate to the purpose of the test.

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.

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

- Accelerations. In order to provide corroborating data for computation of accelerations from measured motions.
- 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 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, either by film or video, 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 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 mean track 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.

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.)

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.

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. When generating irregular waves in a tank, the input signal to the wave maker should be produced such that the generated waves are non-repeatable.

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 sample rate in the data acquisition needs to be fast enough in order to achieve sufficient resolutio 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 Fast Fourier Transform.

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.

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 presented in other appropriate non-dimensional form. 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 defined in Reference 6. 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 should be presented in histograms to depict probability density and as cumulative probability distribution plots for selected responses.

Tabular presentation of all results should be made in addition to plots

3. PARAMETERS

3.1 Parameters to be Taken into Account

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
- Mass distribution (COG, inertias, ...)
- Towing and/or restraining device characteristics (specially DOF)
- Speeds and headings
- Wave characteristics (heights, periods, spectra, dispersions, ...)
- Autopilot control law
- 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:

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

where

$$A=173(\zeta_W)_{1/3}^2/T_1^4$$

$$B=691/T_1^4$$

$$T_1=2\pi m_0/m_1$$

1984 Recommendation for long crested limited fetch sea spectral formulation:

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

where:

$$\gamma=\exp\left[-\frac{(0.191\omega T_1-1)^2}{2\sigma^2}\right]$$

$$\sigma=\begin{cases}0.07 & \omega<5.24/T_1\\ 0.09 & \omega>5.24/T_1\end{cases}$$

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

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

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 an uncertainty analysis is shown in the appendix using the sample analysis of the S-175 ship.

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, 1966, pp.342-350).
   Comparison among motion response obtained from full scale tests, model experiments and computer calculations for destroyer H.M. "Groningen” of the Royal Netherlands Navy

4) Comparison of the Computer Calculations of Ship Motions (11th ITTC, 1966, pp.350-55). Ship response functions for the Series 60 wih C_B=0.70 parent form.

5) Computer Program Results for Ship Behaviour in Regular Oblique Waves (11th ITTC, 1966, pp.408-411).
   Series 60 with Cb=0.60 and 0.70.

6) Experiments in Head Seas For Series 60.

6-1) Comparative Tests of a Series 60 Ship Model in Regular Waves (11th ITTC, 1966, pp.411-415). Series 60 with Cb=0.60.

6-2) Experiments on Heaving and Pitching Motions of a Ship Model in Regular Longitudinal Waves (11th ITTC, 1966, pp.415-418). Series 60 with Cb=0.60.

6-3) Experiments on the Series 60 with Cb=0.60 and 0.70 Ship Models in Regular Head Waves (11th ITTC, 1966, pp.418-420)

6-4) Comparison of Measured Ship Motions and Thrust Increase of Series 60 Ship Models in Regular Head Waves (11th ITTC, 1966, pp. 420-426).

6-5) Estimation of Ship Behaviour at Sea from Limited Observation (11th ITTC, 1966, pp.426-428)

7) Computer Results, Head Seas

7-1) Theoretical Calculations of Ship Motions and Vertical Wave Bending Moments in Regular Head Seas (11th ITTC, 1966, pp. 428-430). Series 60 with Cb=0.70.

7-2) Comparison of Computer Program Results and Experiments for Ship Behaviour in Regular Head Seas (11th ITTC, 1966, pp.430-432). Series 60 with C_B=0.60 and 0.70

7-3) Computer Program Results for Ship Behaviour in Regular Head Waves (11th ITTC, 1966, pp.433-436) Series 60 with Cb=0.60 and 0.70.

7-4) Comparison of Calculated and Measured Heaving and Pitching Motions of a Series 60 with Cb=0.70 Ship Model in Regular Longitudinal Waves (11th ITTC, 1966, pp.436-442).

7-5) Computer Calculations of Ship Motions (11th ITTC, 1966, pp.442)

7-6) Computer Calculations of Ship Motions and Vertical Wave Bending Moment (11th ITTC, 1966, pp. 442-445). Series 60 with Cb=0.60 and 0.70

8) Comparison of the Computer Calculations for Ship Motions and Seakeeping Qualities by Strip Theory (14th ITTC, 1975, pp.341-350) . A large-sized ore carrier

9) Comparison on Results Obtained with Computer Programs to Predict Ship Motions in Six Degrees of Freedom (15th ITTC, 1978, pp. 79-90). S-175 with Cb = 0. 572.

10) Comparison of Results Obtained with Computer Programs to Predict Ship Motions in Six-Degrees-of-Freedom and Associated Responses(16th ITTC, 1981, pp.217-224).

To identify the differences in the various strip theories and computation procedures utilised by the various computer programs and provide guidance for improvement if necessary. S-175 container ship for Fn = 0.275.

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

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

13) 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.

14) Validation, Standards of Reporting and Uncertainty Analysis Strip Theory Predictions (19th ITTC, 1990, pp.460-464). Comparison of results from 5 strip theory programs for the S-175.

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

14-1) Tests of Two Dimensional Models. Added mass, damping and wave exciting forces

14-2) Tests of a Wigley hull form. Added masses, damping, exciting forces and seakeeping motions and loads.

14-3) Tests for S-175.

16) Validation of Seakeeping Calculations (21st ITTC, 1996, pp.41-43). Basic theoretical limitations. Numerical software engineering aspects

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

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

Appendix

A.1 EXAMPLE OF UNCERTAINTY ANALYSIS

An example of an uncertainty analysis based on the S-175 ship is shown.

A.1.1 Analysis of Elemental Errors

<u>Accuracy of Model Geometry and Weight Distribution</u>. The error sources in model geometry are the length between perpendicular (L_{PP}), breadth (B) and draft (T) as shown in Table 4. The error limits for the first two items are estimated from model manufacturing errors. The error in draft comes from the error in model displacement. For the execution of motion test, the weight should be distributed properly inside model ship to satisfy predetermined value of vertical centre of gravity, KG, and longitudinal radius of gyration, k_{yy}. Swinging table type device is used for the determination of KG and k_{yy}. Table 4 and Table 5 show the error limits of above mentioned error sources and error limits for KG and k_{yy}. The detailed procedure of obtaining these values can be found in Yum et al. (1993).

<u>Model Speed</u>. The error limit in model speed is estimated following the procedure suggested by Fogash (1992). Under the assumption that model speed, V_{M}, through the water is equal to the speed of towing carriage, the model speed is determined from

$$V_{\mathrm{M}} = \frac{(n/5000)\pi D}{t} = \frac{f\pi D}{5000} \qquad (1)$$

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 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 results are summarised in Table 4.

Measuring Device and Calibration Errors. The measurement items in regular wave motion test are the wave encounter frequency, ω_e, wave amplitude, ζ_a, heave amplitude, H, and phase, α_H, and pitch amplitude, θ, and phase, α_θ. The servo needle type wave probe is used for the measurement of wave and 4-component motion measuring device is used for heave and pitch motions. The equation used for the analysis of wave amplitude is

$$\zeta_a = \frac{\zeta_p - \zeta_t}{2} \tag{2}$$

where subscript p and t represent wave peak and wave trough respectively. Using Eq. (2), the bias limit of wave amplitude, B_{ζ_a}, becomes

$$(B_{\zeta_a})^2 = \left(\frac{\partial \zeta_a}{\partial \zeta_p} B_{\zeta_p}\right)^2 + \left(\frac{\partial \zeta_a}{\partial \zeta_t} B_{\zeta_t}\right)^2 + +2\rho_{pt}\frac{\partial \zeta_a}{\partial \zeta_p}\frac{\partial \zeta_a}{\partial \zeta_t} B_{\zeta_p} B_{\zeta_t} \tag{3}$$

If we consider the fact that the peak and trough of wave are continuously measured using one servo needle type wave probe, the bias limit of peak value, B_{ζ_p}, and the bias limit of trough value, B_{ζ_t}, are perfectly correlated (ρ_{pt}=1.0) and equal in their magnitudes. This means that the value of Eq. (3) becomes zero and furthermore the bias error of the wave probe does not influence the bias limit in measured wave amplitude at all. The same conclusion can be made for heave and pitch measuring transducers.

Other error sources in measuring devices are calibration errors. These errors are represented by

$$SEE^2 = \frac{1}{M-C}\sum_{k=1}^{M}\left(y_k - y_{LS,k}\right)^2 \tag{4}$$

M : number of data used for calibration
C : number of variable for fitting function
y_k : data
$y_{LS,k}$: fitted value
SEE (standard error of estimate) is considered as precision limit because this value is obtained by a statistical analysis of repeated independent measurements.

All the errors in measuring devices considered so far are errors in the outputs for static inputs. But, for the case of dynamic inputs like motion test, dynamic response errors need to be considered. The traditional way to investigate the dynamic response of an instrument is to consider the differential equation that describes output. And measuring instruments are classified by the order of the governing differential equation. The potentiometers used for the measurement of heave and pitch amplitudes are zero-order instruments in which there are no errors in the output due to the dynamic response. The characteristic (order) of the servo needle type wave probe is not known clearly. In the present study 0.5 mm is used for the dynamic error of the servo needle type wave probe (Hirayama et al, 1988). This error is considered to be asymmetric error because the measured values of wave amplitudes are always smaller than the true values. Table 3 lists all the error limits of measuring devices.

Signal analysis. There are many different methods for the analysis of measured regular signals in motion test. Two most frequently used methods among them are the method of Fourier Transform and the method of peak-to-peak counting. For the present analysis peak-to-peak method is used. In this method, the peak and trough values are searched and analysed to get the amplitude and frequency of a measured signal. Using peak-to-peak method, the wave amplitude, heave and pitch amplitudes and wave encounter frequency and period are obtained by the following equations.

$$\zeta_a = \frac{\bar{\zeta}_p - \bar{\zeta}_t}{2} \tag{5}$$

$$H = \frac{\bar{H}_p - \bar{H}_t}{2} \tag{6}$$

$$\theta = \frac{\bar{\theta}_p - \bar{\theta}_t}{2} \tag{7}$$

$$\omega_e = \frac{2\pi}{T} \tag{8}$$

$$\bar{T} = \frac{1}{N}\sum_{n=1}^{N}\left(T_{p,n+1} - T_{p,n}\right) \tag{9}$$

The bias errors which occur during the process of amplitude analysis of wave, heave and pitch are obtained by using regular sinusoidal waves which have same amplitudes and frequencies as the measured signals. The errors related to the half of data sampling interval are used to obtain these bias errors. These errors are known to be asymmetric.

The precision errors of wave amplitude, heave and pitch amplitudes and wave encounter frequency are obtained by

$$S_{\zeta_a} = \sqrt{\left(\frac{\partial\zeta_a}{\partial\bar{\zeta}_p} S_{\bar{\zeta}_p}\right)^2 + \left(\frac{\partial\zeta_a}{\partial\bar{\zeta}_t} S_{\bar{\zeta}_t}\right)^2} \tag{10}$$

$$S_H = \sqrt{\left(\frac{\partial H}{\partial H_p} S_{\bar{H}_p}\right)^2 + \left(\frac{\partial H}{\partial H_t} S_{\bar{H}_t}\right)^2} \tag{11}$$

$$S_\theta = \sqrt{\left(\frac{\partial\theta}{\partial\bar{\theta}_p} S_{\bar{\theta}_p}\right)^2 + \left(\frac{\partial\theta}{\partial\bar{\theta}_t} S_{\bar{\theta}_t}\right)^2} \tag{12}$$

$$S_{\omega_e} = \left|\frac{\partial\omega_e}{\partial T} S_{\bar{T}}\right| \tag{13}$$

where $S_{\bar{\zeta}_p}$ and $S_{\bar{\zeta}_t}$ are the precision index for the mean value of wave peaks and troughs respectively. Similar notations are used for heave and pitch motions. $S_{\bar{T}}$ is the precision index for the mean value of peak-to-peak periods.

A.1.2 Response Amplitude Operator (RAO)

This section describes the procedure of combining all the errors obtained in A.1.1 and data reduction equations (DRE's) to get heave and pitch RAO's and their overall uncertainties.

For the variables such as L_{PP}, B , d ,KG, k_{yy} and model speed (V_M), the data reduction equations which describe the functional dependency of the heave and pitch RAO's to these variables cannot be found as functional forms. Therefore, the error propagation coefficients for these variables are obtained analytically using ship motion program based on the strip method (Park and Kang, 1989).

The heave RAO, bias limit, precision limit and overall uncertainty are

$$H' = \frac{H}{\zeta_a} \tag{14}$$

$$B_{H'}^{\pm} = \sqrt{\left(\frac{\partial H'}{\partial \zeta_a} B_{\zeta_a}^{\pm}\right)^2 + \left(\frac{\partial H'}{\partial H} B_H^{\pm}\right)^2} \tag{15}$$

$$P_{H'} = \sqrt{\left(\frac{\partial H'}{\partial \zeta_a} P_{\zeta_a}\right)^2 + \left(\frac{\partial H'}{\partial H} P_H\right)^2} \tag{16}$$

$$U_{H'}^{\pm} = \sqrt{\left(B_{H'}^{\pm}\right)^2 + \left(P_{H'}\right)^2} \tag{17}$$

The pitch RAO, bias limit, precision limit and overall uncertainty are

$$\theta' = \frac{\theta}{\left(\frac{360\zeta_a}{\lambda}\right)} \tag{18}$$

$$B_{\theta'}^{\pm} = \sqrt{\left(\frac{\partial \theta'}{\partial \lambda} B_\lambda\right)^2 + \left(\frac{\partial \theta'}{\partial \theta} B_\theta^{\pm}\right)^2 + \left(\frac{\partial \theta'}{\partial \zeta_a} B_{\zeta_a}^{\pm}\right)^2} \tag{19}$$

$$P_{\theta'} = \sqrt{\left(\frac{\partial \theta'}{\partial \lambda} P_\lambda\right)^2 + \left(\frac{\partial \theta'}{\partial \theta} P_\theta\right)^2 + \left(\frac{\partial \theta'}{\partial \zeta_a} P_{\zeta_a}\right)^2} \tag{20}$$

$$U_{\theta'}^{\pm} = \sqrt{\left(B_{\theta'}^{\pm}\right)^2 + \left(P_{\theta'}\right)^2} \tag{21}$$

where the value of wavelength, λ, and its bias limit, B_λ, and precision limit, P_λ, can be obtained using the relation between the absolute frequency, ω, and the encounter frequency, ω_e, and wave dispersion relation in deep water.

For the comparison of RAO, non-dimensional absolute frequency, $\omega\sqrt{L/g}$, is used as an independent variable. The value of non-dimensional absolute frequency, its bias and precision limits and overall uncertainty are

$$B_{\omega'}^{\pm} = \sqrt{\left(\frac{\partial \omega'}{\partial V} B_V\right)^2 + \left(\frac{\partial \omega'}{\partial L} B_L\right)^2} \tag{22}$$

$$P_{\omega'} = \sqrt{\left(\frac{\partial \omega'}{\partial V} P_V\right)^2 + \left(\frac{\partial \omega'}{\partial L} P_L\right)^2 + \left(\frac{\partial \omega'}{\partial \omega_e} P_{\omega_e}\right)^2} \tag{23}$$

$$U_{\omega'} = \sqrt{\left(B_{\omega'}\right)^2 + \left(P_{\omega'}\right)^2} \tag{24}$$

Combining Eqs. (17), (21) and (24), the final overall uncertainties for heave and pitch RAO's become

$$\tilde{U}_{H'}^{\pm} = \sqrt{\left(U_{H'}^{\pm}\right)^2 + \left(\frac{\partial H'}{\partial \omega'} U_{\omega'}\right)^2} \tag{25}$$

$$\tilde{U}_{\theta'}^{\pm} = \sqrt{\left(U_{\theta'}^{\pm}\right)^2 + \left(\frac{\partial \theta'}{\partial \omega'} U_{\omega'}\right)^2} \tag{26}$$

where $\partial H'/\partial\omega'$ and $\partial\theta'/\partial\omega'$ are the slopes of the heave and pitch RAO's respectively, as a function of ω.

A.1.3 Results

Table 6 contains summary of the overall uncertainties of heave and pitch RAO's. The ratios of overall uncertainties to heave RAO's range from ±2.0% to ±3.5% and for pitch RAO's they range from ±3.5% to ±6.0%. At higher encounter frequencies, as the magnitudes of the heave and pitch RAO's decrease, the uncertainty limits tend to increase significantly.

Figure 4 and Figure 5 show the final combined uncertainty limits of the heave and pitch RAO's. Presented in these figures are the analysis results of the RAO's using the strip theory indicated by the triangles (Park and Kang, 1989). The computed values of the heave and pitch RAO's by the strip method were found to lie far outside of the uncertainty limits of 95% confidence level. These differences between the test results and analysis results have been noticed in the report of the 15th and 16th ITTC Seakeeping Committee Comparative Study on Ship Motion Program (1978, 1981).

A.1.4 Conclusions

1) Uncertainty analysis has been successfully applied to the motion test in regular waves.

2) 95% confidence intervals for heave and pitch RAO's were approximately ±3.0% and ±5.0% respectively.

3) The analysis results of motion RAO's were found to lie outside of the uncertainty limits of 95% confidence level of motion test.

4) The extension of present uncertainty analysis to more complex situations such as tests in irregular waves is expected.

Model Ship		S-175
L_{pp}	(m)	4.50
B	(m)	0.6351
D	(m)	0.396
T	(m)	0.2443
∇	(m^3)	0.4101
LCB	(m)	0.0364
C_B		0.5716
GM	(m)	0.0257
KM	(m)	0.2705
k_{yy}/L_{pp}		0.0364
KG	(m)	0.2448

Table 2. Principal particulars of ship model (scale 38.889)

Measurement		
L, B, T	(m)	Model dimensions (L_{pp}, beam, draft)
V	(m/s)	Carriage speed
KG	(m)	Distance from keel to center of gravity
k_{yy}	(m)	Pitch radius of gyration
ζ_a	(m)	Wave amplitude
ω_e	(rad/s)	Encounter frequency
H	(m)	Heave amplitude
θ	(deg)	Pitch amplitude

Analysis	
λ	Wave length
$\omega' = \omega\sqrt{L/g}$	Non-dimensional frequency
$H' = H/\zeta_a$	Heave RAO
$\theta' = \dfrac{\theta\lambda}{360\zeta_a}$	Pitch RAO

Table 3. Objects of uncertainty analysis for motion

Error Sources	Error	Sensitivity	Error Components: Bias Limit	Error Components: Precision Index
Model dimension				
1) LBP (4.50 m)	1.00E-03m	1.00E+00	1.00E-03m	
2) B (0.6531 m)	1.00E-03m	1.00E+00	1.00E-03m	
3) d (0.2443 m)	2.97E-04m	1.00E+00	2.97E-04m	
Swinging table				
1) x (2 m)	1.00E-03m	1.00E+00	1.00E-03m	
2) y_1 (1.950 m)	1.00E-03m	1.00E+00	1.00E-03m	
3) y_2 (1.795 m)	1.00E-03m	1.00E+00	1.00E-03m	
4) W_1 (20 kg)	2.00E-03kg	1.00E+00	2.00E-03kg	
5) W_m (410 kg)	5.00E-01kg	1.00E+00	5.00E-01kg	
6) W_d (169 kg)	1.00E-01kg	1.00E+00	1.00E-01kg	
Timer				
1) Trigger error	1.00E-04sec/FS	1.41E+00	1.41E-04sec	
2) Digital error	1.00E-04sec	1.00E+00	1.00E-04sec	
3) Measurement	2.84E-04sec	1.00E+00		2.84E-04sec
			1.73E-04sec	2.84E-04sec
Accelerometer				
1) Linearity error	5.00E-03volt	1.00E-01rad/volt	5.00E-04rad	
Velocity (1.827 m/s)				
1) Wheel diameter	2.00E-04m	1.15E+01 1/s	2.30E-03m/s	
2) Pulse frequency	1.45E-01pulse/sec	1.00E-04m/pulse	1.45E-05m/s	
3) Digital counter	15pulse/sec	1.00E-04m/pulse		1.50E-03m/s
			2.30E-03m/s	1.50E-03m/s
Wave-probe				
1) Calibration error	4.30E-05/FS	1.50E-01m		6.45E-05m
2) Dynamic error(B)	3.33E-03/FS	1.50E-01m	5.00E-04m	
4-Component				
1) Heave	2.16E-03/FS	3.00E-01m		6.48E-04m
2) Pitch	2.28E-03/FS	3.00E+01deg		6.84E-02deg
A-D Converter				
1) Ch. 1 (wave)	1.17E-04/FS	1.50E-01m		1.76E-05m
2) Ch. 2 (heave)	4.03E-05/FS	3.00E-01m		1.21E-05m
3) Ch. 3 (pitch)	6.67E-05/FS	3.00E+01deg		2.00E-03deg

Table 4. Error Sources for motion tests (V=1.827 m/s)

Error Sources	Error	Sensitivity	Bias Limit	Precision Index
KG(2.4562RE-01m)				
1) Y_2 (1.795m)	1.00E-03m	1.00E+00	1.00E-03m	
2) x (2 m)	1.00E-03m	7.75E-01	7.75E-04m	
3) Wm (410kg)	5.00E-01kg	3.78E-03m/kg	1.89E-03m	
4) W_1 (20kg)	2.00E-03kg	7.75E-02m/kg	1.55E-04m	
5) θ_2 (0.041692rad)				
Bias error	5.00E-04rad	5.62E+01m/rad	2.81E-02m	
Random error	1.43E-07rad	5.62E+01m/rad		8.04E-06m
6) θ_1 (0.12301rad)				
Bias error	5.00E-04rad	6.48E+00m/rad	3.24E-03m	
Random error	1.26E-07rad	6.48E+00m/rad		8.16E-07m
			2.84E-02m	8.06E-06m
G_m(1.54957m)			2.83E-02m	8.06E-06m
G_d(0.70155m)				
1) W_1	2.00E-03kg	8.42E-02m/kg	1.68E-04m	
2) W_d (169kg)	1.00E-01kg	9.96E-03m/kg	9.96E-04m	
3) x	1.00E-03m	9.57E-01	9.57E-04m	
4) y_1 (1.950m)	1.00E-03m	1.18E-01	1.18E-04m	
5) θ_1				
Bias error	5.00E-04rad	1.57E+01m/rad	7.85E-03m	
Random error	1.26E-07rad	1.57E+01m/rad		1.98E-06m
			7.97E-03m	1.98E-06m
k_{yy}(1.07401m)				
1) T_t (3.19712sec)				
Bias error	1.73E-04sec	1.36E+00m/sec	2.35E-04m	
Random error	2.84E-04sec	1.36E+00m/sec		3.86E-04m
2) W_d	1.00E-01kg	4.38E-04m/kg	4.38E-05m	
3) W_m	5.00E-01kg	1.80E-04m/kg	9.00E-05m	
4) G_d				
Bias error	7.97E-03m	1.05E-01	8.37E-04m	
Random error	1.98E-06m	1.05E-01		2.08E-07m
5) G_m				
Bias error	2.83E-02m	2.61E-01	7.39E-03m	
Random error	8.08E-06m	2.61E-01		2.11E-06m
6) T_d (3.526sec)				
Bias error	1.73E-04sec	2.36E-01m/sec	4.08E-05m	
Random error	2.53E-04sec	2.36E-01m/sec		5.97E-05m
			7.45E-03m	3.91E-04m

Table 5. Results of uncertainty analysis of KG and k_{yy} measuring device.

$\omega\sqrt{L/g}$	λ/L	H'	$\tilde{U}_H^-$,(%)	$\tilde{U}_H^+$,(%)	θ'	$\tilde{U}_\theta^-$,(%)	$\tilde{U}_\theta^+$,(%)
1.773	2.00	1.003	0.0197 (1.96%)	0.0217 (2.16%)	1.138	0.0452 (3.99%)	0.0464 (4.08 %)
2.045	1.50	1.124	0.0345 (3.07%)	0.0374 (3.33%)	1.231	0.0449 (3.64%)	0.0475 (3.86%)
2.216	1.28	1.272	0.0406 (3.19 %)	0.0449 (3.53%)	1.108	0.0464 (4.19%)	0.0493 (4.45%)
2.416	1.08	1.042	0.0321 (3.08%)	0.0366 (3.51%)	0.772	0.0418 (5.41%)	0.0442 (5.72%)
2.655	0.89	0.317	0.0332 (10.47%)	0.0340 (10.72%)	0.320	0.0373 (11.66%)	0.0379 (11.88%)
3.430	0.53	0.067	0.0516 (77.5 %)	0.0517 (77.6%)	0.0073	0.0364 (500%)	0.0364 (500%)

Table 6. Overall uncertainty of heave and pitch RAO.

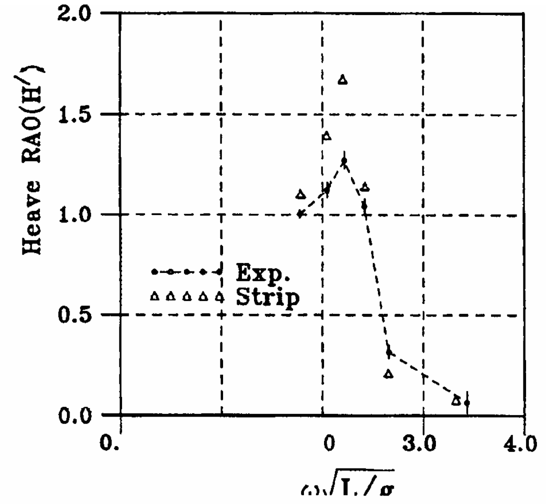

Figure 4. Heave RAO (H') and range of uncertainty.

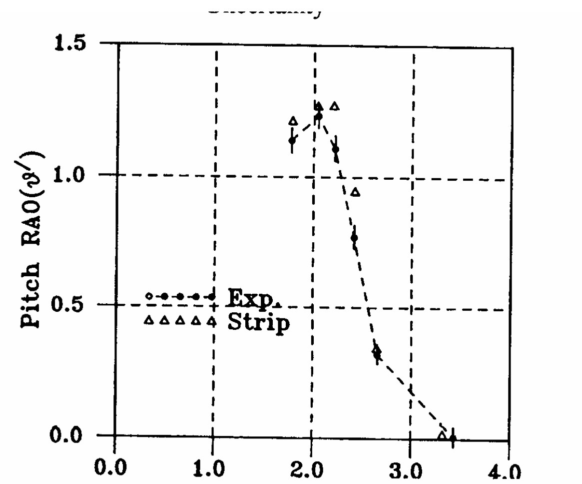

Figure 5. Pitch RAO (θ') and range of uncertainty

5. REFERENCES

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