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DATA ANALYSIS METHODOLOGIES FOR HYDRODYNAMIC EXPERIMENTS IN WAVES

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Abstract:

This paper presents the methodologies developed in order to provide quality control and analyze the data acquired in hydrodynamic seakeeping experiments of physical models in waves. In such experiments, the data files consist of wave elevations and directions, loads, motions, velocities and accelerations for one or multiple bodies. Additionally, mooring, slamming, sea-fastening, fender and other vessel specific load data may be acquired, which requires special analysis techniques. Data products for such experiments primarily consist of the basic statistics of each of the acquired data channels selected segments. Various wave statistics are produced to estimate the significant and other percentile of peaks/troughs/heights of each relevant data signal. This is done using zero crossing analysis. The response amplitude operator analysis is done through spectral analysis. Weibull analysis is done to estimate the maximum and minimum of an occurrence in a projected time. Analysis routines are written to incorporate each of these analysis techniques to produce results both in tabular and graphical formats. The analysis technique for decay experiments in multiple directions of motion, which are integral parts of any sea-keeping experiments, is also presented. Examples of all such analysis are provided where appropriate.

***Keywords*: Data analysis, wave experiments, wave statistics, ZCA analysis, RAO analysis, Weibull analysis

Introduction

The most important product from a physical model experiment is the processed data in a readable format. In most cases the raw data that is acquired through the experimentation is of no use to the end user. It often requires quality checks and data type conversion to make it readable using commonly used software. Due to the increased demand in the offshore industry, the physical model experiments now vary from a moored single body in regular waves to multiple bodies (floating and submerged in water and in air) with relative motions in wave, wind and current environments. Essentially, the data processing becomes complex as the complicacy of the experiments increases. With the number of acquired data channels, period of acquisition and sampling rate increasing, the time to process the data becomes crucial as well. There has been a scarcity in the literature on the details of data analysis processes used to produce the standard data product of such experiments.

The authors present methods for the analysis and quality control of data from model seakeeping experiments. The authors realize that the described methods are not new. The procedures described in the manuscript are similar to those that have been used for many years, for example, by many of the Institutions which perform seakeeping experiments. Also, the aspects related to the analysis of offshore structures physical model tests are covered in detail by Chakrabarti (1994). Additionally, a significant amount of information on the state of the art progress can be found in the ITTC proceedings. This refers also to experimental techniques and analysis procedures for model experiments. Besides the proceedings, the ITTC also produces a large set of Recommended Procedures covering many aspects of the Association's activities. The Recommended Procedures also cover the analysis of experimental data and reporting of results. However, the analysis procedure for wave experimental data has never been published with details of each step as a single article. The steps presented in this paper can be directly used by a data analyst to obtain the results in report format efficiently and accurately.

This paper emphasizes data analysis techniques utilized within Oceanic Consulting Corporation (OCC) for seakeeping experiments in waves. Aspects of data collection, instrumentation, or applications are not described except as they directly relate to data analysis. The authors could not find any reference that describes the data analysis procedure for wave experiments. However, a number of articles were found that describes the ocean

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wave analysis technique. Kinsman (1965) provides useful philosophical and intuitive descriptions of these concepts. Earle and Bishop (1984) and Earle et al. (1984) describe wave analysis procedures involving statistics in an introductory manner. Several papers by Longuet-Higgins (1957, 1965, and 1980) are among the most useful papers which describe statistical aspects of ocean waves. Donelan and Pierson (1983) provide statistical results that are particularly useful for significant data ranges. Dean and Dalrymple (1984) discuss theoretical and practical aspects of waves without emphasis on statistics.

This paper presents the analysis methodologies that provide general data analysis deliverables for a program of experiments in waves. It outlines the steps that can generally be followed to produce the deliverables that are expected by the end users in an organized and accurate way. A flowchart is presented to illustrate the sequence of the analysis process. Details of analytical expressions and examples that are used in developing analysis routines for each steps of analysis are then provided. A description as to how the analysis products are used to produce report quality graphics and tables is then given. The entire procedure can be used by a data analyst to provide a quality check and analyze the data acquired in any experiment that involves single or multiple bodies in waves. To the authors' best knowledge no such publication exists in the public domain

2. Data Analysis Deliverables

The first step in a data analysis job is to identify the deliverables. For most seakeeping experiments in waves, the number of deliverables of the data processing remains the same. For such experiments, the motions, velocities and accelerations are often measured at a convenient location in the model but need translation to the centre of gravity and other preferred locations. Forces of various kinds (mooring, localized wave impact loads, etc.), wave elevations and directions are the other parameters that are measured. A list of typical deliverables for such experiment is provided as follows:

- Measured motions at the model's Centre of Gravity and other required locations
- Derived motions, velocities and accelerations at required locations
- Contact forces, slamming forces and sea fastening forces (if any)
- All seakeeping test data including:
  - Raw and processed time traces.
  - Statistical data of each test program (Unfiltered and filtered)
  - Wave statistics for each test program
  - Response Amplitude Operator analysis with the spectral data. All results from spectral analysis shall be documented with band width, record length, filtering frequencies, smoothing method and standard error estimates.
  - Extremes (most probable maximum) derived with statistical method to be presented for all measured data.
- Special Analysis: Slamming
  - All slamming occurrences registered with time and force.
  - Statistically post processed slamming occurrences including extreme estimates.
- Special Analysis: Fender Load
  - All fender load measurement registered with time, force and deflection.
  - Fender stiffness, target versus measured.
  - Fender force and deflection correlation with motions.
  - Statistically post processed fender impact load occurrences including extreme estimates.
- Special Analysis: Mooring Analysis
  - Mooring forces and moments in the three coordinate directions.
- Results of decay experiments in tabular and graphical formats.

3. Data Analysis Steps

The data recorded in seakeeping experiments is processed through a number of steps as outlined in the flowchart in Figure 1. The analysis steps presented in each of the sub-sections below are identified in the figure. Stage-gating in the analysis steps is strictly followed to maintain high quality of the delivered data. The stage-gates are presented as solid red line in the figure. A large number of analysis routines are developed, checked and implemented to facilitate the data analysis process. All the scripts are written in-house using Matlab®, which are easier to maintain and debug and fasterin terms of processing time than most of other similar routine written in FORTRAN for UNIX system. A detail description of the data analysis steps is presented in the following sub-sections.

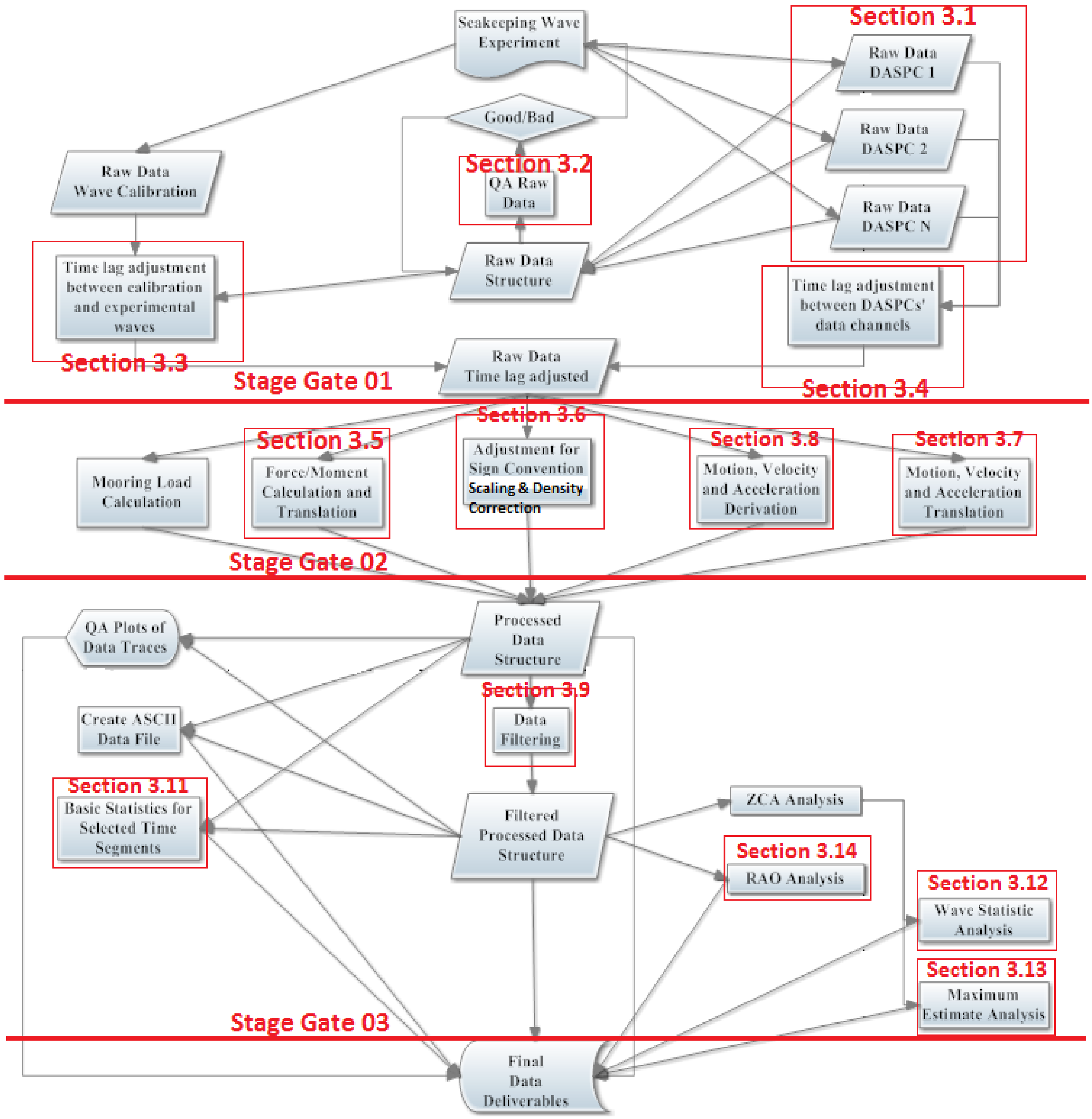

Figure 1: Flowchart showing the analysis methodologies

3.1 Data conversion: raw to MATLABformat

The data acquisition system saves the experimental data in binary format and in a UNIX server. The binary wave data is firstly downloaded from the server and converted to a Matlab structure format using a custom data conversion script. The array formatted data structure has the number of columns equal to the number of data channels. Each column has a number of fields to provide the details of each data signal including the sampling rate, channel group, etc. Generally the raw data structure is called a Test_Struc and has the fields as described in Table 1.

Table 1: Details of the raw data structure fields

Field Name	Field Description
Values	The raw data as acquired for the data signal
Name	Name of the data signal
Units	Unit of the data signal
Group	Group of the data signal; each group either consists of data channels with same sampling rate or data channels acquired in same data acquisition system (DAS)
Dt	Time increment; one over which is the data sampling rate

3.2 Raw data quality check

A preliminary check on the raw data is done to warn the experimental personnel of the possibility of a dead channel, static drifts, and data saturation. This helps to resolve any data acquisition issue before proceeding further in the experimental program, thus avoiding any repeat work.

3.3 Wave phase adjustment

The wave drive signals from the environment calibration condition and the actual experiment condition often have phase difference due to the inherent time variability in machinery startup. This time difference is often adjusted by shifting the calibration wave elevation signal by the amount of time lag obtained from the cross-correlation of the two drive signals. Since the calibration wave probe isn't present during experiments, the adjusted wave elevation signal from the calibration conditions must then be added to the main data structure.

3.4 Data acquisition system phase adjustment

Often, in wave experiments, multiple data acquisition system personal computers (DASPCs) are used to acquire large number of data channels. Often there exists a time lag between the channel groups from each DASPC due to slight delay in triggering the acquisition. This necessitates the synchronization of data channels from different DASPCs. Usually, a synchronization signal is recorded by each DAS to allow phase adjustment to a common time. The synchronization signal distributed to each DAS can be a 1 Hz sine wave generated from a universal voltage source. Using cross correlation the synchronization signals are analyzed to determine the time lag amongst the common signals for each DASPC. With the synchronization signal recorded by facility DAS as the reference, the time lags of the synchronization signals from other DASs are obtained. The remaining data signals for each DAS are shifted using the corresponding time lag values to align all signals to a common time reference. The time lag values for each DAS are reported in the text file outlining the wave time lags.

3.5 Dynamometer forces and moments

Forces and moments in the three coordinate directions are often measured using commercial multi-axes strain gauges. Typically a commercial six component force dynamometer includes six strain gauges arranged in a y-delta pattern inside the sensor. A factory calibration matrix, which includes the cross-talk between the strain gauges, is used to convert the acquired voltage signals from each strain gauge to forces and moments at a reference location for each unit, see Equation (1). Sometimes an in-house developed force dynamometer, with multiple strain-gauges located in different orientations, is used. In such cases, the following formulations are used to convert the strain-gauge readings into forces and moments in the three coordinate directions, see Equation (2).

$$\begin{bmatrix} FV_1 \\ \vdots \\ FV_6 \end{bmatrix} \times \begin{bmatrix} C_{11} & \cdots & C_{16} \\ \vdots & \ddots & \vdots \\ C_{61} & \cdots & C_{66} \end{bmatrix} = \begin{bmatrix} FX \\ \vdots \\ MZ \end{bmatrix} \tag{1}$$

$$\begin{aligned} F_{Xn} &= L_n \times DC_{Xn} \\ F_{Yn} &= L_n \times DC_{Yn} \end{aligned} \tag{2}$$

$\mathrm{F_{Zn}} = \mathrm{L_n} \times \mathrm{DC_{Zn}}$
$\mathrm{M_{Xn}} = -\mathrm{F_{Yn}} \times \mathrm{dZ_n} + \mathrm{F_{Zn}} \times \mathrm{dY_n}$
$\mathrm{M_{Yn}} = \mathrm{F_{Xn}} \times \mathrm{dZ_n} - \mathrm{F_{Zn}} \times \mathrm{dX_n}$
$\mathrm{M_{Zn}} = -\mathrm{F_{Xn}} \times \mathrm{dY_n} + \mathrm{F_{Yn}} \times \mathrm{dX_n}$
$\mathrm{FX} = \sum_{n=1}^{n} \mathrm{F_{Xn}};\ \mathrm{FY} = \sum_{n=1}^{n} \mathrm{F_{Yn}};\ \mathrm{FZ} = \sum_{n=1}^{n} \mathrm{F_{Zn}}$
$\mathrm{MX} = \sum_{n=1}^{n} \mathrm{M_{Xn}};\ \mathrm{MY} = \sum_{n=1}^{n} \mathrm{M_{Yn}};\ \mathrm{MZ} = \sum_{n=1}^{n} \mathrm{M_{Zn}}$

Where, n is the number of strain-gauges;
$FV_1 \ldots FV_6$ are the raw data (in voltages) measured by each component of the commercial dynamometer
$C_{11} \ldots C_{66}$ are the elements of the manufacturer supplied calibration matrix of the commercial dynamometer
DC is the direction cosine for each of the strain-gauge;
dX, *dY*, and *dZ* are the coordinate locations of each of the strain-gauges with respect to the moment reference point;
FXn,…*MZn* are the forces and moments components in the three coordinate directions as contributed by each of the n strain-gauges;
FX, ….,*MZ* are the global forces and moments in the three coordinate directions;

The calculated forces and moments using the calibration matrix in the case of commercial 6-component dynamometers or the directly calculated ones for the in-house built dynamometer is checked prior to and after the installation program by applying known forces and recording the offsets after calculation to find an offset coefficient for each unit. To obtain the adjusted forces, FA, the calculated forces, FC, from the factory calibration matrix are adjusted by multiplying them with the offset coefficient, CO, as seen in Equation (3).

$$F_A = F_C \times C_O \tag{3}$$

The forces and moments are usually transferred to some alternative locations such as model CG, waterline etc. Sometimes rotation of the coordinates of the forces/moments is done using the method described in section 3.7.

3.6 Scaling and density correction

Often the model scale acquired data is converted into full scale data. To obtain that, Froude scaling laws are applied to all data signals. Table 2 identifies the conversion factor used to adjust the model scale data to prototype scale.

Table 2: Froude Scaling Conversion Factors

Signal Type	Unit	Scale Factor
Acceleration	m/s^2	λ^0
Area	m^2	λ^2
Density	kg/m^3	λ^0
Force	N	λ^3
Frequency	s^{-1}	$\lambda^{-0.5}$
Length	m	λ^1
Mass	kg/m^3	λ^3
Moment	N-m	λ^4
Pressure	N/m^2	λ^1
Speed	m/s	$\lambda^{0.5}$
Time	s	$\lambda^{0.5}$

Signals including a force or mass term that are affected by hydrodynamic forces require a density correction. A proportional relationship of the ratio of prototype density to model density is applied to all forces as seen in Equation (4). Full scale density (ρ_{Full}) is assumed to be 1025 kg/m3 for sea water and model density (ρ_{Model}) is taken as 1000 kg/m3 for fresh water.

$$F_{Full} = \left(\frac{\rho_{\mathrm{Full}}}{\rho_{Model}} \right) F_{Model} \tag{4}$$

3.7 Translated motions and accelerations to points of interest

Optical tracking system and accelerometer are often used to measure the motions and accelerations of the floating body during seakeeping experiments. Motions and Accelerations are often measured on a reference point in the model body, which often require translation to several points of interest (POI) about the model using a translation matrix. This is also associated with rotation of the coordinate system (local, model coordinate system to global, inertia coordinate system). The method of translation and/or rotation is based on rigid body motion theory and follows the form of Equation (5) using the translation matrix shown in Table 3.

Table 3: Displaced Motion Translation Matrix – Euler Angle Transformation using X-Y-Z Ordering

cos(Pitch)*cos(Heading)	sin(Roll)*sin(Pitch)*cos(Heading)-cos(Roll)*sin(Heading)	cos(Roll) * sin(Pitch) * cos(Heading) + sin(Roll) * sin(Heading)
cos(Pitch)*sin(Heading)	sin(Roll)*sin(Pitch)*sin(Heading)+cos(Roll)*cos(Heading)	cos(Roll) * sin(Pitch) * sin(Heading) - sin(Roll) * cos(Heading)
-sin(Pitch)	sin(Roll)*cos(Pitch)	cos(Roll) * cos(Pitch)

$$[QB_{POI}] = T \bullet [R_{POI}] + [QB_M] \tag{5}$$

Where:
$[QB_{POI}]$ = Motion matrix at the point of interest in the global reference frame [1x3 row vector];
$[T]$ = Translation matrix (local to global reference frames) [3x3 matrix];
$[R_{POI}]$ = Relative location matrix of point of interest with respect to measurement point [1x3 row vector];
$[QB_M]$ = Motion matrix at the measurement reference location [1x3 row vector], see Figure 2.

3.8 Derived motions, velocities and accelerations

Velocities and accelerations can be derived from the measured motion signals using Fast Fourier Transformation (FFT) based differentiations. Likewise, the velocities and motions can be derived from the measured accelerations using FFT based integrations. Often experiments in waves will have both motion and acceleration of the rigid body measured. The derived motions, velocities and accelerations can be translated to a single point from both sources and cross checked with each other for accuracy of both measurements.

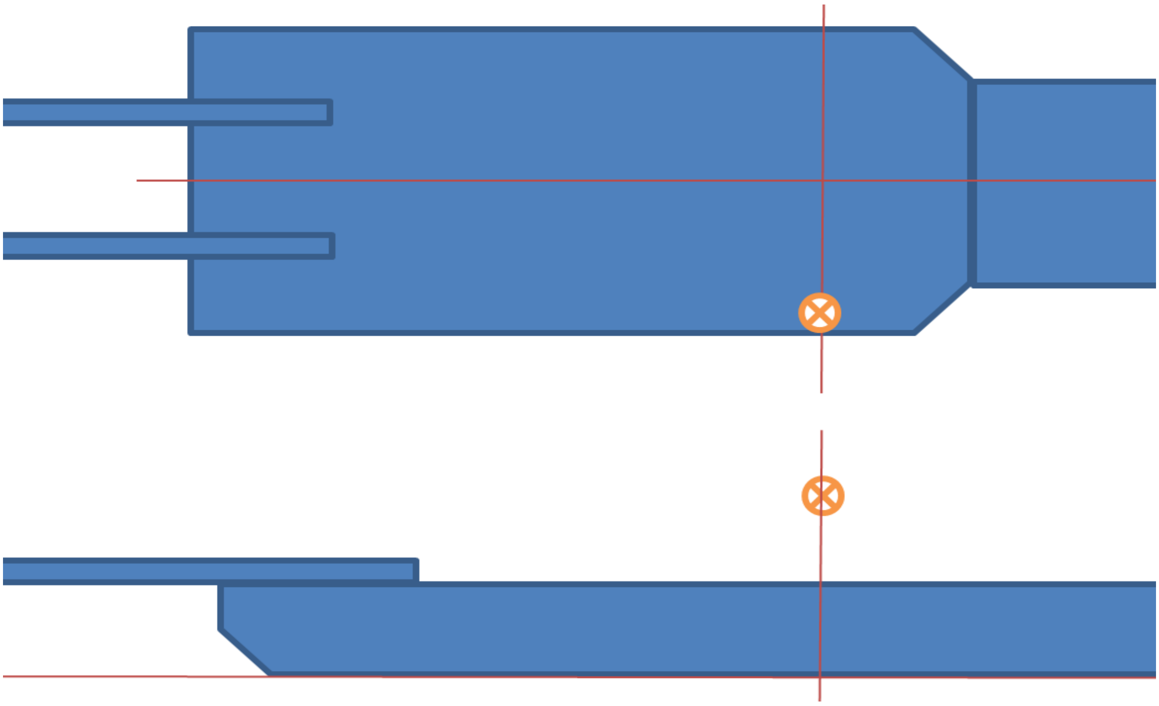

Figure 2: Optical Tracking System Measurement Reference Locations

3.9 Signal filtering

All derived velocities and motions from accelerations (using FFT based integration) and velocities and accelerations from motions (FFT based differentiation) are calculated using a low and high filter frequency cutoff, to remove very slow signal drift and high frequency components, respectively. Generally, all signals are filtered using FFT (Welch 1967) to a low frequency mooring components and high frequency wave components and sometimes very high frequency slamming/pressure components. Figure 3 shows the process of selection of low, wave and high frequency cut-off values for a typical seakeeping experiments in waves with a moored model and with slamming measurements. Generally, the power spectrums of the wave and model response are reviewed to identify and separate the wave induced response part and mooring induced slow drift part. After thorough review, the cut-off frequencies are selected to make sure the high frequency part does not include any low frequency part, see the black lines in Figure 3. Figure 4 shows a number of data time traces before and after they are filtered at a low pass cut-off frequency.

At this stage of the analysis, the overall data quality is checked for possible malfunctioning sensor, slow drift in the calculated channel, correlation between the mooring loads and model motions/accelerations, correlation between model motions and accelerations, trend with previous experiments etc. Suggestions are made to repeat the experiment or check for sensors if the analyst is not comfortable with the processed data.

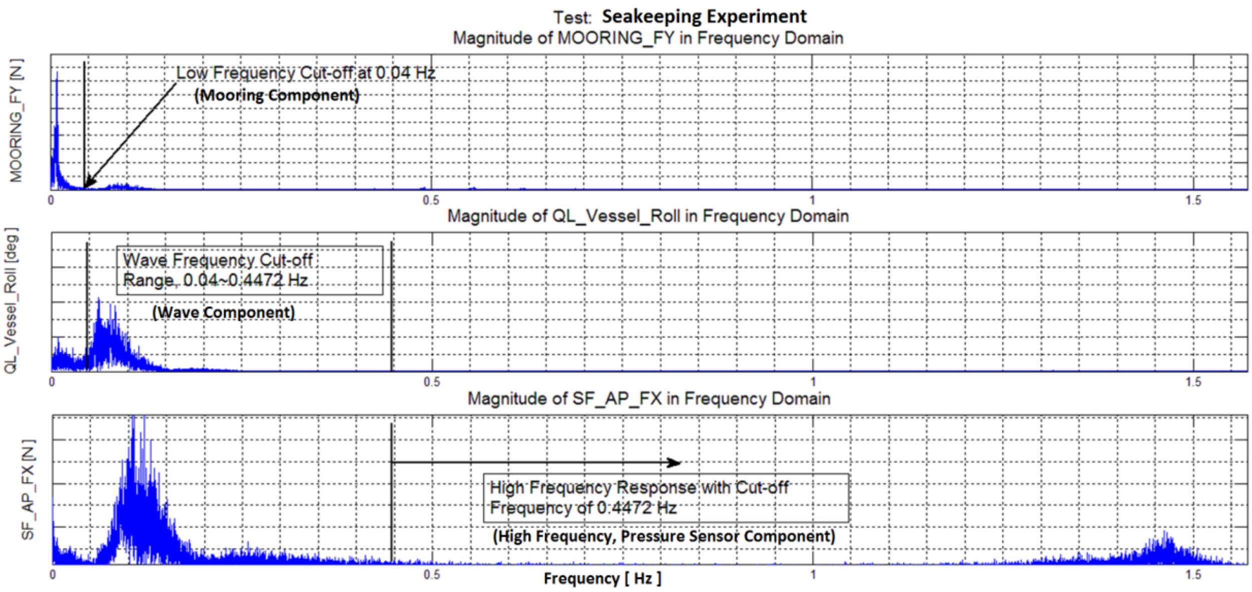

Figure 3: Selection of Wave Filtering Frequencies.

3.10 Test segment selection

Typically, there is a period of time during the start of each wave experiment where the waves are in a transient state prior to reaching a fully developed steady state condition. The transient segment of each time history is disregarded in the wave analysis process to eliminate the non-steady-state data. Generally for the wave experiments, the analyzed test segment can vary between one and twelve hours full scale. Of note, typically the first 20 seconds in model scale of each wave experiment is recorded as a calm water segment (to be used as a tare segment for certain data channel if necessary). Figure 5 shows the time segments in a typical wave experiment.

3.11 Basic statistics

Basic statistics of each data channel are computed for the tare and test segments of each experiment. Maximum, minimum, mean, and standard deviation values for each signal are generally reported. The calculated basic statistics for both segments and for each of the channels are added to the data structure for further usage. Sometimes extended statistics for each channel and for each segment are calculated if requested (see Table 4). This data is also accumulated in a CSV file for further usage.

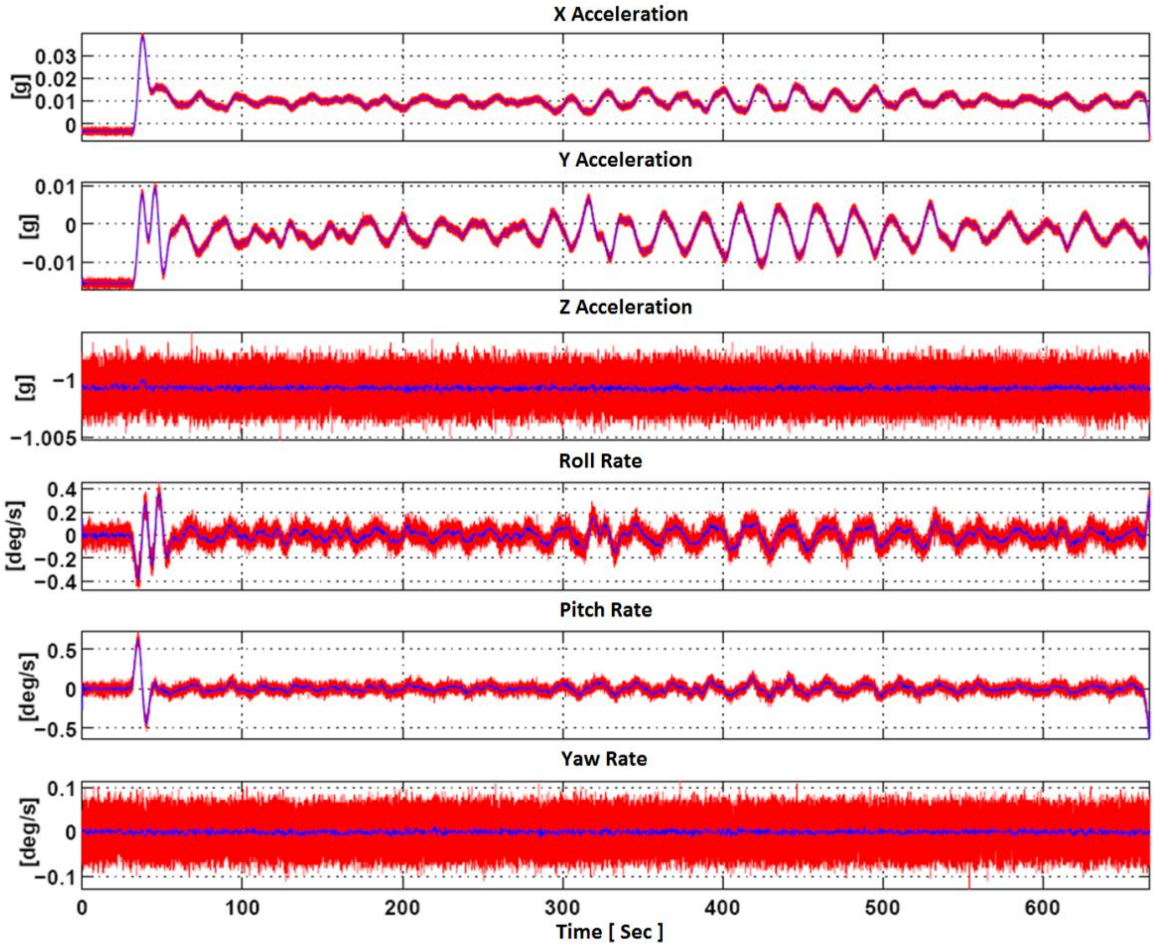

Figure 4: Data Time Trace before and after Filtering (Red-Before Filtering; Blue-After Filtering)

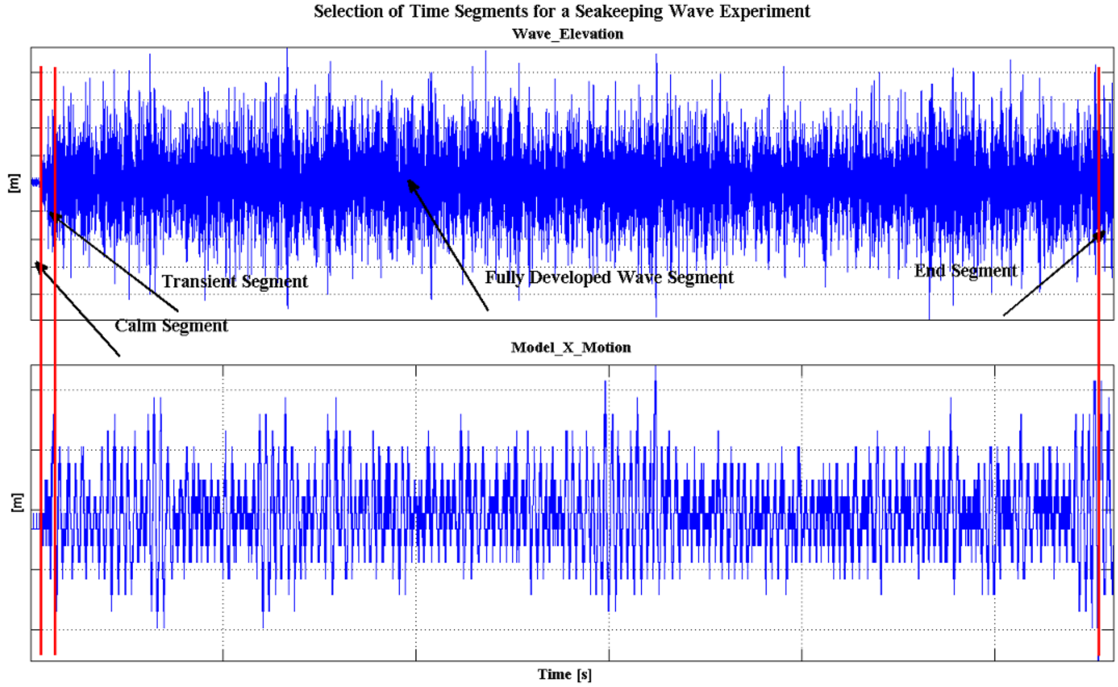

Figure 5: Time Segment Selection in Wave Experiments

Table 4: Definition of all Statistical Element

Item	Definition
Mean	Arithmetic average of a signal.
Min	Minimum value of a signal.
Max	Maximum value of a signal.
Abs max	Maximum of the absolute value of the min and absolute value of the max.
Range	Difference between the maximum and minimum value of a signal.
Variance	A measure of spread describing how far numbers lie from the mean.
Standard deviation	Similar to variance in that it describes the variability of a signal
Skewness	A measure of the asymmetry in a probability distribution.
Kurtosis	A measure of the shape or "peakedness" of a probability distribution.

Variance: A measure of "spread" describing the variability of a signal or how far numbers lie from the mean, see Equation (6).

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(X_i - \overline{X})^2 \tag{6}$$

Standard Deviation: Square root of variance. A high standard deviation indicates numbers are spread out over a large range of values while a low standard deviation shows that numbers lie close to the mean, see Equation (7). Unlike variance, the units for standard deviation are the same as that of the data.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - \overline{X})^2} \tag{7}$$

Skewness: The degree of asymmetry, or departure from symmetry, of a distribution, Equation (8).

$$a_3 = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(X_i - \overline{X}\right)^3}{\left(\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X_i - \overline{X}\right)^2}\right)^3} = \frac{m_3}{\sigma^3} \tag{8}$$

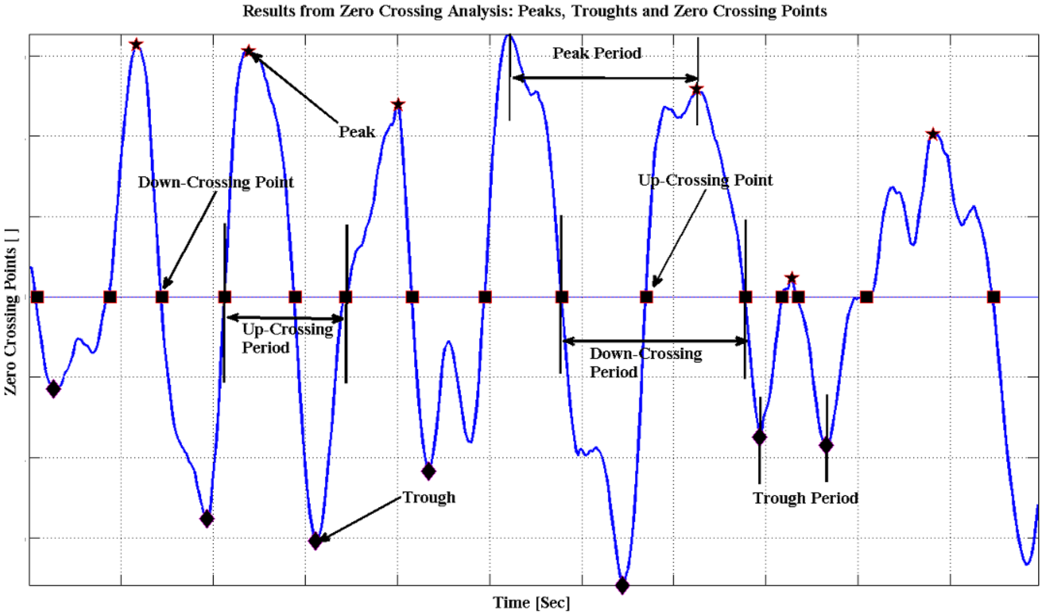

Figure 6: Elements of a Crossing Analysis

Kurtosis: The degree of peakedness of a distribution, usually taken relative to a normal distribution, Equation (9).

$$a_4 = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(X_i - \overline{X}\right)^4}{\left(\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X_i - \overline{X}\right)^2}\right)^4} = \frac{m_4}{\sigma^4} \tag{9}$$

3.12 Wave statistics using crossing analysis

Cyclic signals are analyzed to determine wave statistics. Signal heights, troughs, and crests are evaluated for absolute maximum/minimum, 1/3, 1/10, and 1/100 values. The wave statistics are calculated about a specified reference value (normally taken as the signal mean or zero) for each cyclic signal resulting in the calculation of both static and dynamic values. One-sided signals such as fender loads, deflections, and slamming are also evaluated for wave statistics. Crossing analysis is performed on each of the data channels to calculate each of the peaks, troughs, and crossing items (Figure 6). A list of wave statistics is provided in Table 5. The wave statistics for each of the applicable data channels are added back to the data structure for the final data product.

Table 5: Definition of items in wave statistical analysis

Wave Statistic Item	Description
Peak_avg	Average of all data peaks
Peak_rms	Root mean square of data peaks
Peak_half	Average of 1/2 of the highest data peaks
Peak_sig	Average of 1/3 of the highest data peaks
Peak_ten	Average of 1/10 of the highest data peaks
Peak_100	Average of 1/100 of the highest data peaks
Trough _avg	Average of all trough heights
Trough _rms	Root mean square of all data troughs
Trough _half	Average of 1/2 of the lowest data troughs
Trough _sig	Average of 1/3 of the lowest data troughs
Trough _ten	Average of 1/10 of the lowest data troughs
Trough _100	Average of 1/100 of the lowest data troughs
Height _avg	Average of all data ranges
Height _rms	Root mean square of all data ranges (peak-trough pairings)
Height _half	Average of 1/2 of the highest data ranges (peak-trough pairings)
Height _sig	Average of 1/3 of the highest data ranges (peak-trough pairings)
Height _ten	Average of 1/10 of the highest data ranges (peak-trough pairings)
Height _100	Average of 1/100 of the highest data ranges (peak-trough pairings)
Dpeak _avg	Two times the average data peaks
Dpeak _rms	Two time the root mean square of data peaks
Dpeak _half	Two times the average of 1/2 of the highest data peaks
Dpeak _sig	Two times the average of 1/3 of the highest data peaks
Dpeak _ten	Two times the average of 1/10 of the highest data peaks
Dpeak _100	Two times the average of 1/100 of the highest data peaks
Dtrough _avg	Two times the average of all data troughs
Dtrough _rms	Two times the root mean square of data troughs
Dtrough _half	Two times the average of 1/2 of the lowest data troughs
Dtrough _sig	Two times the average of 1/3 of the lowest data troughs
Dtrough _ten	Two times the average of 1/10 of the lowest data troughs
Dtrough _100	Two times the average of 1/100 of the lowest data troughs

3.13 Maximum estimate analysis

Results of the zero-crossing analysis are also used to estimate most-probable extreme values. The estimated three-hour most-probable extreme values, in full scale, are obtained by the principle of fitting a three-parameter Weibull law to the peak, maximum, or minimum values of each cyclic time history. The highest 1/3 recorded maximums (troughs, peaks, ranges) are usually used to generate the predicted extreme values. Each maximum was sorted into 30 categories (bins) to create a histogram and a Weibull distribution compared to the histogram. If the data did not satisfactorily allow for Weibull analysis it was not included. Weibull plots are included in the data package.

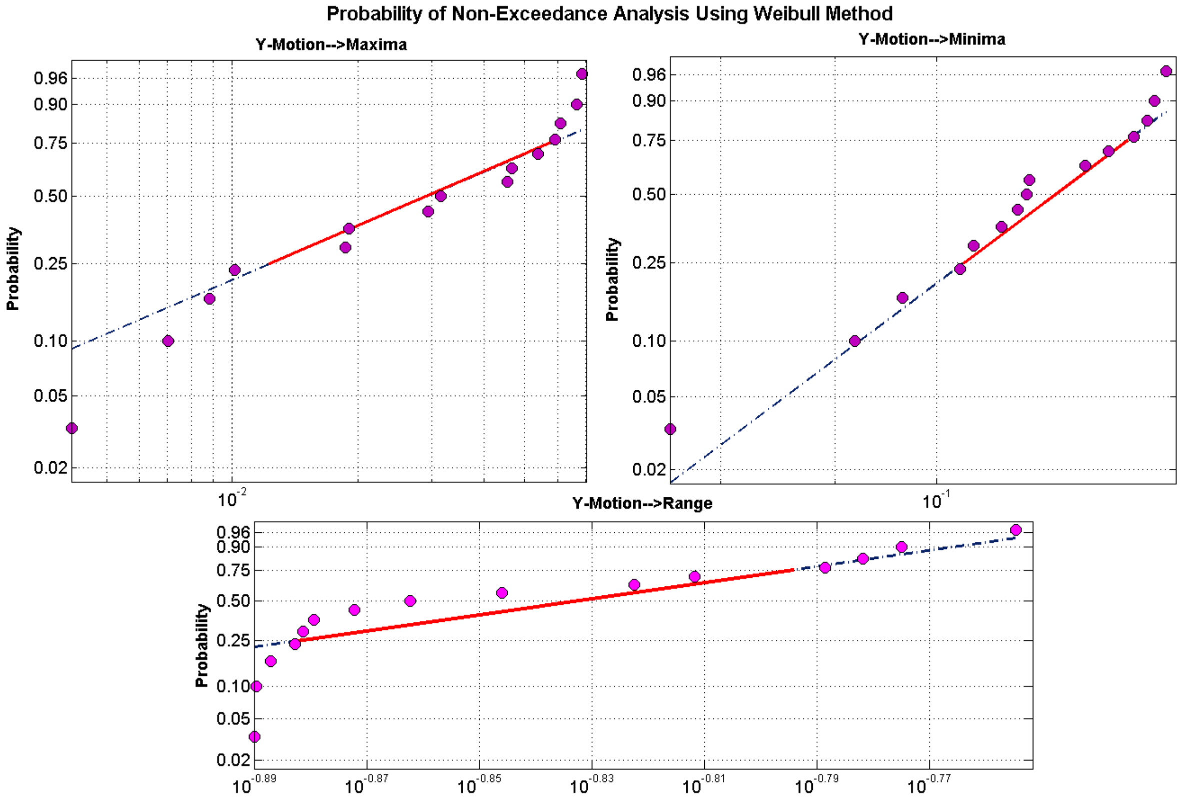

Figure 7: Results of a Weibull Analysis Showing Probability of Non-Exceedance

3.14 Response amplitude operator (RAO) analysis

A Response Amplitude Operator (RAO) analysis is done on select channels using the calibrated wave (from the environment matching) as the reference. The time adjusted data is used for the RAO analysis. The analysis is calculated on a point by point basis using the time history of the selected channel and the time history of the acquired wave. The power spectral analysis is done using the time adjusted calibration wave elevation as base and the concerned data signal as response. The Welch's averaged; modified periodogram method is used to estimate the auto power spectral density of the wave and the response and cross power spectral density between the input and the response. The signals are divided into (number of data points)/25 windows with 50% overlap, each section is windowed with a Hamming window and eight modified periodograms are computed and averaged. Equation (10) presents the expression used in the RAO analysis. Figure 8 shows a sample plot of the output from the RAO analysis of a typical response in a wave experiment.

$$R = \sqrt{\frac{S_{YY}}{S_{XX}}};\ C = \frac{S_{XY} \times \mathrm{conj}(S)}{S \times S_{YY}};\ \theta = \tan^{-1}\left(\frac{Q_{XY}}{K_{XY}}\right) \qquad (10)$$

Where,
R is the RAO of a response
C is the coherency between the response and the excitation
θ is the phase angle between the response and the excitation

S_{XX} is the auto-spectral energy of the wave elevation (input)
S_{YY} is the auto-spectral energy of the response (output)
S_{XY} is the cross-spectral energy of the wave elevation and the response
Q_{XY} is the imaginary component of complex signal P_{XY}
K_{XY} is the real component of complex signal P_{XY}

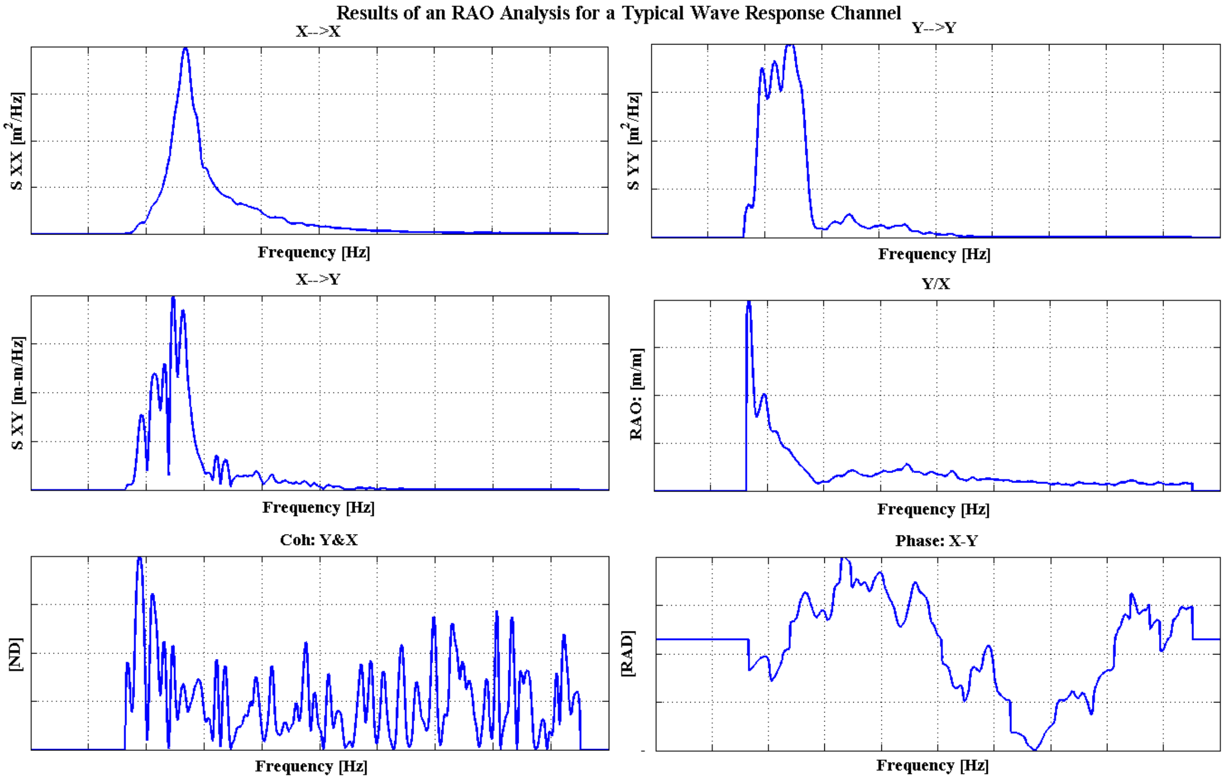

Figure 8: Sample Plot for RAO Analysis

To arrive at the auto spectrum plot, the spectrum energy less than 1% and greater than 99% of total wave energy (area under the curve) are set to zero. The corresponding frequency values are noted and used to zero the values in the other five plots. It must be noted though that the phase relationship does not always tend to zero above the 99% energy cutoff frequency but rather continues at the last computed value. The analyzed values are also added back to the main data structure for each of the concerned data channels.
At this stage, a thorough review of the data product is done to ensure the best possible quality of the data product. It is often recommended to carry out at least one repeat of the experiment for each major setup change. The repeatability should be checked prior to delivering the data to the client.

4. Decay/damping Analysis

A seakeeping experiment usually involves decay experiments in various degrees of freedom, e.g. roll decay, sway decay etc. An excitation is given to the model from its initial position at a certain degree of freedom and the motion is then allowed to damp out. The relevant data channel then processed using the decay/damping analysis.
The damping or decay analysis includes the determination of damping ratio, the equivalent linear and non-linear damping terms and the decay periods. In viscous linear damping, force is assumed to be proportional to velocity. The log decrement, δ, is defined as the natural logarithm of the ratio of any two successive amplitudes and can be expressed as in Equation (11):

$$\delta = \frac{2\pi\zeta}{\sqrt{(1-\zeta^2)}} = \ln\left(\frac{x_j}{x_{j+1}}\right) \tag{11}$$

Where:
ζ = damping ratio;

x = amplitudes;
j = amplitude index.
The damping ratio is defined as in Equation (12):

$$\zeta = \sqrt{\left(\frac{\delta^2}{4\pi^2 + \delta^2}\right)} \tag{12}$$

When z is small, $\sqrt{(1-\zeta^2)} \approx 1$, which,

$$\xrightarrow{\text{yields}} \zeta = \frac{\delta}{2\pi} \tag{13}$$

The linear damping envelope curve is defined as $x_1 e^{-\zeta\omega_n t}$. The equivalent damping is found by equating the energy dissipated by the viscous damping to that of the non-viscous damping force. The equivalent damping is expressed as in Equation (14):

$$c_{eqv} = \frac{8a\omega_n x}{3\pi} \tag{14}$$

From Equation 13 and Equation 14, the log decrement for linear damping can be determined to be as in Equation (15):

$$\delta = \frac{8a}{3m} x \tag{15}$$

In non-linear damping, log decrement is modeled as in Equation (16):

$$\delta = 2\pi\zeta + \frac{8a}{3m} x \tag{16}$$

Using Equation 13 and Equation 16, damping as a function of Equivalent Linear Damping and Equivalent Non-linear damping can be written as Equation (17).

$$\zeta = \frac{c}{2m\omega_n} + \frac{8a}{6m\pi} x = B1 + B2x \tag{17}$$

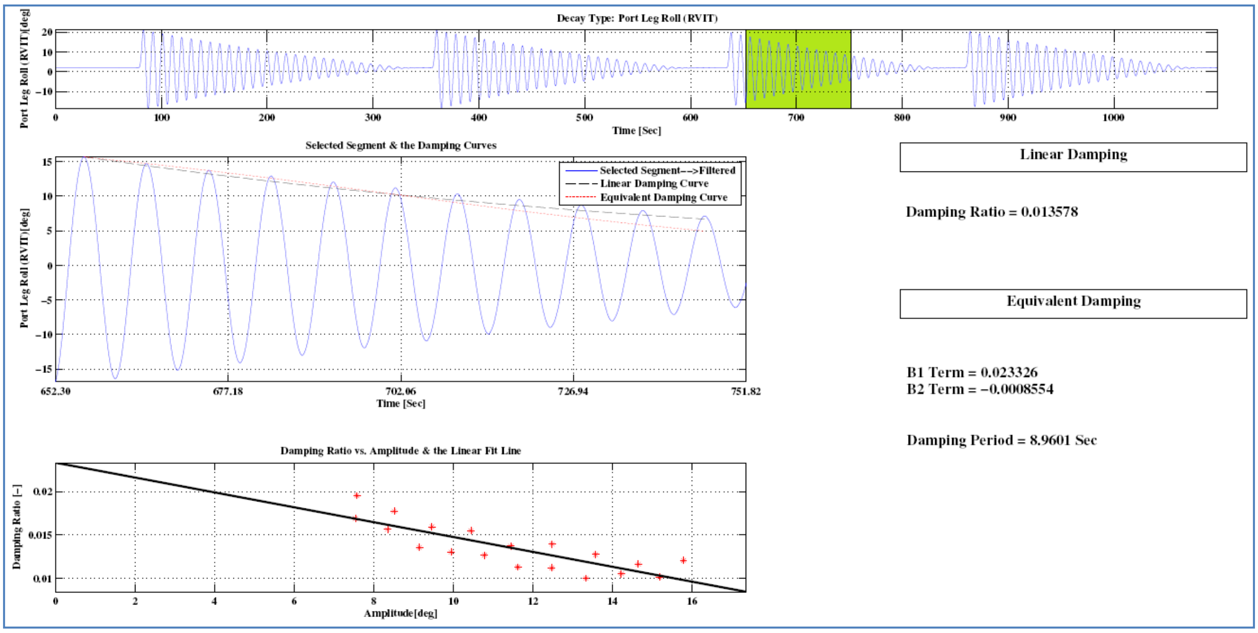

Figure 9: Details of Decay Analysis Output

5. Special Analysis: Mooring Analysis

Often in seakeeping experiments, models are moored using various number and types of mooring lines. Analysis is required to calculated drift forces and moments due to these mooring line forces. The forces (F_X, F_Y, and F_Z,) and moments (M_X, M_Y, and M_Z) are calculated using the following steps:

a. Motions at the fairlead positions in the global coordinates are calculated using the method described in Section 3.8.
b. The relative positions of the fairleads with respect to the anchors in the global coordinates are calculated; also the distance between the fairlead and the corresponding anchor is calculated using Equation (18).

$$dx_i = X_{A(i)} - X_{FL(i)};\ dy_i = Y_{A(i)} - Y_{FL(i)};\ dz_i = Z_{A(i)} - z_{FL(i)};\ l_i = \sqrt{dx_i^2 + dy_i^2 + dz_i^2} \qquad (18)$$

c. The mooring force components in the three coordinate directions are calculated by resolving each mooring line force for the respective directional cosine using Equation (19).
d.

$$tx_i = T_i \times \left(\frac{dx_i}{l_i}\right);\ ty_i = T_i \times \left(\frac{dy_i}{l_i}\right);\ tz_i = T_i \times \left(\frac{dz_i}{l_i}\right) \qquad (19)$$

e. The global forces and moments are calculated using Equation (20).

$$F_X = \sum_{i=1}^{LN} tx_i;\ F_Y = \sum_{i=1}^{LN} ty_i;\ F_Z = \sum_{i=1}^{LN} tz_i$$

$$M_X = \sum_{i=1}^{LN}\left(tz_i \times Y_{FL(i)} - ty_i \times Z_{FL(i)}\right);\quad M_Y = \sum_{i=1}^{LN}\left(tz_i \times X_{FL(i)} - tx_i \times Z_{FL(i)}\right);\quad M_Z = \sum_{i=1}^{LN}\left(ty_i \times X_{FL(i)} - tx_i \times Y_{FL(i)}\right) \qquad (20)$$

In the above equations,

I	index for mooring lines (for four point mooring system i = 1..4)
LN	number of mooring lines (for four point mooring system n = 4)
XFL(i), YFL(i), ZFL(i)	fairlead positions in global coordinates
XA(i), YA(i), ZA(i)	anchor positions in global coordinates
dxi, dyi, dzi	x, y, and z relative positions of fairlead with respect to anchor in global coordinates
li	distance of fairlead from anchor in global coordinates
Ti	Mooring line force in the ith line
txi, tyi, tzi	line forces in ith line in three coordinate directions
F_X, F_Y, F_Z	Total forces in the X, Y, and Z directions
M_X, M_Y, M_Z	Moments about the Z, Y, and Z axes

6. Uncertainty Analysis

Regarding quality control of experimental data, ITTC has recommended that the reporting of experimental data should include a proper uncertainty analysis (ITTC 2002). A detailed uncertainty analysis is carried out for each of the measured and analyzed data set, which is not discussed any further in the paper.

7. Concluding Remarks

The methodologies developed in order to acquire and analyze high quality data from hydrodynamic seakeeping experiments of physical models in waves are presented. A flowchart showing the steps and sequence followed in the analysis is provided.
Deliverables of such experiments are listed before getting into details of each of the major steps in the analysis process. Additionally, analysis methodologies for special measurements such as soft mooring experiments and decays are described. Examples of all such analyses are provided where appropriate. The entire procedure can be used by any user for data quality check and to analyze the data acquired in any experiment that involves single or multiple bodies in waves.
The authors present methods for the analysis and quality control of model tests seakeeping data. The topic is important from the engineering point of view and the material presented gives useful guidelines. Regarding

quality control of experimental data, ITTC recommends that the reporting of experimental data should include a proper uncertainty analysis. This aspect is not discussed in the manuscript.

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