Model Test for Quantitative Analysis of Ship Dynamics in Waves

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Abstract

Arrangement of model test together with numerical evaluation method will be described for quantitative analysis of ship dynamics in waves. The special with this test arrangement is that the incident wave motion around the model can be expressed in term of wave equation. Examples for three cases are demonstrated. One shows the validation of the determined wave equation. The second demonstrates the usefulness of this kind model test for validation of time-domain computer code and the last one gives the measured wave-induced surge and sway force and yaw moment on a fast vessel in quartering waves from a series of semi-captive model test, which are important for analysis of broaching-to problem.

1. Introduction

Model test is still an important tool for analysis of ship dynamics in waves due to the complex hydrodynamics associated with the ship motion, despite the progress in the mathematical and numerical modelling and computer simulation technique. With the increased requirement of safety at sea, great attentions are now focused on the nonlinear motions and capsizing scenario. Thus, advanced model tests are required in order to analyse these problems. In addition, numerical modelling and computer simulation are necessary for the probabilistic assessment, which needs also advanced model test for validations.

Generally, Ship responses in waves are the consequences of the encountered wave history under the previous time. It requires usually a wave group to cause a severe event such as large roll magnitude or broaching-to scenario etc. Detail wave information is then crucial to make proper analysis of ship dynamics in waves from model tests, particularly concerning danger situation.

Wave motions are usually measured under a seakeeping model test at some positions in the wave basin or following the model motion, which provides the wave condition in term of wave height and period for the present test, but not sufficiently for quantitative analysis in time domain, i.e. response history vs. wave history encountered by the model. In order to do this kind of analysis, it requires a wave equation to describe the wave motion around the model. In Garme 1997 and Garme and Hua 1999, a model test arrangement and a numerical method are described enabling to determine the parameter of such wave equation. Recently, a series of semi-captive model test are conducted with the same arrangement principle, see Hua 2002.

This paper will provide a summary of these works and three test cases are given. One shows the validation of the determined wave equation with respect to regular, irregular and crossing wave. The second demonstrates the usefulness of this kind model test for validation of time-domain computer code, and the last one shows the measured wave-induced surge and sway force and yaw moment on a fast vessel in quartering waves from a series of semi-captive model test.

Finally, applications of this kind model test are given.

2. Test arrangement and data process

In addition to the recommended ITTC procedure for seakeeping experiment 7.5-02-07-02.1, the wave height meter should follow the model motion as close as possible while avoiding so much as possible the distortion from the waves generated by the model motions.

Required measure data:

1) Time series of the wave motions and the corresponding coordinate of the used wave height meters
2) Time series of the model motions in all the six degrees of freedom, including the coordinate of the model in space.

3) Time series of the measures of particular interesting for validation such as forces, acceleration at some positions etc.
4) Time series of rudder angle and propeller rate under free running test

Wave equation determination:

The wave motion around the model is determined by means of the measured wave data. The numerical procedure is described as following. Assume a wave equation for a regular wave in the wave basin can be expressed as the following

$$\eta(x,t) = a \cdot \cos(k \cdot x - \omega \cdot t) + b \cdot \sin(k \cdot x - \omega \cdot t) \tag{1}$$

The wave height meter is fixed at the model carriage and follows the model movement with the longitudinal coordinate $x^n(t^n)$ in the space. A time interval is selected for the wave motion with N measured data and the wave equation (1) should satisfies the measured wave data at the different time and space as close as possible, which means

$$\begin{bmatrix} \cos(k \cdot x^1 - \omega \cdot t^1) & \sin(k \cdot x^1 - \omega \cdot t^1) \\ \cos(k \cdot x^2 - \omega \cdot t^2) & \sin(k \cdot x^2 - \omega \cdot t^2) \\ . & . \\ . & . \\ . & . \\ \cos(k \cdot x^N - \omega \cdot t^N) & \sin(k \cdot x^N - \omega \cdot t^N) \end{bmatrix} \cdot \begin{Bmatrix} a \\ b \end{Bmatrix} = \begin{Bmatrix} \eta(x^1, t^1) \\ \eta(x^2, t^2) \\ . \\ . \\ . \\ \eta(x^N, t^N) \end{Bmatrix} \tag{2}$$

Let

$$[M] = \begin{bmatrix} \cos(k \cdot x^1 - \omega \cdot t^1) & \sin(k \cdot x^1 - \omega \cdot t^1) \\ \cos(k \cdot x^2 - \omega \cdot t^2) & \sin(k \cdot x^2 - \omega \cdot t^2) \\ . & . \\ . & . \\ . & . \\ \cos(k \cdot x^N - \omega \cdot t^N) & \sin(k \cdot x^N - \omega \cdot t^N) \end{bmatrix} \tag{3}$$

so,

$$[M] \cdot \begin{Bmatrix} a \\ b \end{Bmatrix} = \begin{Bmatrix} \eta(x^1, t^1) \\ \eta(x^2, t^2) \\ . \\ . \\ . \\ \eta(x^N, t^N) \end{Bmatrix} \tag{4}$$

and

$$\begin{Bmatrix} a \\ b \end{Bmatrix} = \left([M]^T \cdot [M]\right)^{-1} \cdot [M]^T \cdot \begin{Bmatrix} \eta(x^1, t^1) \\ \eta(x^2, t^2) \\ . \\ . \\ . \\ \eta(x^N, t^N) \end{Bmatrix} \tag{5}$$

The coefficients a and b in the wave equation are, as seen in the above determined by means of the Least Square Method.

The wave equation can then be used to calculate, for example the wave motion at the ship mass center and other wave kinematics data around the model.

This method is also applicable for irregular wave consisting more than one regular wave component by setting the wave equation

$$\eta(x,t) = \sum_{i=1}^{N} a_i \cdot \cos(k_i \cdot x - \omega_i \cdot t) + b_i \cdot \cdot \sin(k_i \cdot x - \omega_i \cdot t) \tag{5}$$

The coefficients a_i and b_i in the above equation can then be determined as previously described.

3. Three test cases

Case 1: Wave motion analysis

The waves in the wave basin were measured by means of two wave height meters, both following the model at a distance where slight influence from model-created waves was expected; see Fig.1. The tests were performed in regular, irregular, and crossing waves. Crossing refers to two wave systems propagating towards each other, intersecting at right angles. Each irregular wave was represented by three regular wave components. The three-component wave is justified by its simplicity.

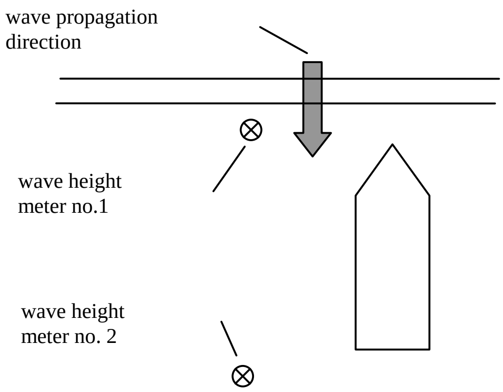

Fig.1 Principal position of the two wave height meters.

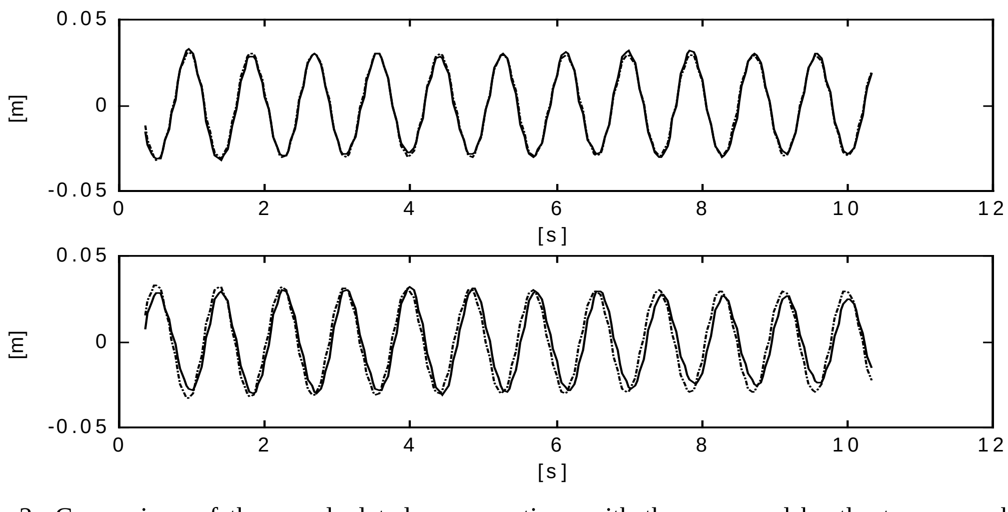

Fig. 2 Comparison of the re-calculated wave motions with the measured by the two wave height meters in a regular wave, upper and down graphs for wave height meter No.1 and no.2 respectively. The dashed line is re-calculated.

Wave equations were determined with data from the wave height meter No.1. The equations could accurately re-calculate not only the measured signal they were based upon, but also, generally, the measurements from the other wave height meter, see Fig. 2, 3 and 4.

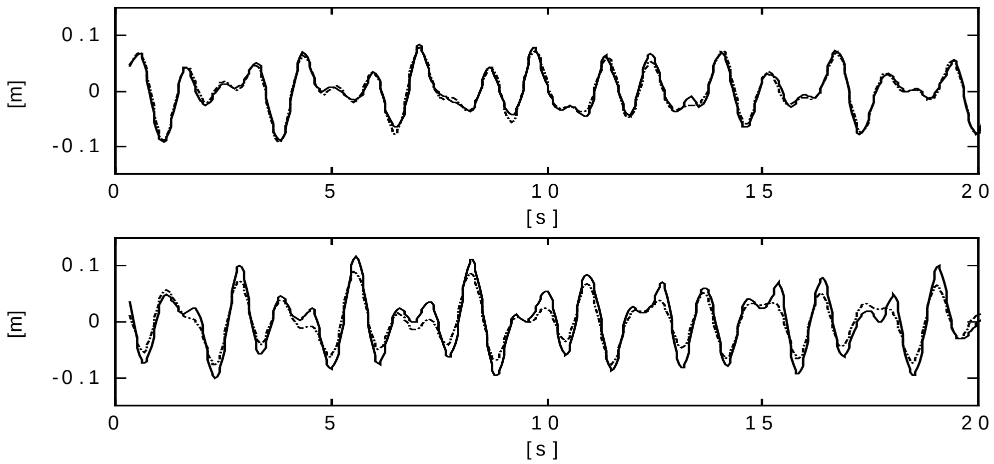

Fig. 3 Comparison of the re-calculated wave motions with the measured by the two wave height meters in a long-crested three-component wave systems, upper and down graphs for wave height meter No.1 and no.2 respectively. The dashed line is re-calculated.

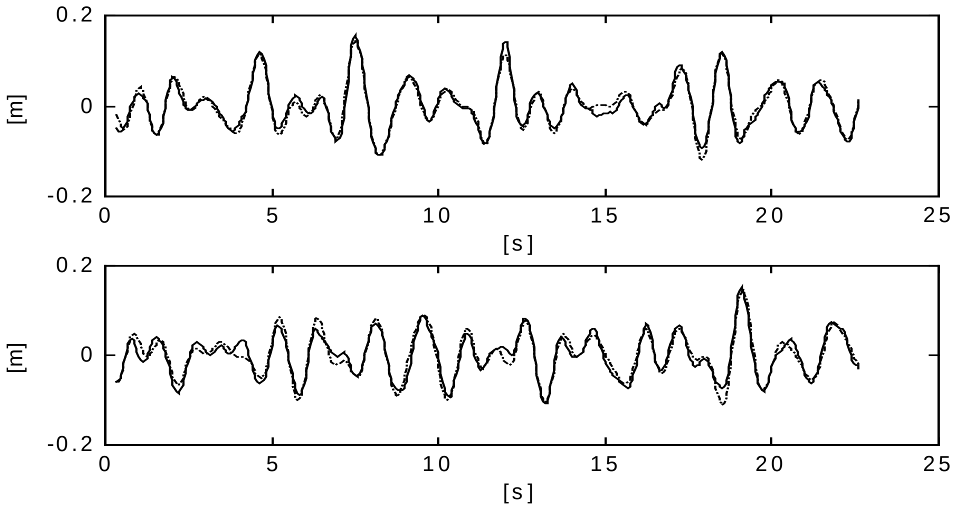

Fig. 4 Comparison of the re-calculated wave motions with the measured by the two wave height meters in a crossing waves consisting of two irregular three-component wave systems, upper and down graphs for wave height meter No.1 and no.2 respectively. The dashed line is re-calculated.

Case 2: Free running test

To demonstrate the usefulness of the determined wave equation, a motion simulation code (Hua & Palmquist, 1995), is used for time-domain simulation of the ship motions in heading waves, with the wave equations and the initial motion conditions from the model measurement (Garme, 1997).

First, the heave and pitch motion of the ro-ro ship in a heading regular wave is simulated with the wave equation from the model measurement. The wave amplitude is about 2.89 m and wave frequency 0.558 rad/s (Test No. 32 in Garme (1997)). The ship speed is 8.51 knots.

Fig.5 shows the simulated and model-measured heave and pitch motions as functions of time. Generally, the simulated amplitudes of the heave and pitch motion are lower than the measured. The phase relationships of the simulated motions are in good agreement with the model measurement. It should be pointed out that the model measurement was carried out with a self-propelled model while the computer simulation corresponds to a towed model. Nevertheless, the comparison provides good insight into the reliability of the mathematical model, and the possibilities of modifying it.

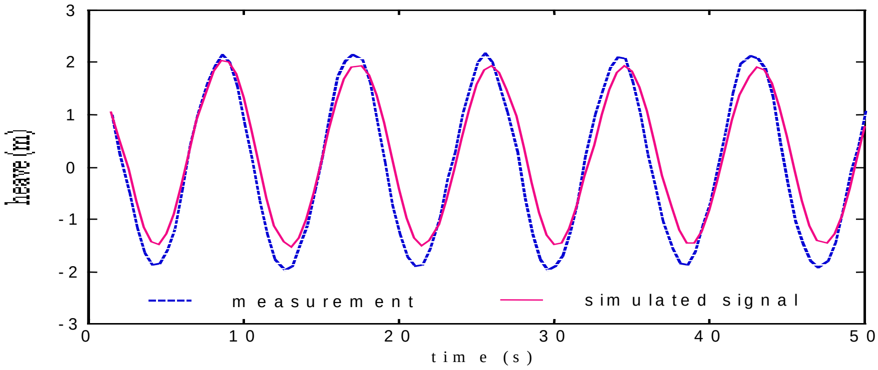

Fig.5a Time history of heave motion in regular waves and the corresponding computer simulated signal.

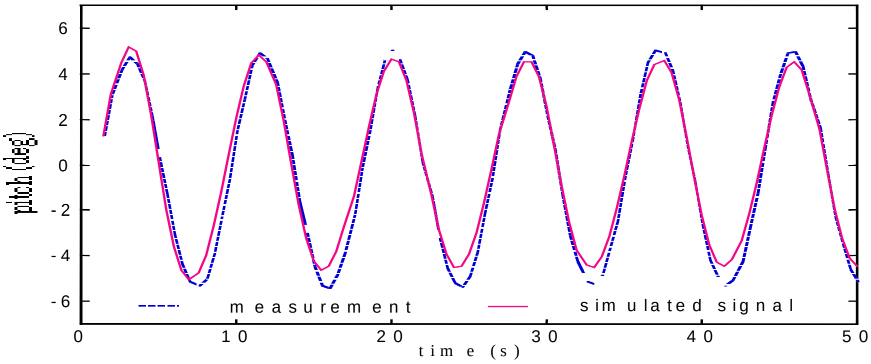

Fig.5b Time history of pitch motion in regular waves and the corresponding computer simulated signal.

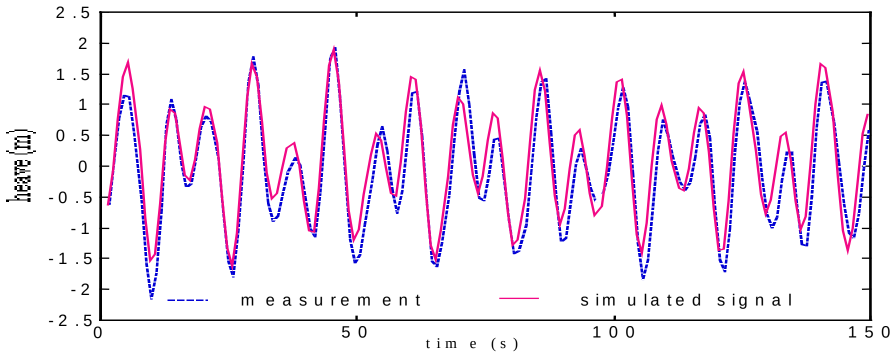

Fig. 6a Time history of heave motion in irregular waves and the corresponding computer simulated signal.

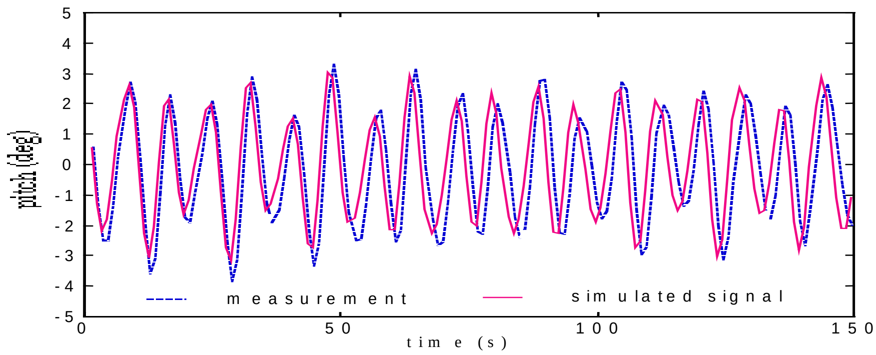

Fig. 6b Time history of pitch motion in an irregular wave and the corresponding computer simulated signal.

An irregular wave is represented by three regular waves in the model measurement. The primary purpose is to validate the superposition theory for the wave motion, which is the basis of the linear seakeeping theory. Fig. 6 shows the simulated time history of heave and pitch motions in such an irregular heading wave in comparison with the model measured. The ship speed is 14.84 knots in full-scale (Test No. 66 in Garme (1997)).

Case 3: Semi-captive model test

Usually, validation of a numerical model takes place by comparing the simulated ship motions with the model measured. But sometimes it is necessary to validate the important force terms in the motion equations when a studied problem has the characteristics of a complex dynamic system. A typical example is ship motions in quartering waves and the associated broaching problem.

Semi-captive model test means combined force and motion measurement. The model allows free motions in some degrees of freedom and has to be restrained at the rest of degrees for the force measurement. The advantage is that the measured result becomes more relevant for the physical condition as required for study.

In the following, result from a model test of a patrol ship running in a regular quartering wave is presented. The wave incident angle is 30 degrees and the wavelength twice the ship length. The model speed in Froude number is 0.5.

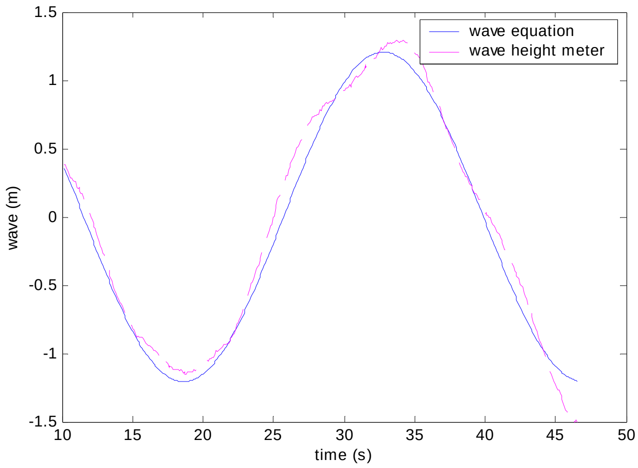

Figure 7 Wave motion given by the wave equation in comparison with the measured by the wave height meter.

Figure 7 shows the wave motion at the location of the wave height meter. The wave motion reconstructed from the wave equation fits the original measured signal quite well. The extracted first order heave and pitch motion are very near the measured ones and follow the wave and wave slope motion respectively as shown in Figure 8 by comparing with the wave motion amidships. Thereby, the transfer functions of heave and pitch respectively at this wave condition can be easily determined for both amplitude and phase lag by comparing with the wave motion amidships.

Figure 9 shows the wave-induced surge and sway force and yaw moment respectively in the three sub-figures. The difference between the extracted first order surge force and the measured is almost constant, which is actually quite near the value of the resistance in calm water. The sway force and yaw moment are dominated by their first order components respectively.

In Hua 2002, the measured result is used for validation of theoretical calculation. At SSAP, semi-empirical expressions are also derived for calculation of the wave-induced surge and sway forces and yaw moment, which are used for assessment of the course-keeping ability of fast ships in following waves and for development of operation criteria, see Hua 2004.

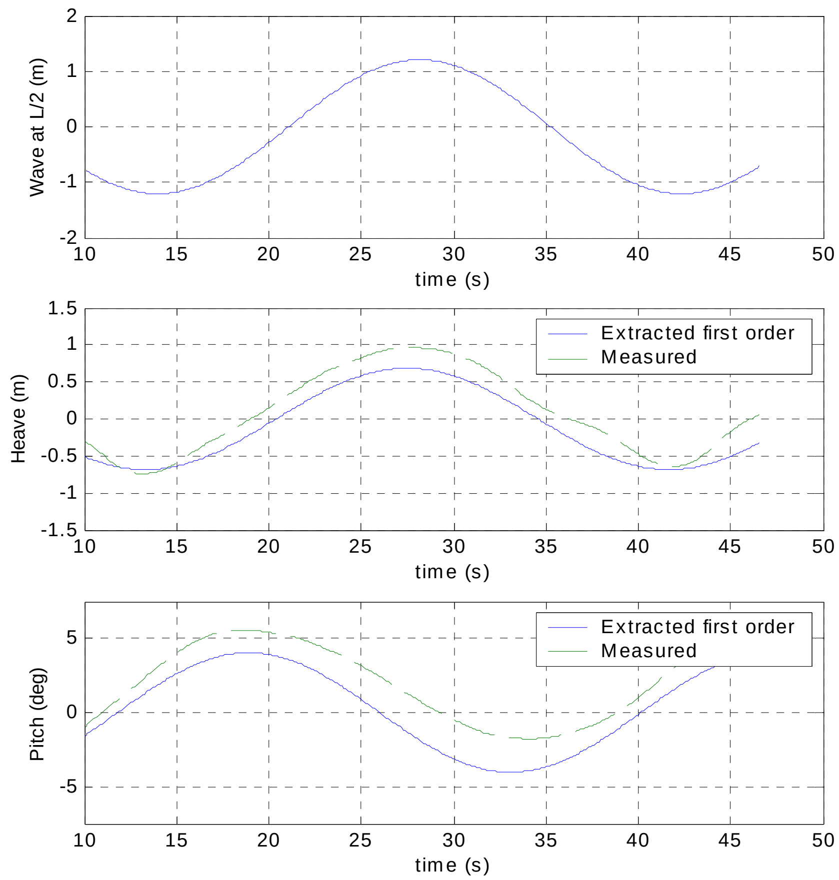

Figure 8 Wave motion at amidships and heave and pitch motion in a quartering wave

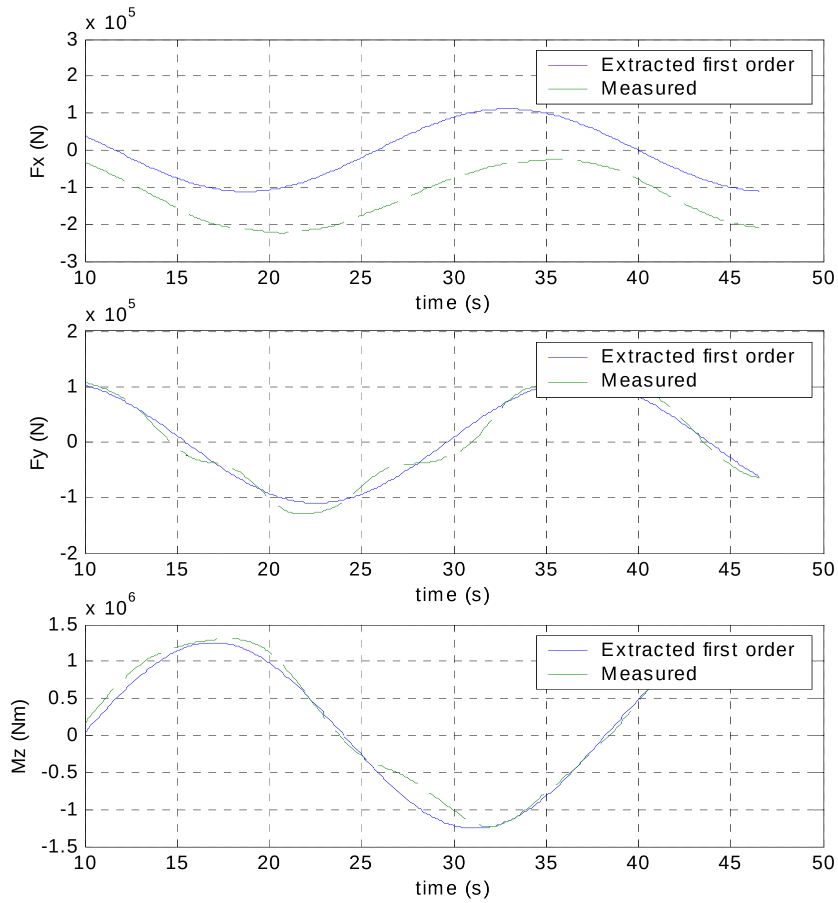

Figure 9 Wave-induced surge, sway force and yaw moment in a quartering wave.

4. Conclusion

The previously case examples have demonstrated that the presented test arrangement and evaluation method are proper for quantitative analysis of seakeeping problems and for validation of numerical models such as the following

- Stability loss in following waves
- Parametrically excited roll motion in following waves
- Water ingress in waves due to hull damage
- Slamming pressure and loads on high speed vessels in bow and heading waves
- Efficiency reduction of a propeller due to the wave and wave-induced ship motions
- Effect of wave and wave-induced ship motions on the rudder force

References

Garme, K. 1997. "Model Seakeeping Experiments Presented in the Time-Domain to Facilitate Validation of Computational Tools," *TRITA-FKT Report 9727, ISSN 1103-470X*, Division of Naval Architecture, Royal Institute of Technology (KTH), Stockholm

Garme, K. and Hua, J, 1999. "A Method to Analyse Seakeeping Model Measurement in Time-Domain." *ISOPE'99*, Brest, France

Hua, J, and Palmquist, M 1995. "A Description of SMS –A Computer Code for Ship Motion Simulation." *TRITA-FKT Report 9502, ISSN 1103-470X*, Division of Naval Architecture, Royal Institute of Technology (KTH), Stockholm

Hua,J, 2002. "Semi-Captive Seakeeping Model Measurement for Validation of Theoretical Calculation." *SSPA Research Report No 121*, 2002, Sweden

Hua, J., 2004. "Assessment of the Course-Keepping Ability of a Fast Ship in Following Waves." Submitted *to Journal of Ship Mechanics* for publication