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by

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A BOUSSINESQ-TYPE WAVE MODEL COUPLED TO A DIFFRACTION MODEL TO SIMULATE WAVE-INDUCED SHIP MOTION

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ABSTRACT

Aim of the research is to develop and validate a numerical method for determining the wave forces on a ship as induced by a non-uniform wave field such as can be found in a harbour basin. This is important for the prediction of the downtime, i.e. the time that loading and unloading of a ship is not possible due to large ship motions. In this paper, one such modeling system and its validation are described. It concerns the coupling of the 2DH (2D horizontal) time domain nonlinear Boussinesq-type wave model TRITON, developed by WL | Delft Hydraulics, with the multibody panel method DELMULTI, developed by the TU Delft. The latter model is a 3D model, capable of computing a ship's response to waves in frequency domain. Essential to this modeling system is that the forces are computed from the complete, undisturbed wave motion, without analysis of frequencies and / or direction. From comparing simulation results with measurements for different situations (unidirectional regular waves and various passing ship events), it can be concluded that TRITON and the coupling TRITON – DELMULTI provide accurate representations of the wave field and of the wave-induced forces and moments on a ship.

SOMMAIRE

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KEYWORDS: Ship motion, wave model, diffraction model, nonlinear wave effects.

1. INTRODUCTION

Ships moored in ports are affected by waves. These waves can be wind generated (sea or swell waves) or induced by passing ships. In this paper, we present a model chain that aims at computing a wave field, the wave-induced forces on a ship and its resulting motion. The complete model chain consists of four steps:

1. wave generation is computed,
2. wave propagation from the source to the moored ship is computed,
3. the wave-induced forces exciting the moored ship are computed,
4. the resulting ship's motions are computed.

This model chain allows for the computation of the motions of a ship moored in an arbitrarily shaped harbour basin. In the present work, we restrict ourselves primarily to items 2 and 3.

Essential to the model chain introduced in the present work is that the forces are computed from the complete, undisturbed wave motion, without analysis of frequencies and / or direction.

In Chapter 2, a description of each of the four steps in the model chain is given. Chapter 3 addresses the most innovative part of the present work, namely the coupling between the wave model and the diffraction model that computes the wave-induced forces. Validation for a regular unidirectional wave in open water forms the topic of Chapter 4. Another, more complex validation case is discussed in Chapter 5. This concerns computation of the forces on a ship due to a passing ship event. Summary, conclusions and recommendations are given in Chapter 6.

2. OVERVIEW OF THE MODEL CHAIN

As stated in the introduction, the model chain consists of four steps. Each of them is briefly described.

2.1. Wave generation

The first model in the model chain concerns wave generation. If one is interested in the influence of wind waves, a description of the wave field at the seaward boundary of the computational model is required. If one is interested in the influence of ship-induced waves, the velocity of the passing ship and its hull shape are important factors in determining the resulting wave pattern. An example of a model that is able to simulate the wave pattern around a moving ship is RAPID, see Raven (1996). In the passing ship validation case discussed in Chapter 5, yet another method is used.

2.2. Wave propagation

The second model in the chain is a wave model to simulate wave propagation and penetration in a harbour. The wave conditions obtained in step (1) serve as input for the wave propagation computations. In the present study, wave propagation from the source where waves are generated to the moored ship is computed using the Boussinesq-type wave model TRITON (Borsboom (2000)). This model is under development at WL | Delft Hydraulics. TRITON is a 2DH (2D horizontal) time-domain model that solves for the orbital velocities (depth-integrated), surface elevation and non-hydrostatic pressure (depth-averaged). The model accounts for the effects of wave dispersion, shoaling, diffraction, refraction as well as nonlinear wave-wave interactions. The latter is important, because transfer of wave energy to lower frequencies is accounted for: ships are particularly sensitive to waves with wave lengths comparable to the length of the ship, and these waves fall in the category low-frequency waves. Therefore it is important to get good estimates of these low-frequency waves.

The wave field in a harbour is usually very complex due to the complex geometry. The complex water motion in a harbour interacts with moored vessels and thus causes complex moored vessel motions and mooring loads. TRITON can be set up for complex harbour geometries, including the modelling of (partial) reflections at quay walls and the resulting standing wave patterns. However, the validation cases described in the present paper are restricted to open water situations.

2.3. Wave-induced forces

In the present model chain, the third model is DELMULTI. This is a validated frequency-domain 3D multi-body linear diffraction model. It predicts the wave-induced forces. It is possible to include the surrounding geometry (e.g., quay walls) in DELMULTI. Some references to this model are Pinkster (1980), Pinkster (2004) and Van Oortmerssen (1976).

The wave forces on the moored ship can be classified into first-order, second-order and higher-order contributions. In the present work, all first-order and nearly all second-order contributions are taken into account. As is well-known, the first-order contributions are the Froude-Krilov force and the diffraction force. The only second-order contribution that is neglected, is the wave-wave interaction between the incident waves and the waves diffracted and radiated by the moored ship. This contribution is usually negligibly small. We note that the second-order contribution stemming from nonlinear wave effects is automatically taken care of. This is an automatic consequence of TRITON being a nonlinear wave model.

2.4. Resulting ship's motions

The resulting ship motions follow from integration of the equation of motion taking into account the ship's geometry. For a free ship, DELMULTI can do this job. If fenders and mooring lines are present, their characteristic must be included. This can be done by means of a program like BAS, see Mynett et al. (1985).

3. COUPLING BETWEEN TRITON AND DELMULTI

The innovative part of the present work consists of the coupling between TRITON and DELMULTI. This is discussed in this section. We repeat that the major advantage of the present approach lies in the fact that the forces are computed from the complete, undisturbed wave motion, without analysis of frequencies and / or direction. This will be made clear.

For ease of presentation, we restrict ourselves to the open water situation, i.e. the only geometry present in DELMULTI is the ship. The shape of the ship's hull is described as a 3D panel model consisting of O(1000) flat quadrilaterals (panels). On each panel, time series of the velocities and pressures are established by TRITON. Furthermore, TRITON evaluates time series of the surface elevation at the still water line. This requires two things:

1. The exact location of the panel centers in the TRITON model.
2. 3D information about the pressure and the velocity.

Realization of the first item requires knowledge of the location and orientation of the ship in the TRITON model domain. Note that the ship itself is not present in the wave field computation, i.e. the wave field does not 'feel' the presence of the ship. In other words, the wave field is undisturbed.

Realization of the second item requires a step from 2DH (TRITON) to 3D (DELMULTI). This is necessary, since the pressure and velocity vary in the vertical. From a reverse transformation of the TRITON model equations, expressions are derived to obtain the vertical variation of the orbital velocities and the pressure from the available surface elevations and depth-integrated orbital velocities. Evaluation of these expressions is cheap, and is done as part of the time-stepping procedure in TRITON. The resulting time series of the velocities and pressure at all panels are, together with the surface elevation at the still waterline, written to file.

After having finished the TRITON computation, the aforementioned data file is used as input for the diffraction model. DELMULTI transforms the time series of the velocity and pressure to frequency domain by means of an FFT. The frequency components (both amplitude and phase are important) replace the classical long-crested regular wave velocities and pressures that serve as input to the conventional frequency domain panel models. For each frequency component, the diffraction problem for the 3D ship is solved, as first done by Van Oortmerssen (1976). In frequency domain, the hydrodynamic forces are obtained in the standard way. By means of an inverse FFT, time series of the forces are obtained. Note that the latter step requires phase information obtained in the FFT procedure; this poses no problem.

The second-order wave forces are obtained, in time domain, by evaluation of the expressions that follow from direct pressure integration. Besides the undisturbed wave field and the first-order diffraction solution just obtained, time series of the surface elevation at the waterline are required. These time series are provided by TRITON. As stated above, the incoming wave field contains nonlinear contributions, since TRITON is a nonlinear model. In other words, nonlinear wave effects are incorporated in the present approach to obtained wave-induced forces 'for free'.

Note that different approaches are possible for the coupling between a Boussinesq-type wave model like TRITON and the diffraction calculation. O'Brien et al. (2000) used a strip theory approach based on the estimated wave direction and wave number at the location of each cross-section. Bingham (2000) used a panel description of the ship and applied the Haskind relations to calculate the wave forces. A time-domain panel method, including a coupling with TRITON, is described in Van der Molen et al. (2004, 2005).

4. VALIDATION – REGULAR WAVES IN OPEN WATER

We consider a large 200 kDWT tanker, with dimensions 310 x 47.2 x 18.9 meter, as also studied by Van Oortmerssen (1976). We have chosen a unidirectional regular wave with wave period $T = 28.3$ s. The wave direction is 180^0 with respect to the x-axis in the ship coordinate system, i.e. the wave is coming head-on, see Figure 1. The wave condition corresponds to a dimensionless frequency of $\omega\sqrt{L_{ship}/g} = 1.25$, with $L_{ship} = 310$ m the length of the ship and g the gravitational constant. At this wave frequency, the surge, heave and pitch are relatively large, see Figure 3.10 of Van Oortmerssen (1976). The still water depth is equal to 22.68m. The wave amplitude is taken 0.5m, which implies that nonlinear wave effects are small. Linear theory yields a wave length of 414m.

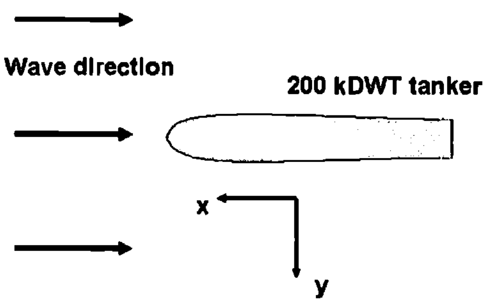


Figure 1. Situation sketch of a 200 kDWT tanker in open water.

The wave-induced forces at the tanker and the resulting motions of the tanker (no mooring lines present) are shown in Figure 2 and Figure 3. For reference, in these figures we have included time series of the surface elevation ζ of the undisturbed wave at the ship's center of gravity. The following observations can be made:

- The only relevant force and motion components are surge, heave and pitch. The other three components are virtually zero (should theoretically be exactly zero). The deviation from zero stems from fluctations in the y-velocity component. The magnitude of these fluctuations is in order of the machine precision, hence this is acceptable.
- The second-order wave forces are negligibly small compared to the first-order wave forces.
- The surge force and surge motion are about 90^0 behind respectively ahead of ζ; the heave force and heave motion are in phase with ζ, and the pitch force and motion are about 90^0 behind ζ. This all agrees with expectations.
- The magnitude of the computed forces is in close correspondence with the computations and measurements as done by Van Oortmerssen. The transfer function value of a force component for a regular wave is defined as the maximum value of the force component divided by the maximum surface elevation (wave amplitude). In
-
- Table 1, these values are given for the three components relevant for the present case. The Van Oortmerssen values are obtained from Figure 3.10 in Van Oortmerssen (1976). The values in Table 1 denoted by DELMULTI are taken from a DELMULTI output file that contains the transfer function value as computed by DELMULTI, based on the ship's geometry. The transfer function values can be obtained from Figure 2 as well. This is done by dividing the amplitude of the forces by the wave amplitude a. This yields the table values indicated by TRITON – DELMULTI.

Table 1. Transfer function values of the wave-induced forces and moments at the primary wave frequency.

	F_x / a $[10^3 \text{kN/m}]$	F_z / a $[10^3 \text{kN/m}]$	M_y / a $[10^6 \text{kN} \cdot \text{m/m}]$
Van Oortmerssen	14.3	49.1	6.86
DELMULTI	13.97	45.83	7.024
TRITON – DELMULTI	14	46	7.0

Conclusion is that, for regular unidirectional waves, the proposed model chain, including the coupling TRITON – DELMULTI, functions properly and leads to accurate results.

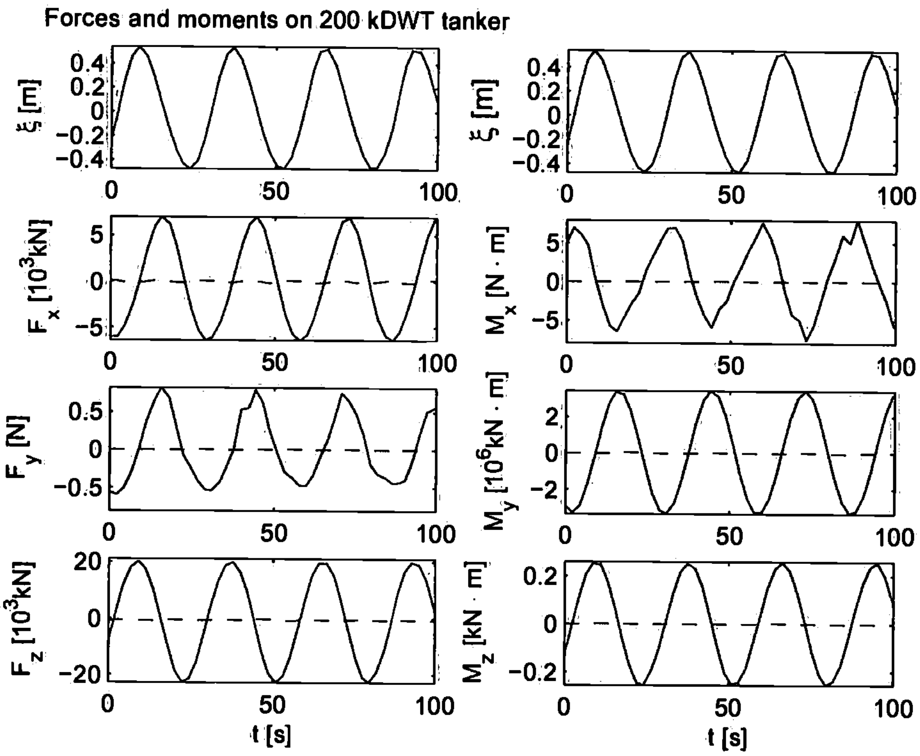


Figure 2. Wave-induced forces and moments on 200 kDWT tanker. Continuous line: sum of first- and second-order forces; dashed line: second-order forces.

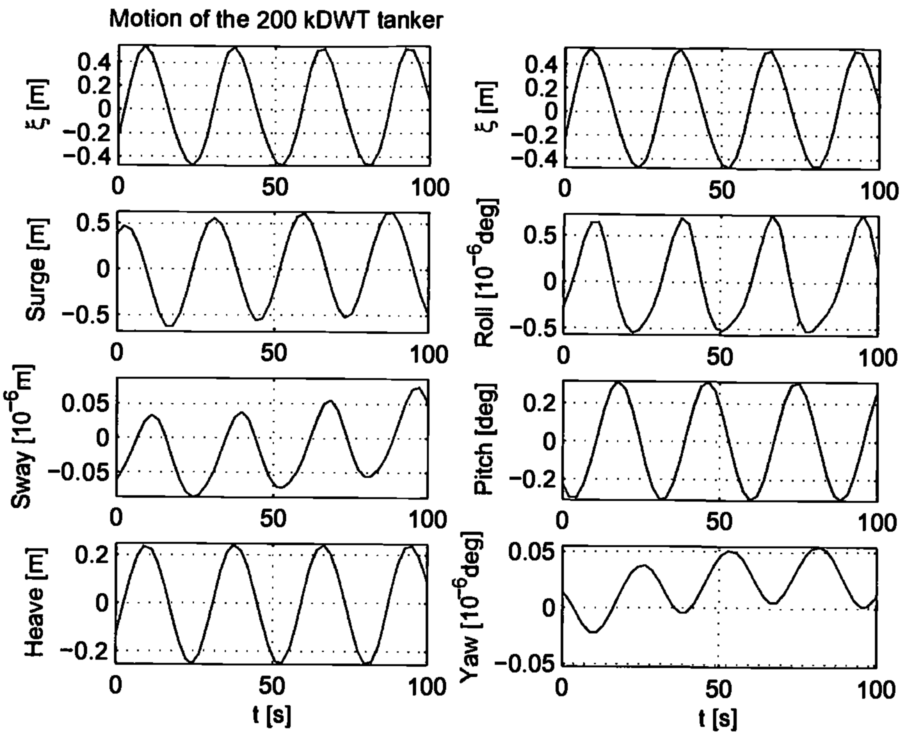


Figure 3. Wave-induced motion of 200 kDWT tanker.

5. VALIDATION – PASSING SHIP EVENTS

5.1. Introduction

In 2003, laboratory experiments have been performed in the Vinje basin at WL | Delft Hydraulics to measure wave forces on a Panamax container ship and, in separate series, wave conditions at the container ship's location. In the latter series, the ship is not present in the basin. Some of these measurements have been performed for an open water situation (i.e., there is no model of a harbour in the basin). Some of the studied wave conditions represent wave fields caused by a passing ship.

In the validation cases described in this chapter, we restrict ourselves to that type of problem. For a passing ship situation, time series are relatively short (typically a few minutes) compared to a situation in which one considers wave penetration in a harbour (typically one hour). Note that a passing ship event contains many wave periods and directions. This makes passing ship situations suitable for the development and validation of the method, since no restrictions with respect to the wave field are assumed, while the time series are relatively short.

The passing of the ship has been modeled by realizing a certain motion of the wave board paddles, see Figure 1. For this particular signal, the wave board motion is similar to that of a snake. In order to steer the TRITON model, the surface elevation must be prescribed at the incident wave boundary, i.e. at the side of the wave board. This requires a transformation from the (known) movement of each paddle to the resulting surface elevation at the paddle. This is done as follows. Let $x = x(t)$ be the movement of a wave paddle, then the prescribed surface elevation $\zeta = \zeta(t)$ at the paddle is computed using linear long wave theory: $\zeta = \sqrt{\frac{h}{g}}\frac{dx}{dt}$. Here, h is the still water depth. By applying linear long wave theory, we have neglected the presence of nonlinear and dispersive effects in the boundary condition signal.

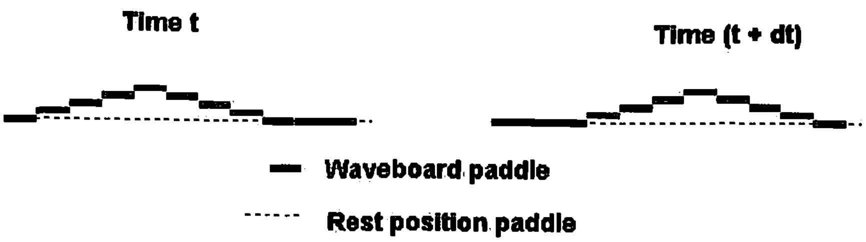


Figure 1. 'Snake principle' in wave board steering: top view.

We consider two validation test cases: a passing ship moving at a subcritical speed ($F = 0.86$) and a passing ship moving at a supercritical speed ($F = 1.5$). Here, the Froude number is defined as $F = u/\sqrt{gh}$, where u is the (uniform) velocity of the passing ship.

Concrete sidewalls left and right of the wave board are present in the laboratory experiment. These sidewalls extend up to 9.4m into the basin. These sidewalls are included in the numerical experiment.

All TRITON simulations are performed on model scale. The ratio prototype – model scale is 100. The data transferred to DELMULTI is scaled to prototype scale using Froude's scaling law.

The numerical work described in the present chapter consists of two parts:

- Validation of the wave propagation model TRITON, including modeling of the waves generated by the passing ship, see Section 5.2.
- Validation of the coupling TRITON – DELMULTI, see Section 5.3.

5.2. Validation of TRITON

Two cases are considered: a supercritical and a subcritical case.

Supercritical case

An animation of the computed wave field is available in file video1_paper094.avi. Note the influence of the sidewalls next to the wave board. The following is concluded:

- From the animation, of which some instances are displayed in Figure 2, we deduce that we can identify three time intervals, each showing a different wave pattern. In the first interval, from 10s to 22s, the ship is passing. After 22s, the passing of the ship is over. In the second interval, from 22s to about 30s, wave reflections at the sidewalls occur. The strongest component of this wave reflection hits the ship after 35s. In the third interval, starting at about 30s, a reasonably complex pattern of reflections and re-reflections is present.
- There is a good quantitative agreement between computations and experiments observed, see Figure 3.
- There is a time difference of about 0.6s between the arrival of the measured and the simulated wave train at the location of the ship. Possible causes for this difference are an incorrect value of the water depth or inaccuracies in the coordinates of the location of the ship. For the computation of the wave forces, this time difference is not relevant.
- The magnitude of the surface elevation and velocity of the critical wave is larger in the simulation than in the laboratory experiment. After the first peak, the magnitude of the quantities drops more rapidly in the simulation than in the laboratory experiment. In addition, the time interval between successive peaks in the simulated wave train is larger than in the laboratory experiment. There are various possible causes for these differences, and they are listed here. We did not study them further.
  (i) The use of linear long wave theory in the transformation from wave board signal to resulting surface elevation, may lead to deviations. A typical value for the nonlinearity (typical value for surface elevation divided by still water depth) is 0.1, which implies that nonlinearities can have a significant effect. Also, a typical value for the 'wave period' is 1s (see Figure 3), which corresponds to a measure for dispersion (kh) of about 1.0. This is far from the long wave limit ($kh = 0$).
  (ii) The neglect of currents in the TRITON simulation. The movement of the paddles, with a stroke of about 15cm in the laboratory experiment, leads to currents near the wave board, especially between the paddles. These local effects, in which vorticity is generated and in which dissipation is relatively large, are not modeled and are thus absent in the TRITON simulations.

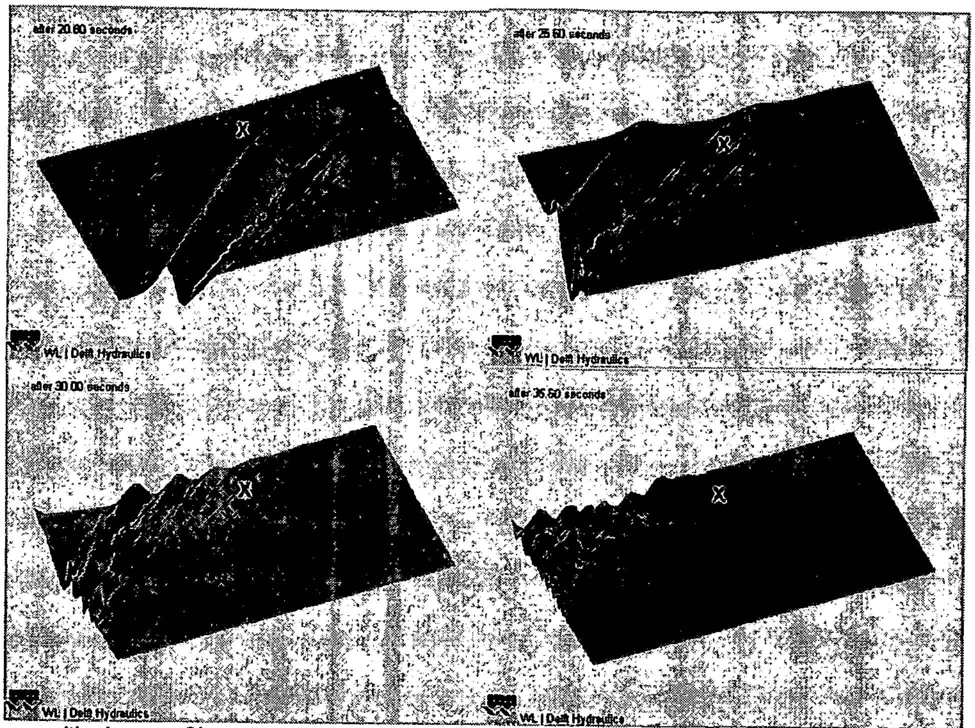
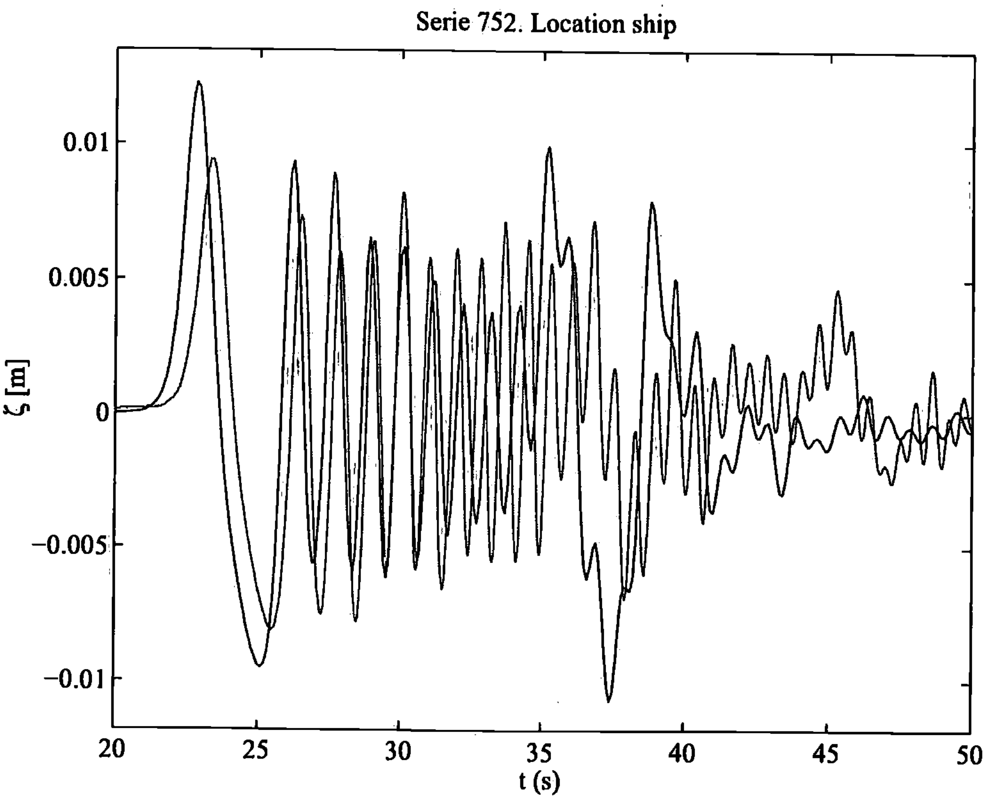


Figure 2. Supercritical case. Shown is the surface elevation at some instances. The location of the container ship is indicated by 'X'.



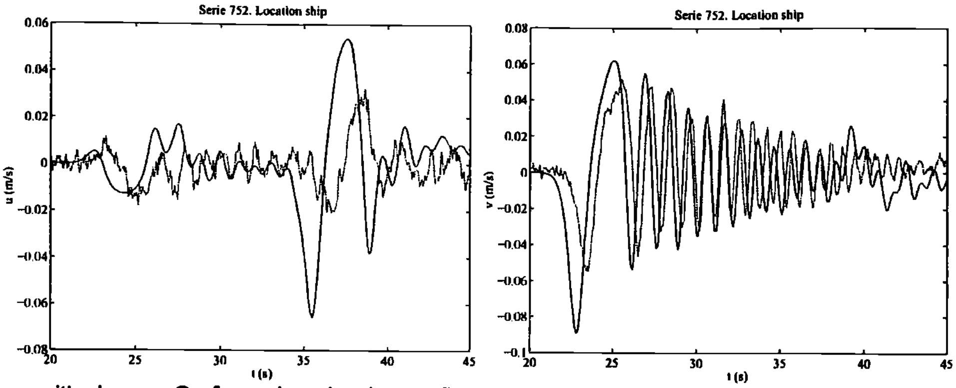


Figure 3. Supercritical case. Surface elevation (upper figure) and velocities in the ship coordinate system (lower two figures) at the center of the ship. The red line represents the measurements, and the black line the results of the TRITON computations.

Subcritical case

An animation of the computed wave field is available in file video2_paper094.avi. Some instances of the wave field are shown in Figure 4. In this case, the ship goes back and forth along the wave board. From the results (Figure 5 to 7), we deduce the following:

- As can be seen in the animation and Figures 4 and 5, the initial passage creates very small waves at the location of the ship. The largest waves are created when the ship reaches the sidewalls of the basin.
- In general, there is a good qualitative agreement between simulations and laboratory experiments. The largest deviations at the ship occur in the time windows 50s to 55s, 65s to 75s and 85s to 95s. It is observed that also the laboratory experiment is less well reproducible in these time windows.
- Because the time series show a rather complex behaviour, we have Fourier transformed the surface elevation at the location of the ship, between 20s and 100s, see Figure 7. As also observed for the supercritical case, there is more wave energy present in the simulations than in the laboratory experiments. This is probably due to the way in which the surface elevation at the wave board is prescribed.

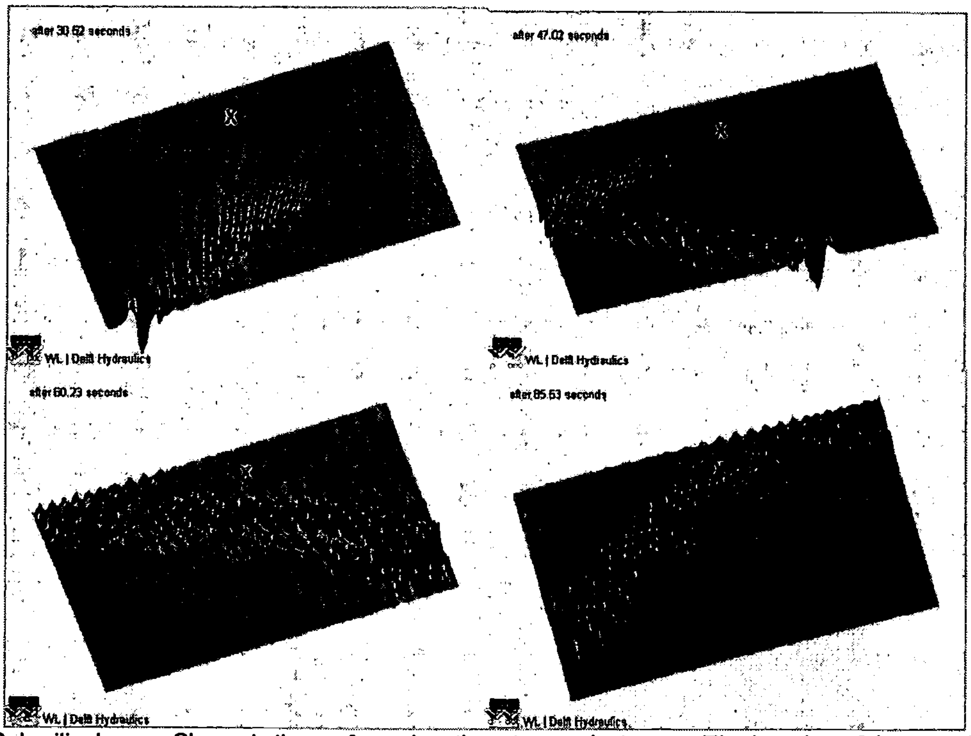


Figure 4. Subcritical case. Shown is the surface elevation at some instances. The location of the container ship is indicated by 'X'.

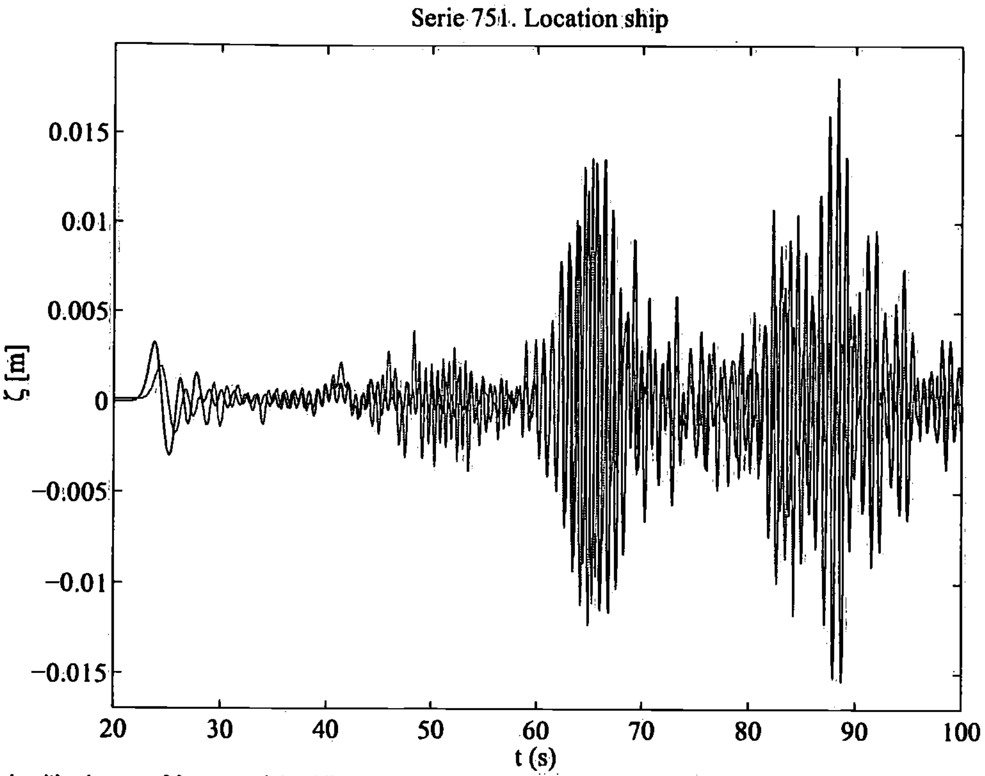
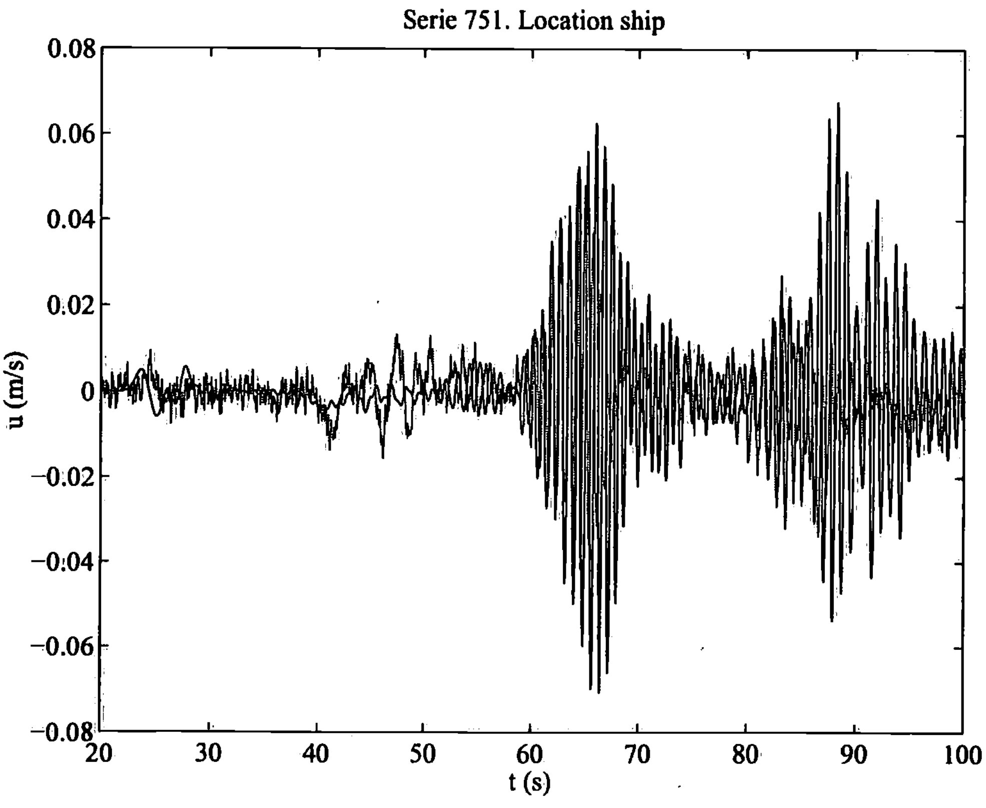


Figure 5. Subcritical case. Measured (red line) and computed (black line) surface elevation at the center of the ship.



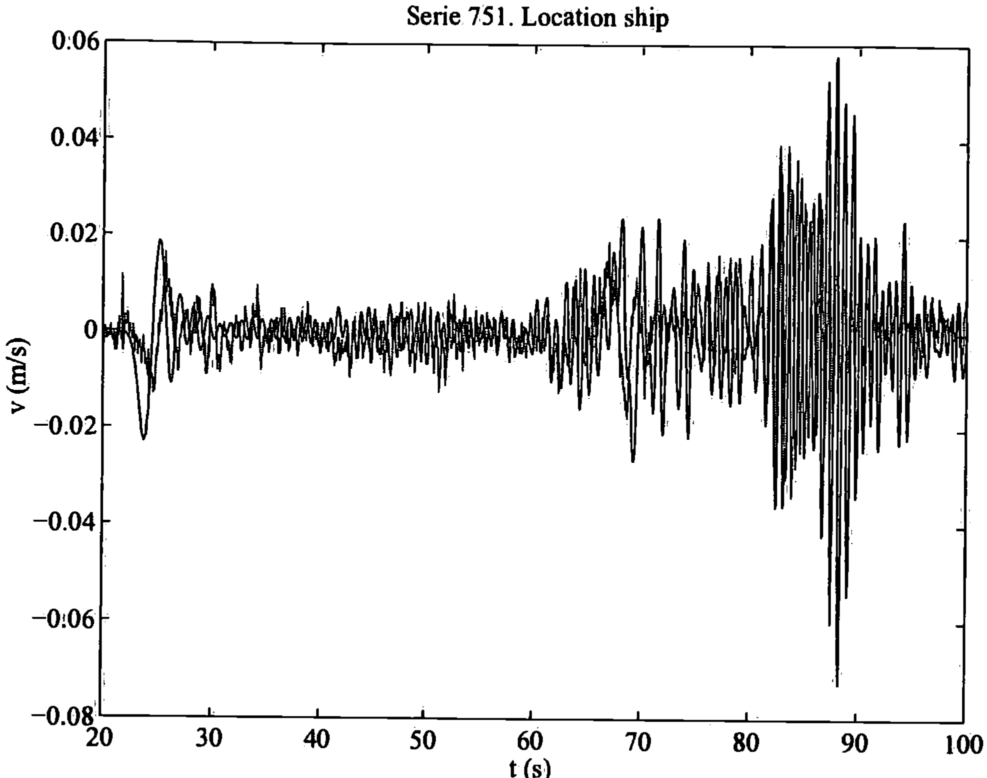


Figure 6. Subcritical case. Measured (red line) and computed (black line) velocities at the center of the ship, in the ship coordinate system.

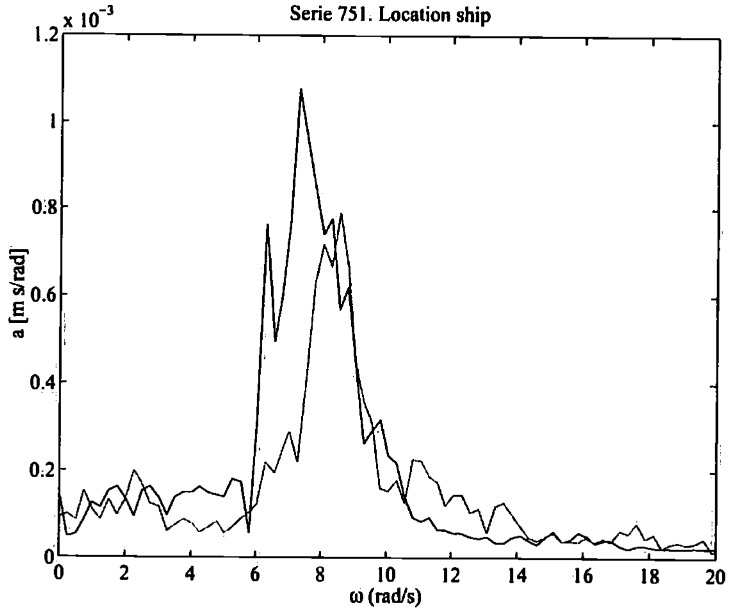


Figure 7. Subcritical case. Measured (red line) and computed (black line) wave amplitude at the center of the ship as function of the radial frequency.

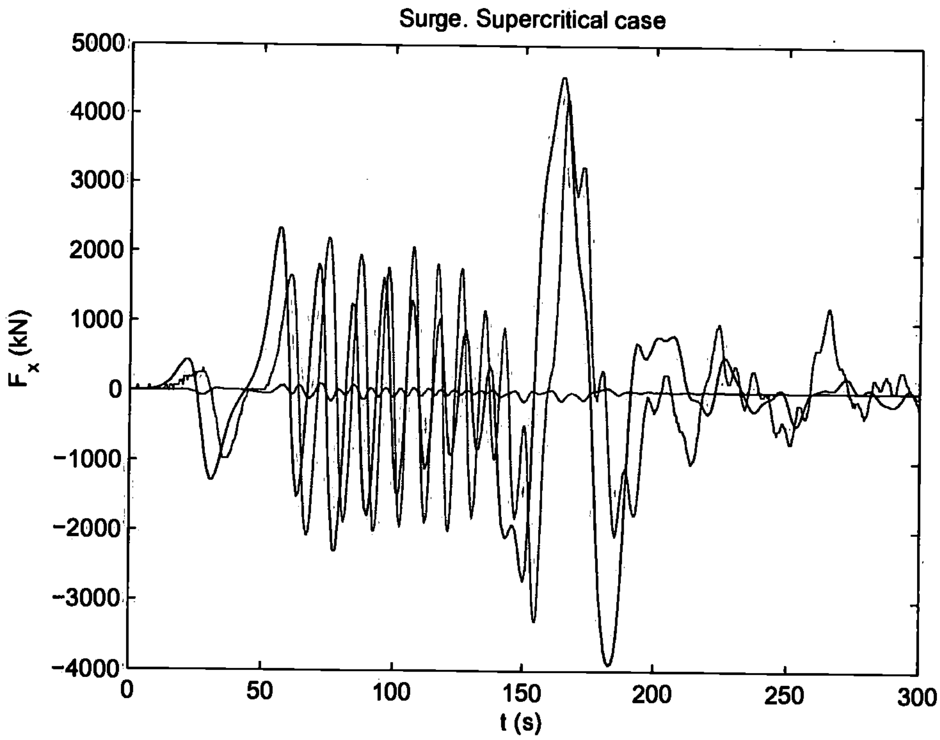
5.3. Validation of DELMULTI

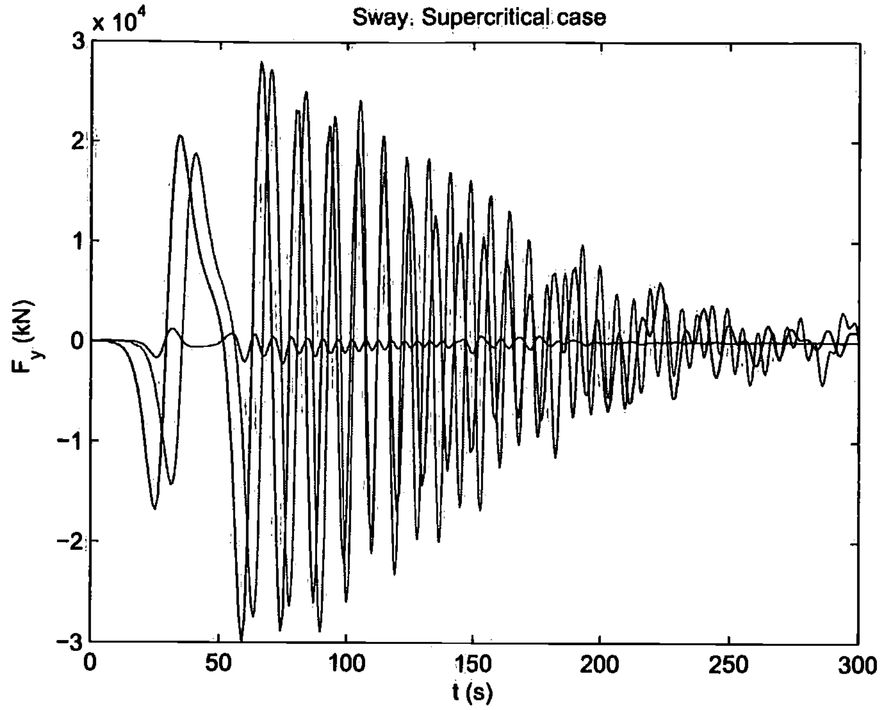
Data in the form of time series of the pressure and velocity at the ship's hull and time series of the surface elevation at the waterline are obtained from TRITON and transferred to DELMULTI. The latter package is used to compute the wave-induced forces and moments on a ship. The two cases described in the previous section are considered: a supercritical and a subcritical case.

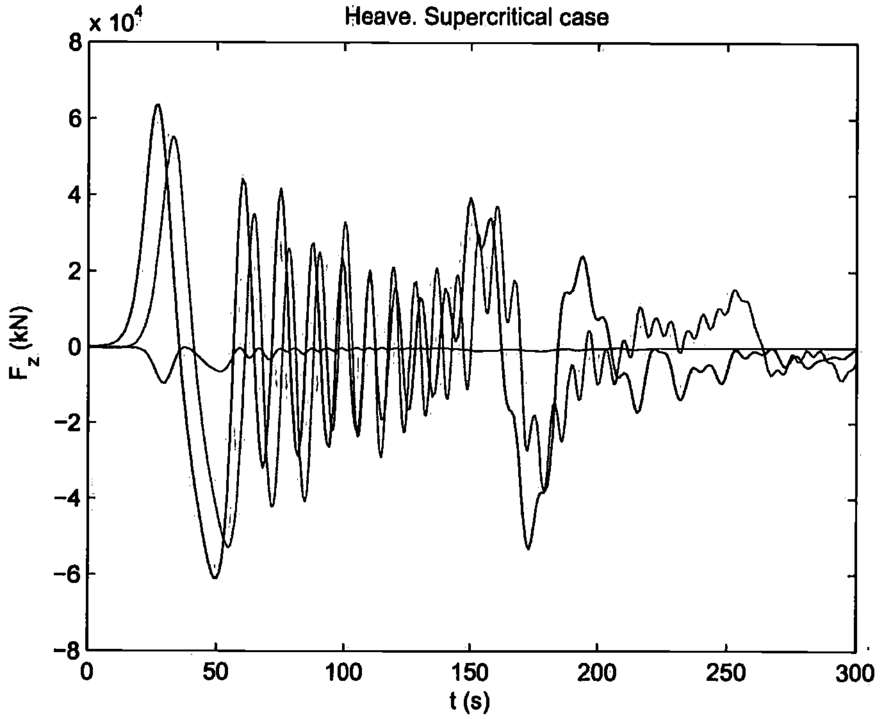
Supercritical case

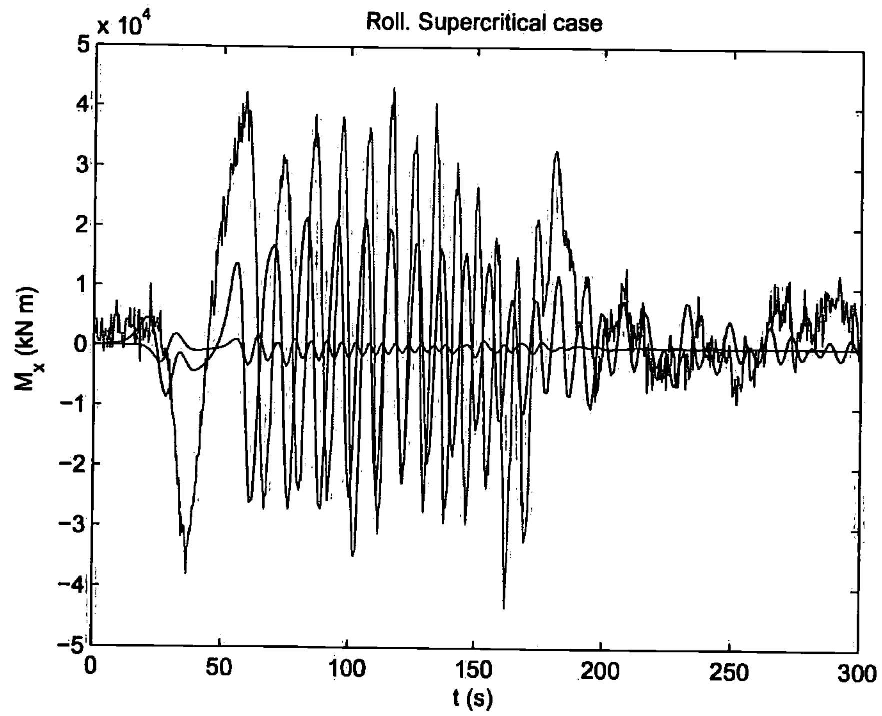
In Figure 8, the computed forces and moments (sum of first- and second-order contributions, and the second-order contributions) are compared with their measured counterparts. We note the following:

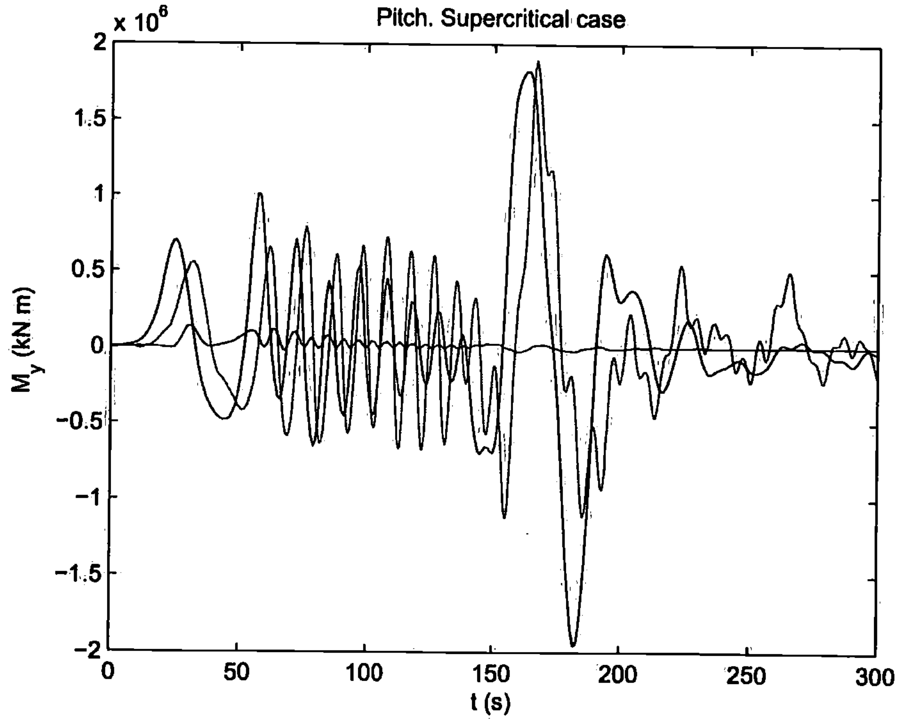
- There is a good agreement between simulations and laboratory experiments. This implies that the model chain introduced here does a good job.
- The differences between simulation and laboratory experiment show the same trends as the differences in surface elevation and velocities, see Section 5.2, the third and fourth bullet under item 'supercritical case'. This all strongly suggests that the data transfer from TRITON to DELMULTI as well as DELMULTI itself function properly: the differences between the measured and simulated forces can mainly be attributed to differences between the measured and simulated wave field.
- The magnitude of the second-order forces and moments is small (10 percent or less) compared to the first-order forces and moments.
- The results for the roll moment do not correspond very well. It is very likely that this has to do with systematic errors in the measurements. It turned out that the measurements leading to the roll consist of contributions that show a very similar trend but are of opposite sign. Hence, relatively small errors (e.g., calibration errors) in these contributions can have a large impact on the resulting results for the roll moment.




Sway. Supercritical case
x 10^4
3
2
1
0
-1
-2
-3
F_y (kN)
0
50
100
150
200
250
300
t (s)


Heave. Supercritical case
x 10^4
8
6
4
2
0
-2
-4
-6
-8
F_z (kN)
0
50
100
150
200
250
300
t (s)


x 10^4
Roll. Supercritical case
5
4
3
2
1
0
−1
−2
−3
−4
−5
M_x (kN m)
0
50
100
150
200
250
300
t (s)


x 10^6
Pitch. Supercritical case
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
M_y (kN m)
0
50
100
150
200
250
300
t (s)

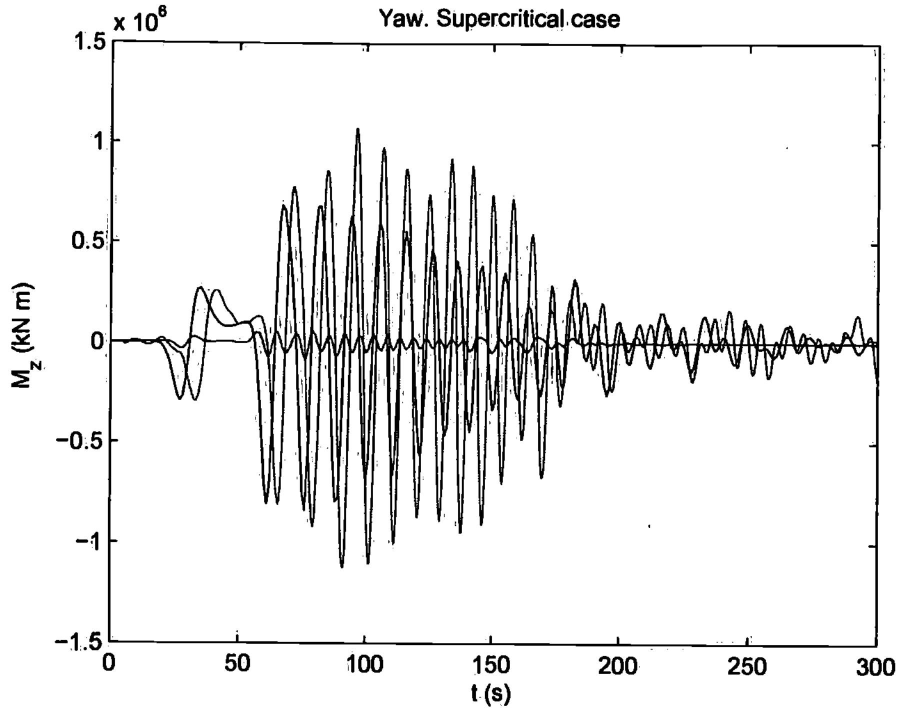
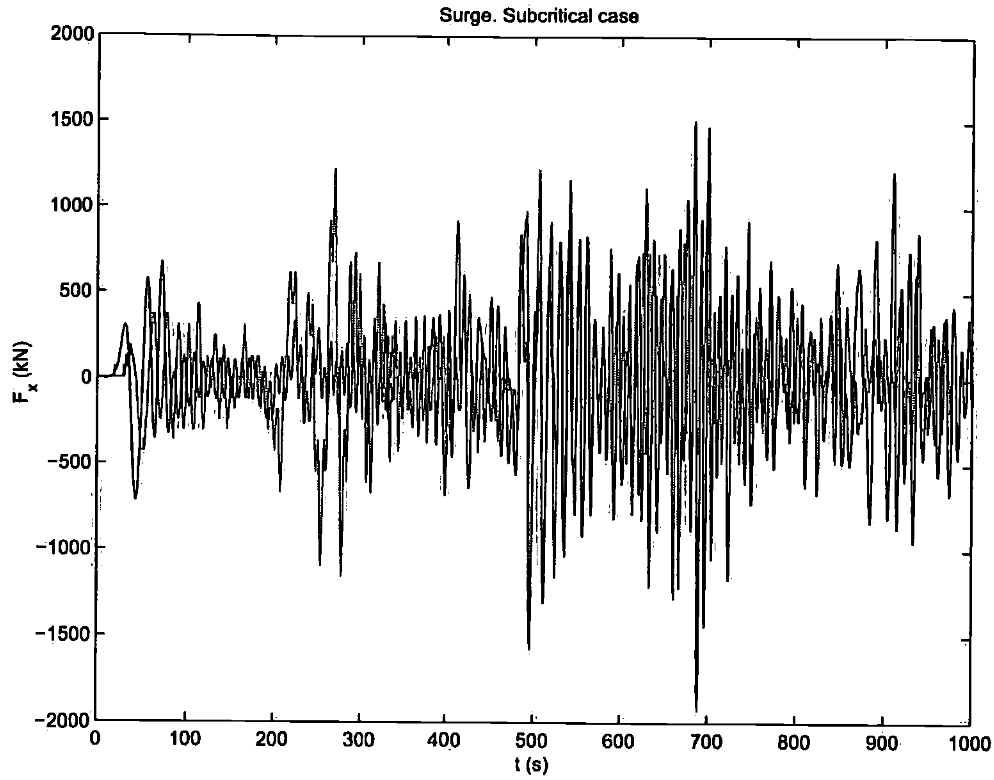


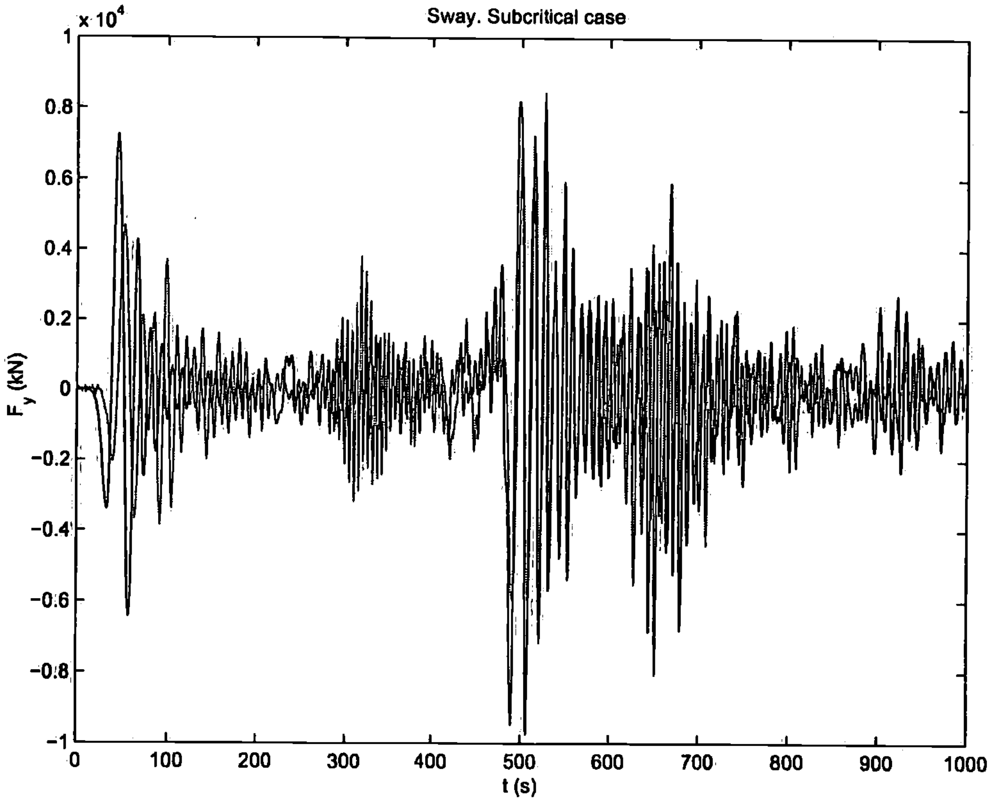
Figure 8. Supercritical case. Time series of the measured (red line), the sum of the computed first- and second-order (black line), and the computed second-order (blue line) forces and moments.

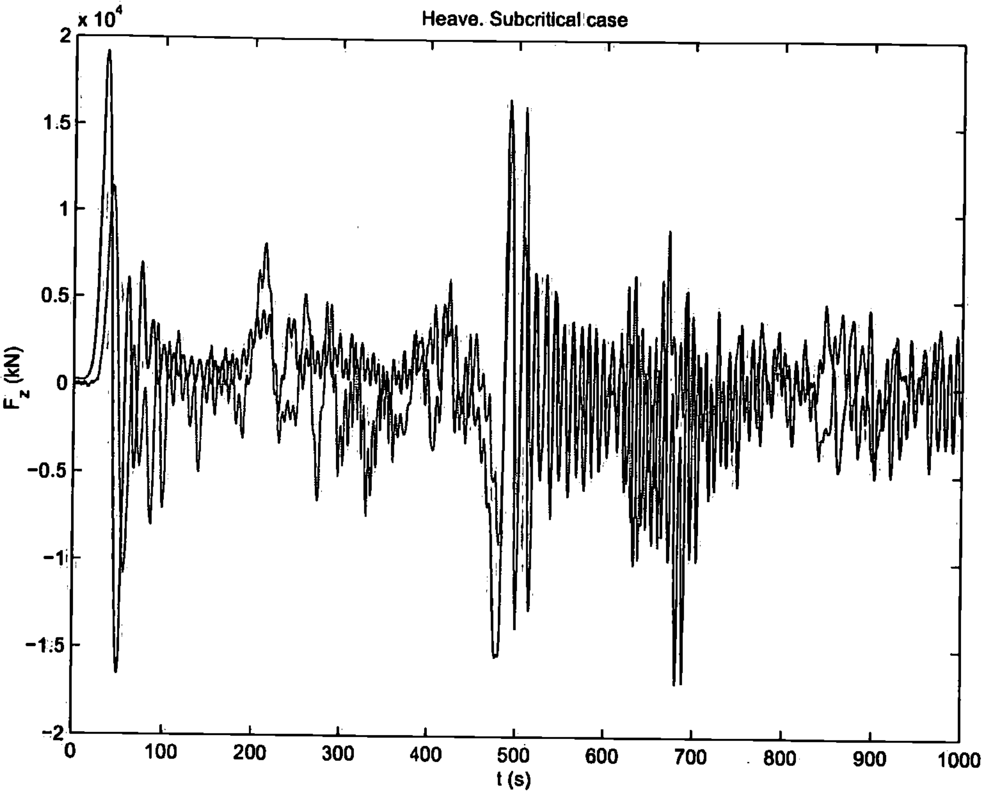
Subcritical case

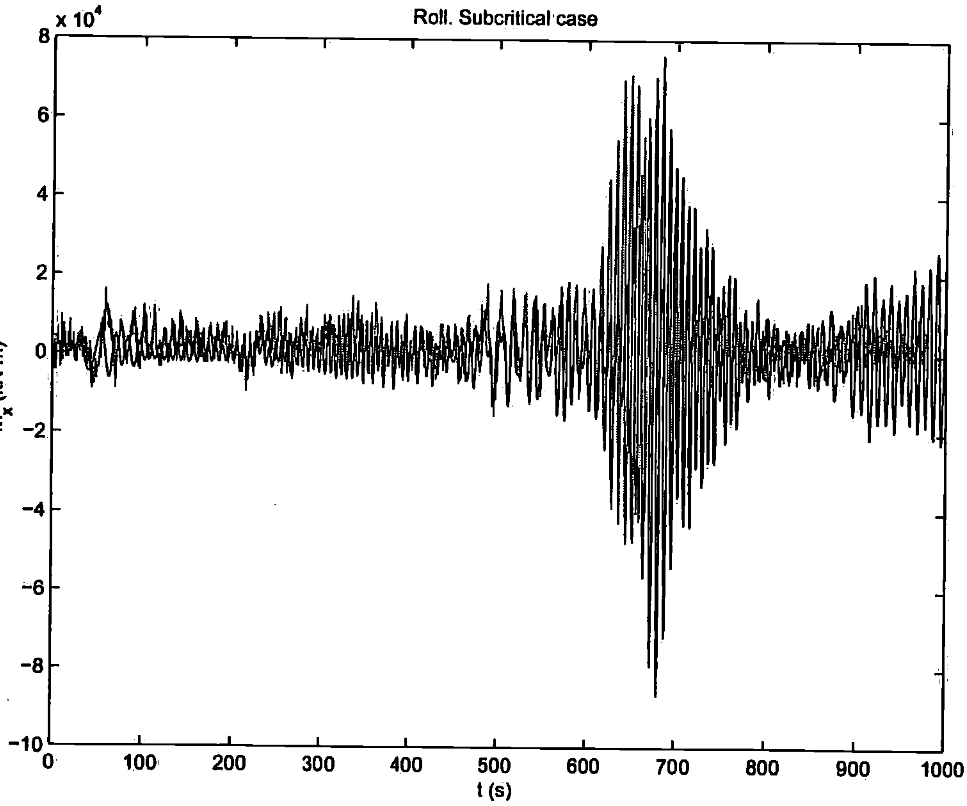
In Figure 9 and 10, the computed forces and moments (sum of first- and second-order contributions, and the second-order contributions) are compared with their measured counterparts. In Figure 11, these quantities are given as function of the radial frequency. We note the following:

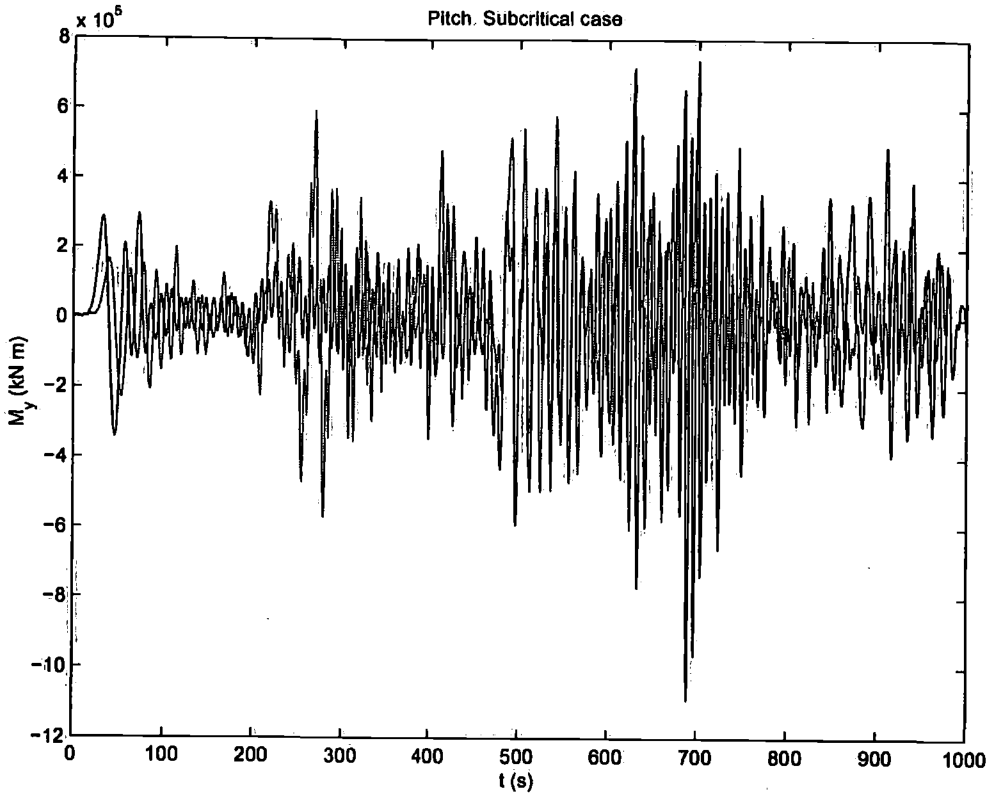
- On the overall, a reasonably good agreement for all forces and moments is obtained.
- The magnitude of the second-order forces and moments is usually 20 percent or less compared to the first-order forces and moments.


Surge. Subcritical case
2000
1500
1000
500
0
-500
-1000
-1500
-2000
F_x (kN)
0
100
200
300
400
500
600
700
800
900
1000
t (s)


Sway. Subcritical case
x 10^4
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
F_y (kN)
0
100
200
300
400
500
600
700
800
900
1000
t (s)


Heave. Subcritical case
x 10^4
F_z (kN)
t (s)


Roll. Subcritical case
x 10^4
M_x (kN m)
t (s)



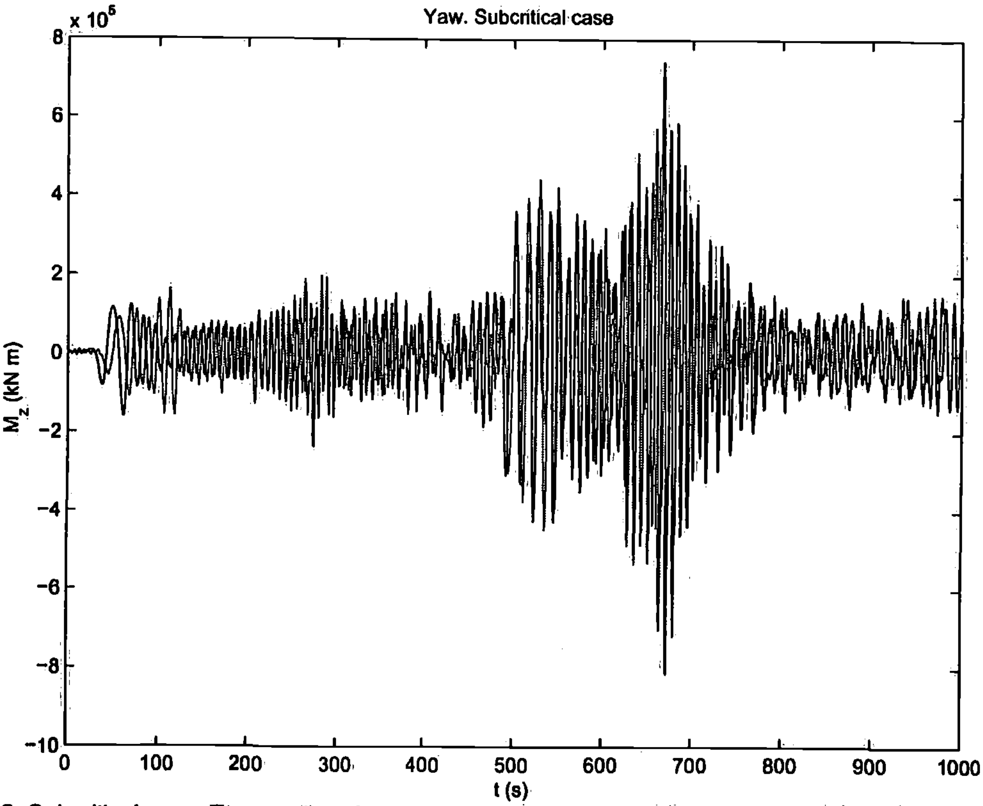
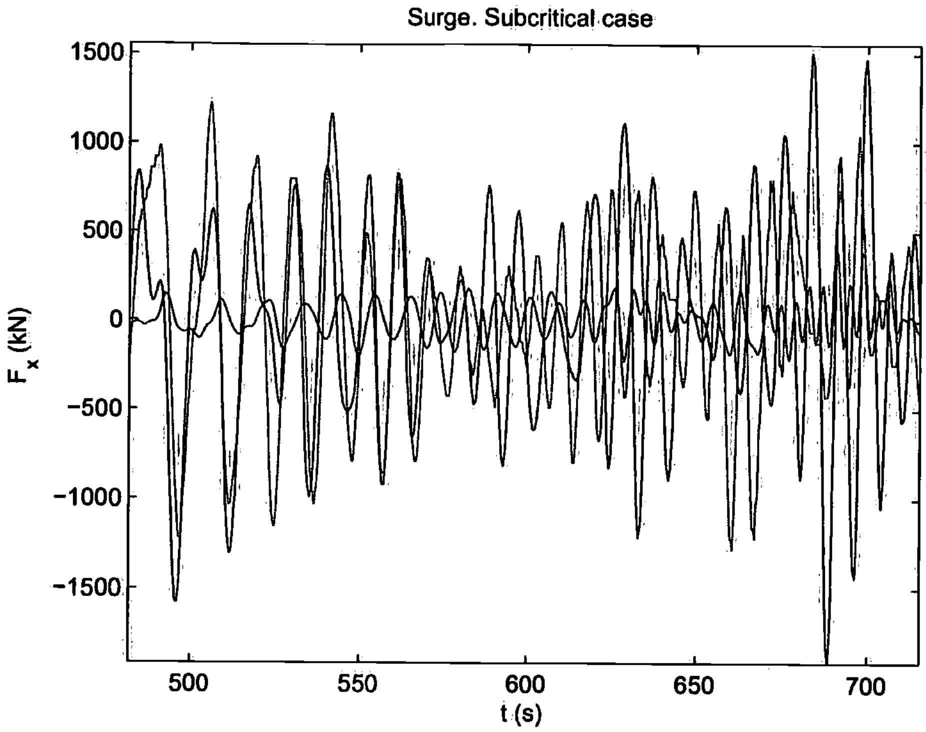
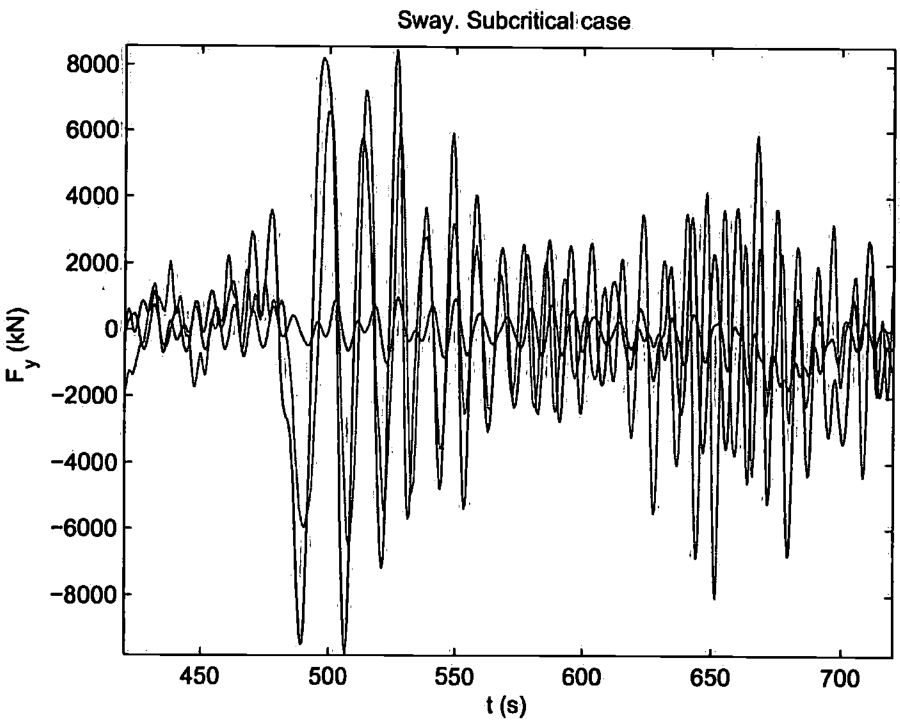
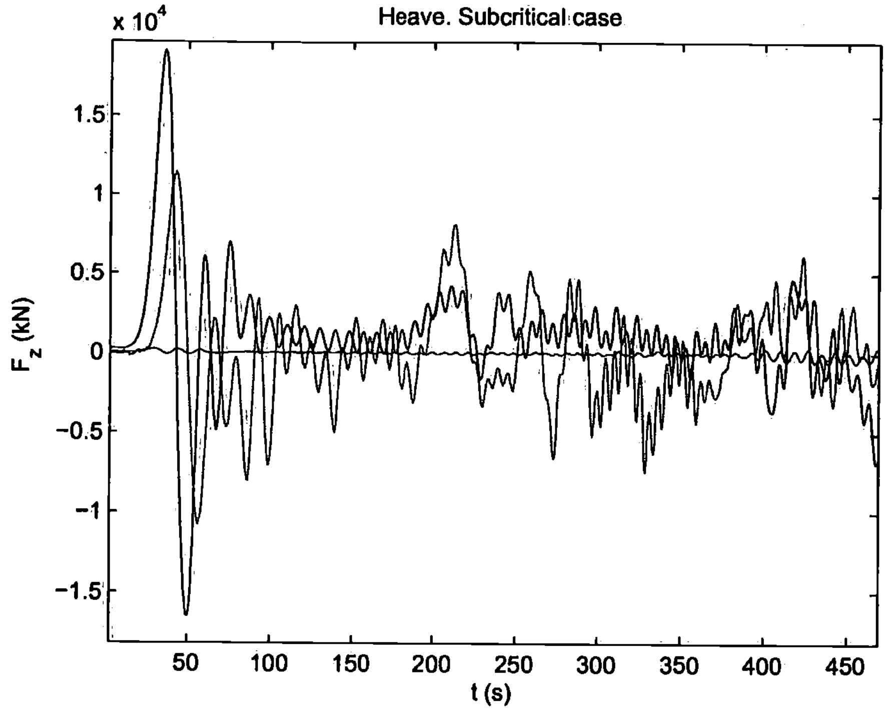
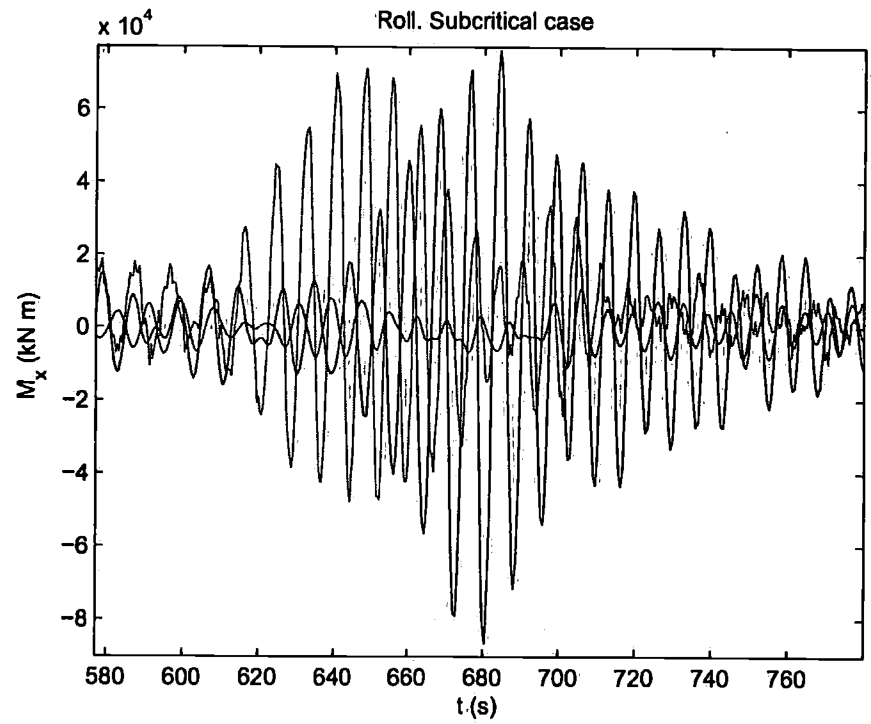


Figure 9. Subcritical case. Time series of the measured (red line) and the computed (black line) forces and moments.


Surge. Subcritical case
1500
1000
500
0
−500
−1000
−1500
F_x (kN)
500
550
600
650
700
t (s)


Sway. Subcritical case
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
F_y (kN)
450
500
550
600
650
700
t (s)


Heave. Subcritical case
x 10^4
F_z (kN)
t (s)
1.5
1
0.5
0
-0.5
-1
-1.5
50
100
150
200
250
300
350
400
450


Roll. Subcritical case
x 10^4
M_x (kN m)
t (s)
6
4
2
0
-2
-4
-6
-8
580
600
620
640
660
680
700
720
740
760

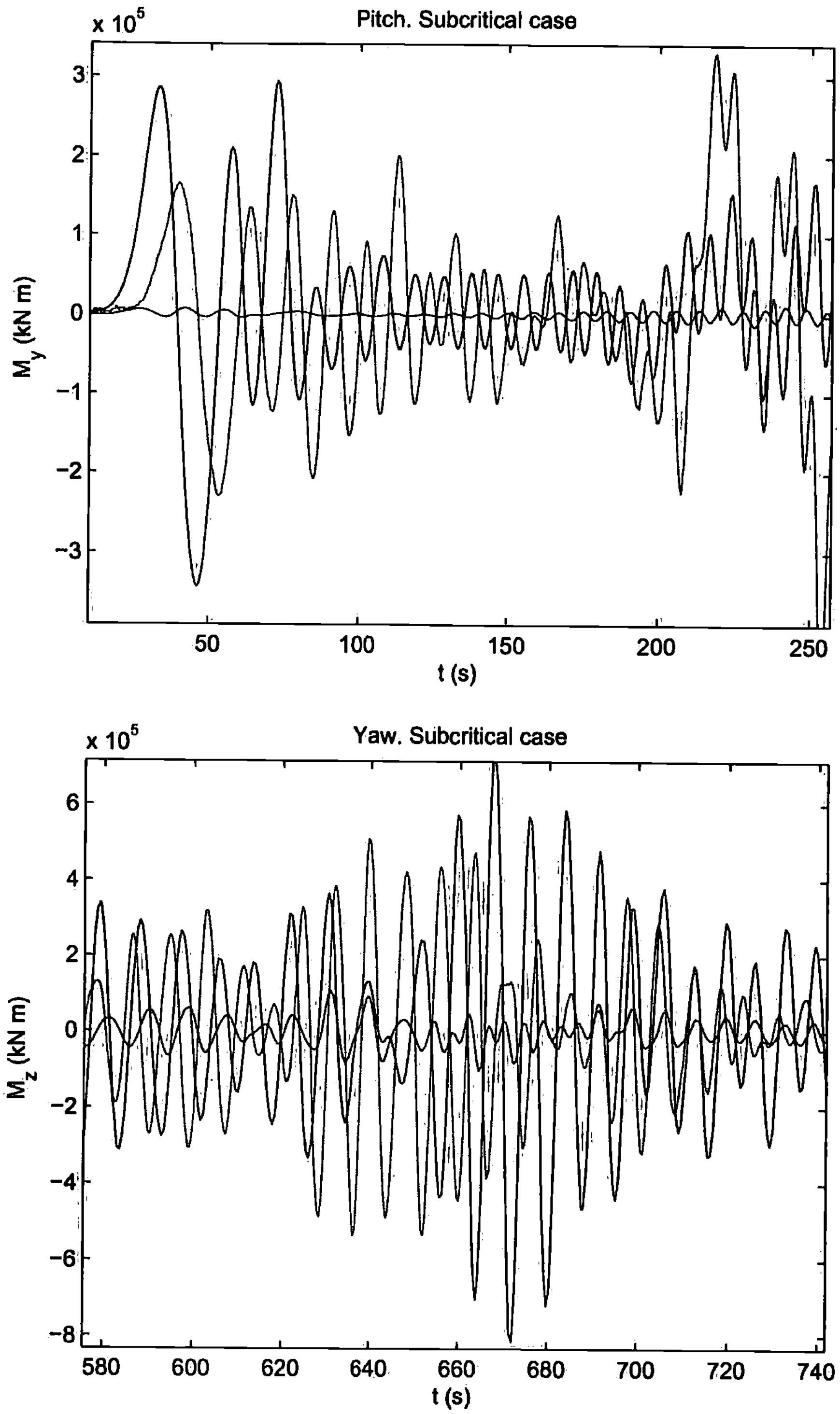


Figure 10. Subcritical case. Parts of the time series of the measured (red line), the sum of the computed first- and second-order (black line), and the computed second-order (blue line) forces and moments.

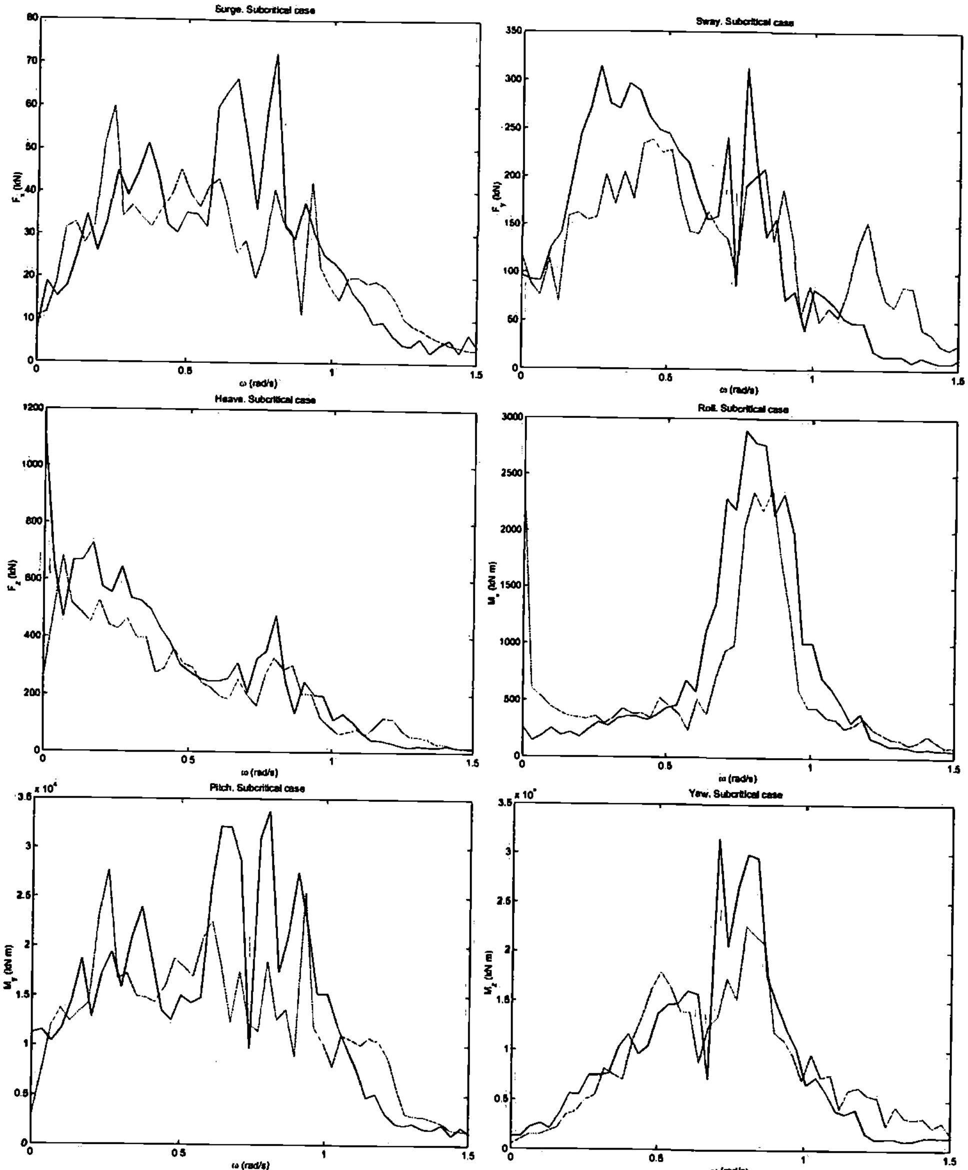


Figure 11. Subcritical case. Measured (red line) and computed (black line) forces and moments as function of the radial frequency.

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1. Summary and conclusions

Aim of the research is to develop and validate a numerical method for determining the wave forces on a ship as induced by a non-uniform wave field such as can be found in a harbour basin. This is important for the prediction of the downtime, i.e. the time that loading and unloading of a ship is not possible due to large ship motions. In this paper, a novel modeling system and its validation are described. It concerns the coupling of the nonlinear Boussinesq-type wave model TRITON, developed by WL | Delft Hydraulics, with the multibody panel method DELMULTI, developed by the TU Delft. Essential to this modeling system is that the forces are computed from the complete, undisturbed wave motion, without analysis of frequencies and / or direction.

The complete model chain to calculate the wave-induced forces on a ship and its resulting motion consists of four steps:

1. wave generation is computed,
2. wave propagation from the source to the moored ship is computed,
3. the wave-induced forces exciting the moored ship are computed,

4. the resulting ship's motions are computed.

This model chain allows for the computation of the motions of a ship moored in an arbitrarily shaped harbour basin. In the present work, we restrict ourselves primarily to items 2 and 3.

The 2DH time-domain Boussinesq-type wave model TRITON is employed to compute the wave propagation. It is designed to model dispersion, shoaling, refraction, diffraction as well as nonlinear wave-wave interactions. The model can also be applied in complex harbour geometries.

First- and second-order wave forces on the moored vessel and the resulting motion can be computed using the package DELMULTI. This is a validated frequency-domain 3D multi-body linear diffraction code.

The innovative part of the present work consists of the coupling between TRITON and DELMULTI. Given a 3D panel model of the ship, TRITON fills a file containing time series of the velocities and pressures at the panels, and surface elevations at the still waterline. Evaluation of data at the panels requires a step from 2DH (TRITON) to 3D (DELMULTI), which is obtained from reverse transformation of the TRITON model equations. Evaluation of these expressions is cheap, and is done as part of the time-stepping procedure in TRITON. These time series are used as input for the diffraction model. DELMULTI transforms the time series of the velocity and pressure to frequency domain by means of an FFT. The frequency components replace the classical long-crested regular wave velocities and pressures that serve as input to the conventional frequency domain panel models. For each frequency component, the diffraction problem for the 3D ship is solved. In frequency domain, the hydrodynamic forces are obtained in the standard way. By means of an inverse FFT, time series of the forces are obtained. Note that the latter step requires storage of phase information in the transformation from time to frequency domain; this poses no problem. The time series of the surface elevation at the still waterline is used for the evaluation of the second-order wave forces; this is done in time domain. Note that the incoming wave field contains nonlinear contributions, since TRITON is a nonlinear model. In other words, nonlinear wave effects are incorporated in the present approach 'for free'.

In Chapter 4, a rather simple test case to validate the coupling TRITON – DELMULTI is discussed. It concerns the computation of the forces and moments on a 200 kDWT tanker and the resulting motion induced by a unidirectional regular wave. A very good agreement between simulations and literature results is obtained.

In Chapter 5, we compare experimental data with numerical simulations for waves induced by a passing ship and the resulting forces on a container ship. The studied situation is an open water situation, i.e. no harbour model was present. We have considered two validation test cases: a passing ship moving at subcritical speed and a passing ship moving at supercritical speed. The passing of the ship has been simulated in the laboratory experiment by realizing a certain motion of the wave board paddles. The known motion of the paddles has been used to derive wave boundary conditions for TRITON. For the supercritical case, good agreement between measurements and laboratory experiments for both the wave field and the wave-induced forces is achieved. For the subcritical case, agreement seems less, but that may well be explained by the very complex wave pattern; in the laboratory experiments even the wave field was not very well reproducible.

We note that a passing ship event contains many wave periods and directions. This makes passing ship situations suitable for the development and validation of the method, since no restrictions with respect to the wave field are assumed, while the time series are relatively short. In other words, though the validation has been performed for a passing ship situation, it may be expected that the model chain can be successfully applied to any wave field that can be encountered.

In summary, it can be concluded that TRITON and the coupling TRITON – DELMULTI provide rather accurate computations of the wave fields and the resulting forces and moments on a moored ship.

6.2. Recommendations

1. Other, more complex validation tests must be considered. In particular, the Vinje basin validation experiments in which a container ship was moored in a harbour are a good candidate for this.

2. The amount of data that is transferred to DELMULTI becomes rapidly very large (one arrives easily at several hundreds of MB). Possible ways to reduce it are: (i) write data to the coupling file with larger timesteps and larger meshwidths, and (ii) use fewer panels in DELMULTI. Both ways will affect the accuracy, but we do not know yet by how much. This has to be studied.

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