Analysis of vertical motions and bending moments on a Bulk Carrier by model tests and numerical predictions

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Abstract

The paper presents an analysis and comparison between experimental data and numerical predictions of the heave motion, pitch motion and vertical bending moment at midship induced by irregular waves on a Bulk Carrier. The experimental data was obtained with a scaled model on a seakeeping tank. Head and following waves are analyzed together with different Froude numbers. The wave conditions include moderate to severe irregular waves, as well as short duration wave records with very large amplitude single waves inserted (abnormal waves).

The predictions are carried out with a linear seakeeping code which has the option to calculate the ship responses in the frequency domain or in the time domain. The second option is useful for direct analysis of the responses in the time domain. The time domain version of the code calculates the hydrodynamic forces using convolution integrals of memory functions, infinite frequency added masses and radiation restoring coefficients. The experimental data and numerical results are compared in terms of transfer functions of the motions and vertical bending moments at midship. Direct comparisons of experimental time records and time domain simulations are also carried out. Finally the importance of the nonlinear effects on the vertical motions and loads is assessed and discussed.

1. Introduction

Seakeeping analysis is an important aspect that should be incorporated into the design phase of the ship. If this analysis is considered within the design loop, it is in principle possible to obtain more efficient and safer ship structures. The ship operability in waves can also be improved enhancing the ability of the ship to carry out its mission, which in the case of commercial ships means a more profitable unit. Finally, planning of ship operations will also benefit from the application of procedures based on seakeeping programs. Two different seakeeping problems need to be considered. The first one is a problem of ship operability, meaning the ability of the ship to carry out its mission within acceptable standards of comfort for the crew or passengers and acceptable loads for the cargo, equipment and ship structures. Usually it is required that a set of ship responses, like for instances roll motion, relative motions and accelerations, do not surpass certain small to moderate limiting values. Small to moderate ship motions mean in most cases linear responses, thus in general one may apply linear seakeeping methods to analyse the ship operability in waves.

Another aspect that requires consideration is the survivability of the ship, without significant damages, which, among other aspects, includes the structural strength to withstand the largest structural loads induced by waves. The interest here is on the determination of the largest structural loads, which is inherently a nonlinear problem because it is related to very large amplitude motions between the ship and the waves. For this reason, in many cases nonlinear seakeeping methods must be used to estimate the design wave loads on ship structures.

The common use of numerical methods for assessing the seakeeping of ships, therefore to predict their motions and loads in waves, started after the strip theories developments in the 60´s. Strip theories continue being widely used in practice and probably the most cited strip theory is that presented by Salvesen et al. (1970). These methods, providing good results for the vertical responses of slender conventional ships, are relatively simple to implement and use in small computers. For the horizontal modes of motion and loads viscous effects may become important and in this case empirical corrections may be introduced to improve the results.

Although strip theories have their range of applications, they are based on two-dimensional cross flow approach and the three dimensional effects are introduced in a simplistic way. To account properly for the interactions between different sections and the forward speed effects in the free surface boundary condition, it was necessary develop three dimensional panel methods. The majority of these solutions are based on the boundary integral equation method and the unsteady potentials are solved either in the frequency or in the time domain, using Green function methods or Rankine source methods. Using Green function methods only the hull boundary needs to be discretized. The singularities which are located in the discretized boundary satisfy the free surface boundary condition, but have difficult numerical solutions. Examples of authors who presented numerical solutions are Inglis and Price (1980), Wu e Eatock-Taylor (1987), Ohkusu and Iwashita (1989).

An alternative to the use of the complex Green functions in the frequency domain panel methods was proposed by Nakos and Sclavounos (1990) and Bertram (1990) who applied Rankine sources. These singularities, being much simpler to calculate, do not satisfy the free surface boundary condition, thus the discretized domain must be extended to the free surface.

The three dimensional panel methods are well established to deal with the problem of stationary structures (for example Lee and Newman, 2004), however, for moving ships, the interaction between the forward speed steady flow and the oscillatory flow brings numerical difficulties for the solution and for this reason the linear boundary conditions are usually applied with some level of simplification. In practice the existing panel codes do not give significantly better results than the strip theories.

The best way to assess the quality of seakeeping code predictions is to compare the numerical results with experimental data obtained in a seakeeping tank with ship models. The laboratory conditions assure that the characteristics of the physical model are accurately acquired, as well as the wave conditions, so that they can be correctly reproduced by the numerical model. The present paper presents experimental results of the heave and pitch motions of a Bulk Carrier obtained in a seakeeping laboratory (Clauss et al. 2009). Head and following irregular waves were tested for several ship speeds. Severe wave conditions were considered. The experimental data is compared with linear predictions from a seakeeping code based on a strip theory.

2. Theory

Formulation of the Problem

Consider a coordinate system fixed with respect to the mean position of the ship, *X=(x,y,z),* with ***z*** in the vertical upward direction and passing through the center of gravity of the ship, ***x*** along the longitudinal direction of the ship and pointing to the bow, and ***y*** perpendicular to the later and in the port direction. The origin is in the plane of the undisturbed free surface. The ship advances with constant speed and heading with respect to incident harmonic waves, which induce rigid body oscillatory motions represented by three translations and three rotations.

Neglecting the viscous effects the hydrodynamic problem may be formulated in terms of potential flow theory, thus the fluid velocity vector may be represented by the gradient of a velocity potential. Consider a volume a fluid bounded by the mean wetted surface of the ship, the free surface, the sea bottom and lateral boundaries far away from the ship. The velocity potential must satisfy the Laplace equation within the volume of fluid and conditions in all boundaries, namely a free surface condition, a body kinematic condition, a bottom condition and a radiation condition.

Assuming a slender hull at slow forward speed and small enough amplitudes of the unsteady motions and incident waves, the potential can be expressed in the linearized form:

$$\Phi = -Ux + \Phi^{S} + \Phi^{I} + \Phi^{D} + \sum_{i=1}^{6} \Phi_{j}^{R} \tag{1}$$

where the first two terms represent the steady flow due to the presence of the ship advancing through the free surface being *U* the forward speed of the ship and Φ^{S} the steady perturbation potential. Φ^{I} is the incident potential and Φ^{D} is the diffracted potential related to the perturbation in the incident wave due to the presence of the hull. Φ_j^R is the radiated potential due to an unsteady motion in the j-mode.

Substitution of the potential (1) into the linearized Bernoulli´s equation results in the hydrodynamic pressure. Integration of the oscillatory pressure terms over the wetted surface of the hull results in two groups of hydrodynamic forces, namely the radiation and the exciting forces. The latter are further decomposed in Froude Krylov forces associated with the incident wave field and diffraction forces associated with the wave scattering. Integration of the hydrostatic pressure over the oscillatory wetted hull results on the hydrostatic forces. Finally, through the dynamic equilibrium of forces one obtains the equations of motions and structural loads.

Frequency Domain Solution

The difficulty of the problem stated in the last paragraphs consists on finding the solution of the boundary value problem to obtain the velocity potentials. Different methods have been proposed to solve this problem, which basically depend on the restrictions imposed in some parameters that govern the solution. A strip method is used in the present frequency domain solution, namely the one proposed by Salvesen et al. (1970). The assumptions are the following: the amplitude of the waves and of the ship motions are small, the frequency of oscillation is high, the ship is slender and the speed is low. Based on these assumptions, the three dimensional (3D) boundary value problem is reduced to a set of two dimensional (2D) problems along the ship length. In practice it is like the ship is represented by a set of 2D strips and the flow over each one is basically 2D because there is no cross flow between strips. The 3D effects associated with the forward speed are represented in a simplistic way and they depend of the angle of the hull (pitch and yaw angles) with the uniform flow related to the ship's speed.

The 2D boundary value problems are solved by the Frank close fit method (Frank, 1967). This is a boundary integral method where singularities of unknown strength are distributed over the submerged cross section. They satisfy the Laplace equation and the free surface boundary condition and their strength is determined by the application of the kinematic body boundary condition.

Finally the ship radiation forces are represented by frequency dependent added mass, A_{kj}, coefficients and damping coefficients, B_{kj}. The coefficients associated to the heave and pitch motions are:

$$A_{33} = \int a_{33} dx \qquad (2) \qquad\qquad B_{33} = \int b_{33} dx \qquad (3)$$

$$A_{35} = -\int \ell a_{33} d\ell - \frac{U}{\omega^2} B_{33} \qquad (4) \qquad\qquad B_{35} = -\int \ell b_{33} d\ell + U A_{33} \qquad (5)$$

$$A_{53} = -\int \ell a_{33} d\ell + \frac{U}{\omega^2} B_{33} \qquad (6) \qquad\qquad B_{53} = -\int \ell b_{33} d\ell - U A_{33} \qquad (7)$$

$$A_{55} = \int \ell^2 a_{33} d\ell + \frac{U^2}{\omega^2} A_{33} \qquad (8) \qquad\qquad B_{55} = \int \ell^2 b_{33} d\ell + \frac{U^2}{\omega^2} B_{33} \qquad (9)$$

where the integrations are along the ship's length, a_{33} and b_{33} are the cross sectional heave added mass and damping coefficients, U is the ship speed and □ the frequency of the forced motions.

The heave and pitch Froude Krilov exciting forces and diffraction forces are represented in terms of cross sectional heave coefficients f_3^I and f_3^D:

$$F_3^I = \zeta^a \int_L \left(e^{ik_0 x \cos\beta} f_3^I \right) d\ell \qquad (10)$$

$$F_5^I = -\zeta^a \int_L \left(e^{ik_0 \ell \cos\beta} \ell f_3^I \right) d\ell \qquad (11)$$

$$F_3^D = \zeta^a \int_L \left(e^{ik_0 \ell \cos\beta} f_3^D \right) d\ell \qquad (12)$$

$$F_5^D = -\zeta^a \int_L \left\{ e^{ik_0 \ell \cos\beta} \left(\ell f_3^D + \frac{U}{i\omega} f_3^D \right) \right\} d\ell \qquad (13)$$

where is the harmonic wave amplitude, k_0 is the wave number, x is the longitudinal coordinate along the ship and β is the heading angle of the ship speed vector with respect to the incident waves (180º for head waves).

The equations of motion results from the equilibrium between external forces (hydrodynamic) and the inertial forces associated to the ship mass. The result for heave and pitch motions is:

$$\begin{cases} (M + A_{33})\ddot{\xi}_3 + B_{33}\dot{\xi}_3 + C_{33}\xi_3 + A_{35}\ddot{\xi}_5 + B_{35}\dot{\xi}_5 + C_{35}\xi_5 = F_3^I + F_3^D \\ A_{53}\ddot{\xi}_3 + B_{53}\dot{\xi}_3 + C_{53}\xi_3 + (I_{55} + A_{55})\ddot{\xi}_5 + B_{55}\dot{\xi}_5 + C_{55}\xi_5 = F_5^I + F_5^D \end{cases} \quad (14)$$

M is the ship's mass, I_{55} the pitch moment of inertia, C_{kj} the hydrostatic restoring coefficients. The unknown oscillatory ship motions, ξ_3, ξ_5, are obtained from the solution of the differential equations. The global structural loads, namely the cross sectional vertical bending moment and shear force, can be calculated, once the motions are known, as the difference between the external forces and the inertial forces on the segment of the ship forward of the cross section.

Time Domain Solution

The frequency domain method presented in the previous section is useful since it provides an efficient and very fast solution. Coupled with the standard spectral methods (St. Denis and Pierson, 1953) it gives linear statistics of the ship responses in irregular sea states. When nonlinear effects become important for the ship motions and global structural loads, especially in large amplitude waves and for ships with small block coefficient, then the solution must be obtained in the time domain. The time domain solution is also useful for direct assessment of the wave effects on the ship responses, which can be done with direct simulation of the wave elevation and related ship responses.

A nonlinear time formulation was proposed by Fonseca and Guedes Soares (1998a, b) and it will be briefly described in the following paragraphs. The method is based on the hypothesis that the dominant nonlinear contributions are associated to the buoyancy forces (hydrostatics and Froude Krylov), therefore these are calculated accurately accounting for the nonlinear effects, while the radiation and diffractions can be kept linear. In practice it means that the relative motions are of large amplitude, although the waves can be assumed with small amplitude (small steepness). The other assumptions of the method are similar to the ones presented for the frequency domain method.

Equating the hydrodynamic external forces to the mass and gravity forces one obtains the equations of motion. These equations, which combine linear and nonlinear terms, are solved in the time domain by a numerical procedure. For heave and pitch the equations are:

$$\begin{aligned}&\left(M + A_{33}^{\infty}\right)\ddot{\xi}_3(t) + \int_{-\infty}^{t}\left[K_{33}^{m}(t-\tau)\dot{\xi}_3(\tau)\right]d\tau + \\ &C_{33}^{m}\xi_3(t) + A_{35}^{\infty}\ddot{\xi}_5(t) + \int_{-\infty}^{t}\left[K_{35}^{m}(t-\tau)\dot{\xi}_5(\tau)\right]d\tau + \\ &C_{35}^{m}\xi_5(t) + F_3^{H}(t) - Mg + F_3^{gw}(t) = F_3^{D}(t) + F_3^{I}(t)\end{aligned} \tag{15}$$

$$\begin{aligned}&\left(I_{55} + A_{55}^{\infty}\right)\ddot{\xi}_5(t) + \int_{-\infty}^{t}\left[K_{55}^{m}(t-\tau)\dot{\xi}_5(\tau)\right]d\tau + \\ &C_{55}^{m}\xi_5(t) + A_{53}^{\infty}\ddot{\xi}_3(t) + \int_{-\infty}^{t}\left[K_{53}^{m}(t-\tau)\dot{\xi}_3(\tau)\right]d\tau + \\ &C_{53}^{m}\xi_3(t) + F_5^{H}(t) + F_5^{gw}(t) = F_5^{D}(t) + F_5^{I}(t)\end{aligned} \tag{16}$$

where, in addition to the symbols already defined, $F_{3,5}^{H}$ and $f_{3,5}^{gw}$ represent respectively the nonlinear hydrostatic forces and the green water on deck forces. A_{kj}^{∞}, C_{kj}^{m} and $K_{kj}^{m}(t)$ represent respectively infinite frequency added masses, radiation restoring coefficients and memory functions. These coefficients and functions are used to calculate the time domain radiation forces according to the formulation presented by Cummins (1962). The restoring radiation coefficients represent a correction to the hydrodynamic steady forces acting on the ship due to the steady flow. The convolution integrals represent the effects of the whole past history of the motion accounting for the memory effects due to the radiated waves. The memory functions and the radiation restoring coefficients are obtained by relating the radiation forces in the time domain and in the frequency domain by means of Fourier analysis:

$$K_{kj}^{m}(t) = \frac{2}{\pi}\int_{0}^{\infty}\left\{B_{kj}(\omega)\cos\omega t\right\}d\omega \tag{17}$$

$$C_{kj}^{m}(t) = \omega^2\left[A_{kj}^{\infty} - A_{kj}(\omega)\right] - \omega\int_{0}^{\infty}K_{kj}^{m}(\tau)\sin(\omega\tau)d\tau \tag{18}$$

where $A_{kj}(\omega)$ and $B_{kj}(\omega)$ are the frequency dependent added mass and damping coefficients calculated with a strip theory method presented in the previous section.

3. Experimental Program

The model tests were conducted in the seakeeping basin of the Ocean Engineering Division, Technical University Berlin (TUB), at a model scale of 1:70. Clauss et al. (2009) present details of the experimental setup and analysis of the experimental data. A brief summary is described in the following paragraphs. The basin is 110m long, with a measuring range of 90 m, the width is 8m and the water depth is 1m. On one side an electrically driven piston type wave generator is installed. The wave generator is fully computer controlled and the software is implemented to generate regular waves, transient wave packages, deterministic irregular sea states with defined characteristics as well as tailored critical wave sequences. On the opposite side a wave damping slope is installed to suppress interfering wave reflections.

To transfer the real-sea registrations into the wave tank, an optimization approach for the experimental generation of tailored wave sequences with predefined characteristics was applied (Clauss and Schmittner, 2005). This method enables the generation of scenarios with a single high wave superimposed to irregular seas. During the experimental optimization, special emphasis is laid on the exact reproduction of the wave height, crest height, wave period as well as the vertical and horizontal asymmetry of the target wave. With this technique real-sea registrations including single abnormal waves are reproduced in the seakeeping basin, like the well known New Year Wave (Cherneva and Guedes Soares, 2008; Clauss and Klein, 2009), to evaluate the effect of these abnormal waves on floating structures.

Table 1 presents the main characteristics of the Bulk Carrier. Figure 1 shows the wooden model. For the investigation of the vertical wave bending moment, the model is subdivided into two segments at Lpp/2, being connected with three force transducers. Two transducers are installed close to the deck level and one underneath the bottom of the model. The force transducers register the longitudinal forces during the experiments. Based on the measured forces and the given geometric arrangement of the three force transducers the resulting vertical wave bending moment and the longitudinal forces are obtained. On this basis, the superimposed vertical wave bending moment resulting from the vertical and horizontal forces on the hull is determined.

Table 1: Main Particulars of the containership

Length between perpendiculars	Lpp	177	[m]
Breadth	Bwl	30	[m]
Draught	T	16.2	[m]
Displacement	Δ	52556	[t]
Block coefficient	CB	0.818	[-]
Longitudinal centre of gravity	Xcg	2.94	[m]
Vertical centre of gravity	Zcg	5.97	[m]
Scale of the model	λ	1:70	[-]

Figure 1: Wooden model of the Bulk Carrier (scale 1:70) subdivided into two segments at the mainframe to measure the vertical wave bending moment.

During the tests the ship motions are recorded by an optical tracking system. The free surface elevation has been measured at two positions with surface piercing resistance-type wave gauges installed on the towing carriage. The wave gauges have been installed in such a way that the surface elevation is determined at the forward perpendicular as well as at the midship section at the equilibrium position of the towing arrangement for the stationary ship – knowing that the ship slightly oscillates in x-direction due to the restricted but not eliminated surge motion. For the tests at stationary conditions the undisturbed surface elevation has been measured without the ship whereas it has been directly measured during the test runs for the cruising vessel since the radiated ship's wave field does not affect the cruising wave gauges. Clauss et al. (2010) present further details of the experimental setup.

Table 2 gives a brief description of the list of experiments. The New Year Wave, which was measured at the Draupner platform in North Sea in 1995, was recreated in the tank embedding in a dedicated irregular seastate. This giant wave had a maximum wave height of 26.45m and a wave crest height of 18.34m and the seastate is characterized by a significant wave height of 13.22m (Hmax/Hs=2.0).

Table 2: Predefined waves tested

No	Type of wave	Target	Heading [º]	Fn
1	New Year Wave	Midship	180º / 0º	0 / 0.05
2	Single Freak Wave North Alwyn	Midship	180º / 0º	0 / 0.05
3	Designed Critical Wave Sequence	Midship	180º / 0º	0 / 0.05

Similarly, one of the abnormal waves measured at the North Alwyn platform in the North Sea and reported by Guedes Soares et al. (2003) was generated in the tank. This wave had a maximum wave height of 21.0m, with a maximum wave crest height of 15.75m and the corresponding significant wave height is 10.94m, with an abnormality index of Hmax/Hs=1.92. In table 2, “Target” means the position on the ship model where the abnormal wave crest is generated, which is either the midship or the forward perpendicular. Only head and following waves were considered, together with and several Froude numbers.

4. Comparison between Experimental data and Numerical Results

Transfer Functions

The time series resulting from the experiments work is processed by means of a MatLab computer code using the method of energy spectrum. This method use the standard Fourier transform to find out the distribution of energy across different frequencies components of the sea state. This analysis was usually carried out by first computing the autocorrelation function and then the Fourier transform; this helped to reduce the computational time. However, to date with aid of computer codes implemented to calculate the discrete Fourier transform the analysis can be done more directly by:

$$U_{xx}(w_n) = \frac{X(w_n)X^*(w_n)\Delta t}{\pi N} \tag{19}$$

$$U_{xy}(w_n) = \frac{X^*(w_n)Y(w_n)\Delta t}{\pi N} \tag{20}$$

$$RAO(w) = \frac{U_{xy}(w)}{U_{xx}(w)} \tag{21}$$

where Uxx is Auto Spectrum, *Uxy* is Cross Spectrum, *RAO* is the linear transfer function (LTF), '*X*' and '*Y*' are the Fourier transform of input and output time series, 'ω' is the radial frequency and '*N*' is the total number of samples in a realization, auto spectrum, cross spectrum and LTF for the vertical motions and vertical bending moment is obtained and comparison of the transfer functions between the numerical and experimental results shown on the following pages.

Figures 2 and 3 present the transfer function amplitude of heave, pitch and vertical bending moment at midship respectively for Froude numbers of 0 and 0.05. The left graphs show the results in head sea and the right graphs show the results in following sea, where the continuous lines represent the experimental data and the dashed lines the numerical predictions. All graphics are presented in non-dimensional form, where the nondimensional frequency is represented by $\varpi\sqrt{L_{pp}/g}$, and the linear transfer functions amplitudes in heave, pitch and vertical bending moment (at midship) are given by: $[\xi_3/\zeta^a]$, $[\xi_5/k\zeta^a]$ and $[M_5^* = M5/\rho g B L_{pp}^2 \zeta^a]$ respectively (ρ, g, B and L_{pp} are respectively the water density, acceleration of gravity, ship's beam and length between perpendiculars).

The analysis was carried out for the vertical motions and vertical bending moment, and the results are compared between the numerical and the experimental values followed by a discussion. The numerical results of heave motion (see Figure 2) show a good agreement between the experimental and the numerical values in the range under analysis. It can also be observed that in head sea (β=180º) and Froude number, *Fn* = 0, there is an under estimation of heave motion. In the case of pitch motion, the numerical values show good approximation to the experimental values at the medium to high frequency range, however for low frequencies the differences increase as the frequency decreases. This might be due to spectral method used to obtain the linear transfer function (LFT), since at low frequencies the values of the energy densities are very small for both Auto Spectrum and the Cross Spectrum. The numerical transfer function of the vertical bending moment at midship over predicts the experimental results, especially for following waves.

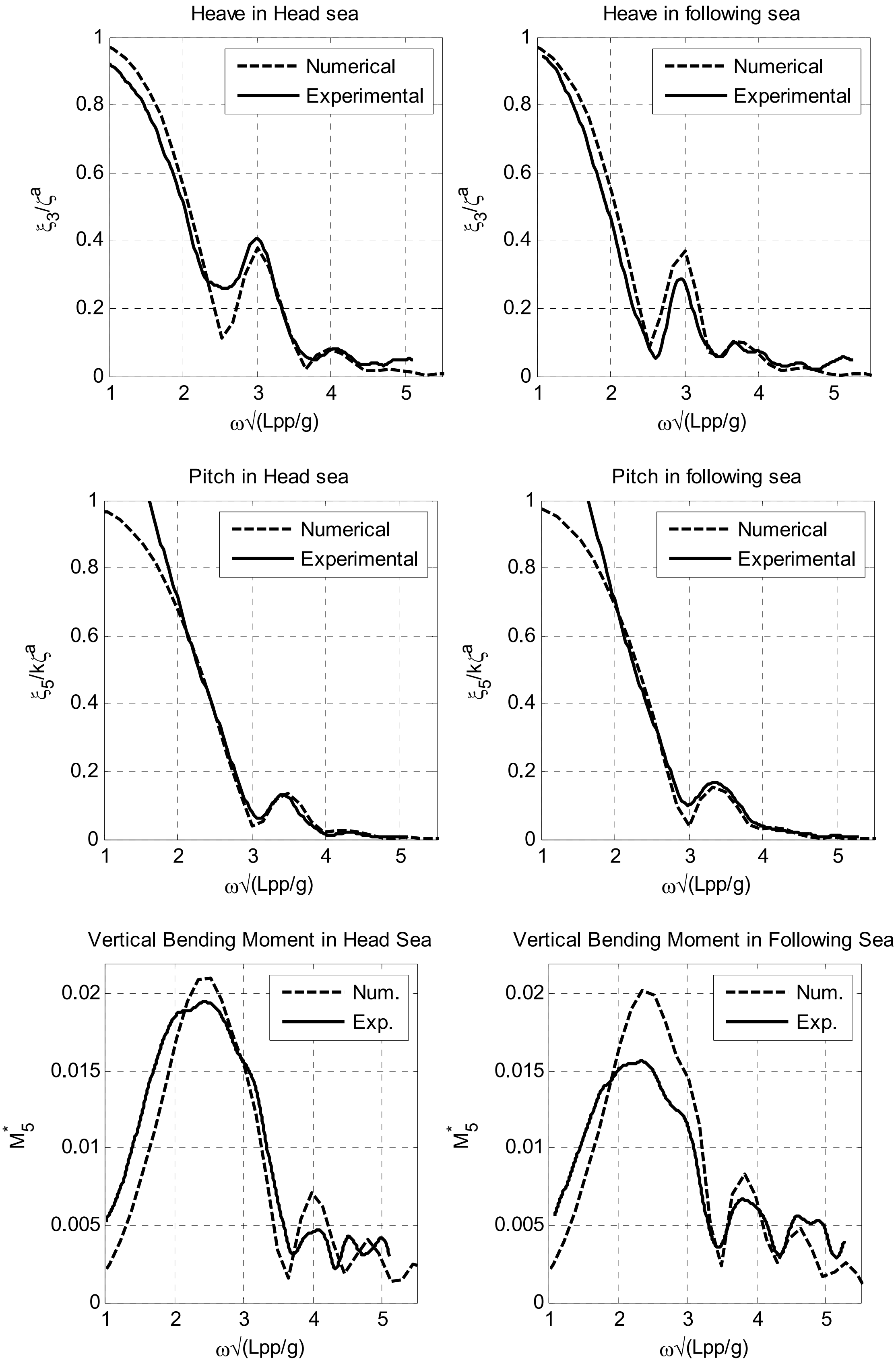

Figure 2: Transfer function amplitude of heave, pitch and vertical bending moment at midship for Fn = 0.0 and head and following waves. Comparison between experimental data and numerical predictions.

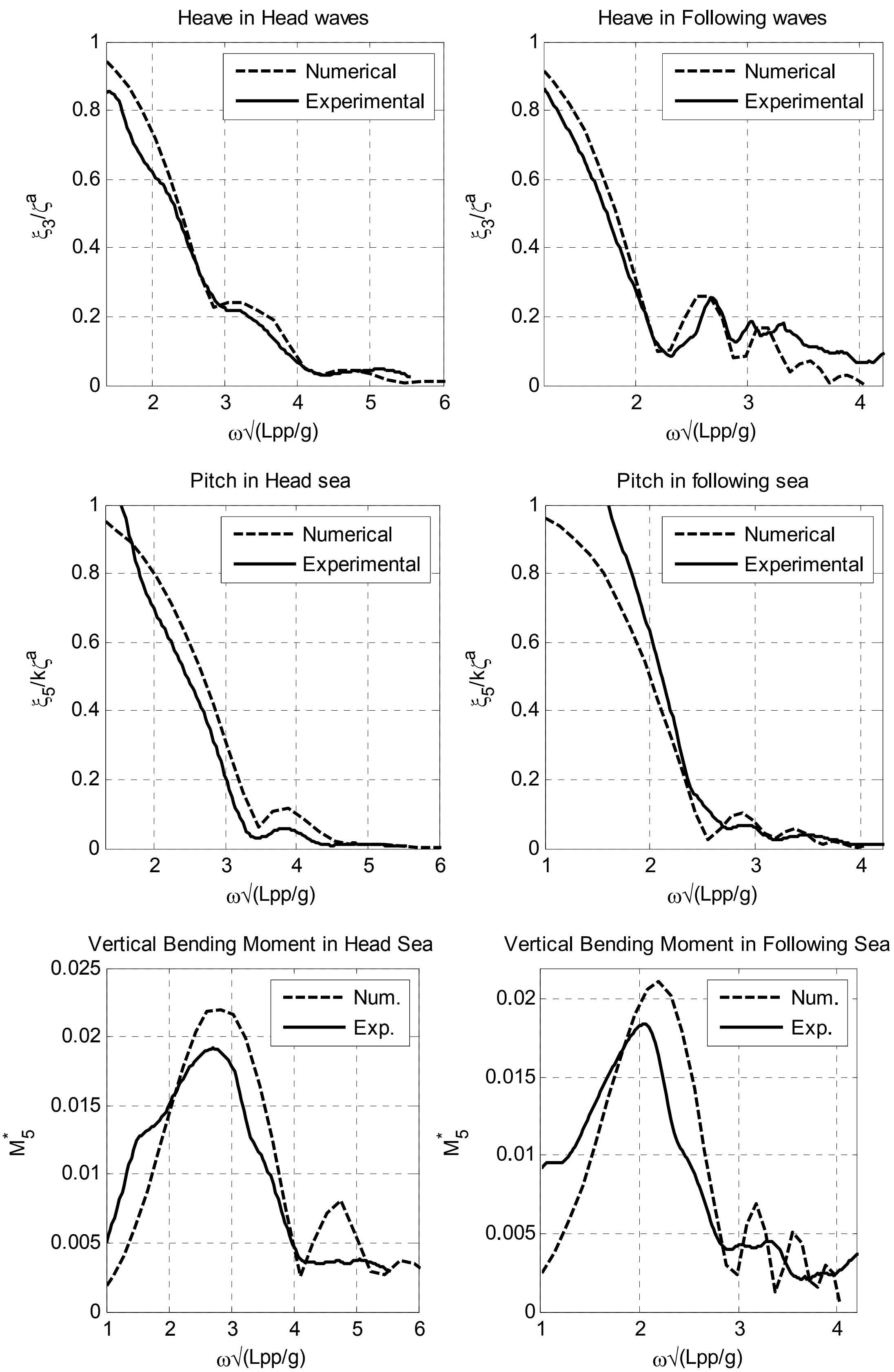

Figure 3: Transfer function amplitude of heave, pitch and vertical bending moment at midship for Fn = 0.05 and head and following waves. Comparison between experimental data and numerical predictions.

Direct comparison of time domain records

This section presents direct comparison between the measured time records and linear numerical simulation for Froude number zero and head seas. Figures 4 to 6 show the comparison of the wave elevation at midship, heave, pitch and vertical bending moment at midship. The graphs in the three figures correspond to measurements and simulations in deterministic wave sequences named respectively as: the New Year Wave (figure 4), Single North Alwyn Freak Wave (figure 5) and Designed Critical Wave Sequence (figure 6). All results are for the natural ship scale. The continuous lines represent the experimental data and the dashed lined the numerical predictions.

As can be observed by the wave elevation graphs, the measured wave elevation is exactly reproduced by the numerical code. The procedure to calculate the related exciting forces is described by Fonseca et al. (2006). The graphs show a very good agreement between experimental data and predicted results. Small differences are observed for pitch since the numerical results slightly tend to underestimate the positive peaks. This might be related to nonlinearities effects which are neglected by the numerical calculations. Regarding the vertical bending moment at midship one observes a tendency to overestimate the hogging peaks, while some sagging peaks are under estimated.

Conclusions

This work presents an analysis of the vertical motions and bending moments on a Bulk Carrier induced by waves. The linear ship responses are calculated by a strip theory seakeeping code, which computes the solution either in the frequency domain or in the time domain, and the predictions are compared with experimental data obtained with model tests in a seakeeping tank. The experimental transfer functions are derived from Fourier analysis of the time records obtained in irregular waves. The time records are of relatively short duration, therefore the resulting transfer function are expected to have some experimental uncertainty. The agreement between the numerical transfer functions and the experimental ones is reasonably good, although the vertical bending moment at midship is overestimated.

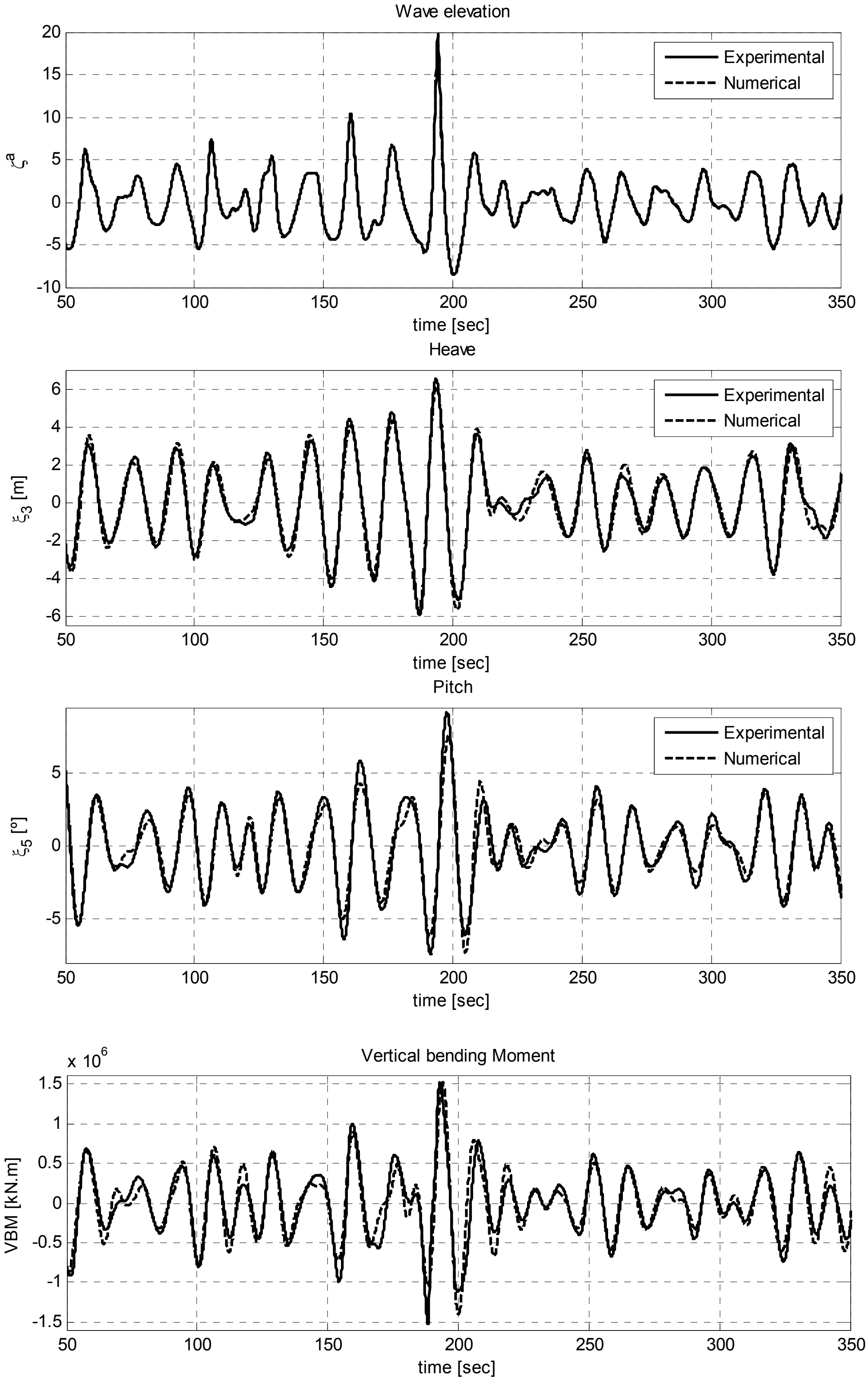

Figure 4: Time series of wave elevation, heave, pitch and vertical bending moment at midship for Fn = 0 and head waves. Direct comparison between experimental data and numerical predictions for New Year Wave.

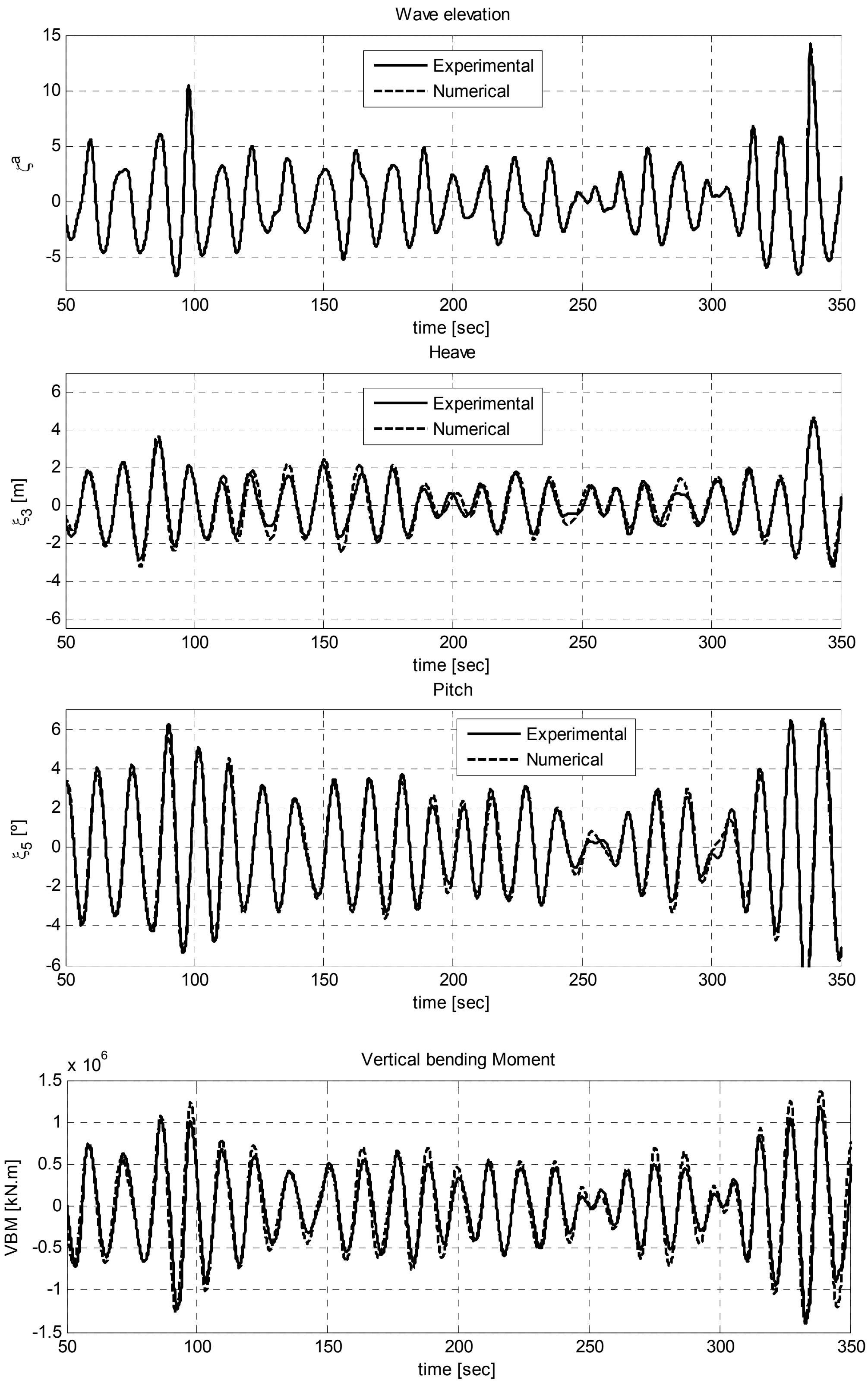

Figure 5: Time series of wave elevation, heave, pitch and vertical bending moment at midship for Fn = 0 and head waves. Direct comparison between experimental data and numerical predictions for Single Freak Wave North Alwyn.

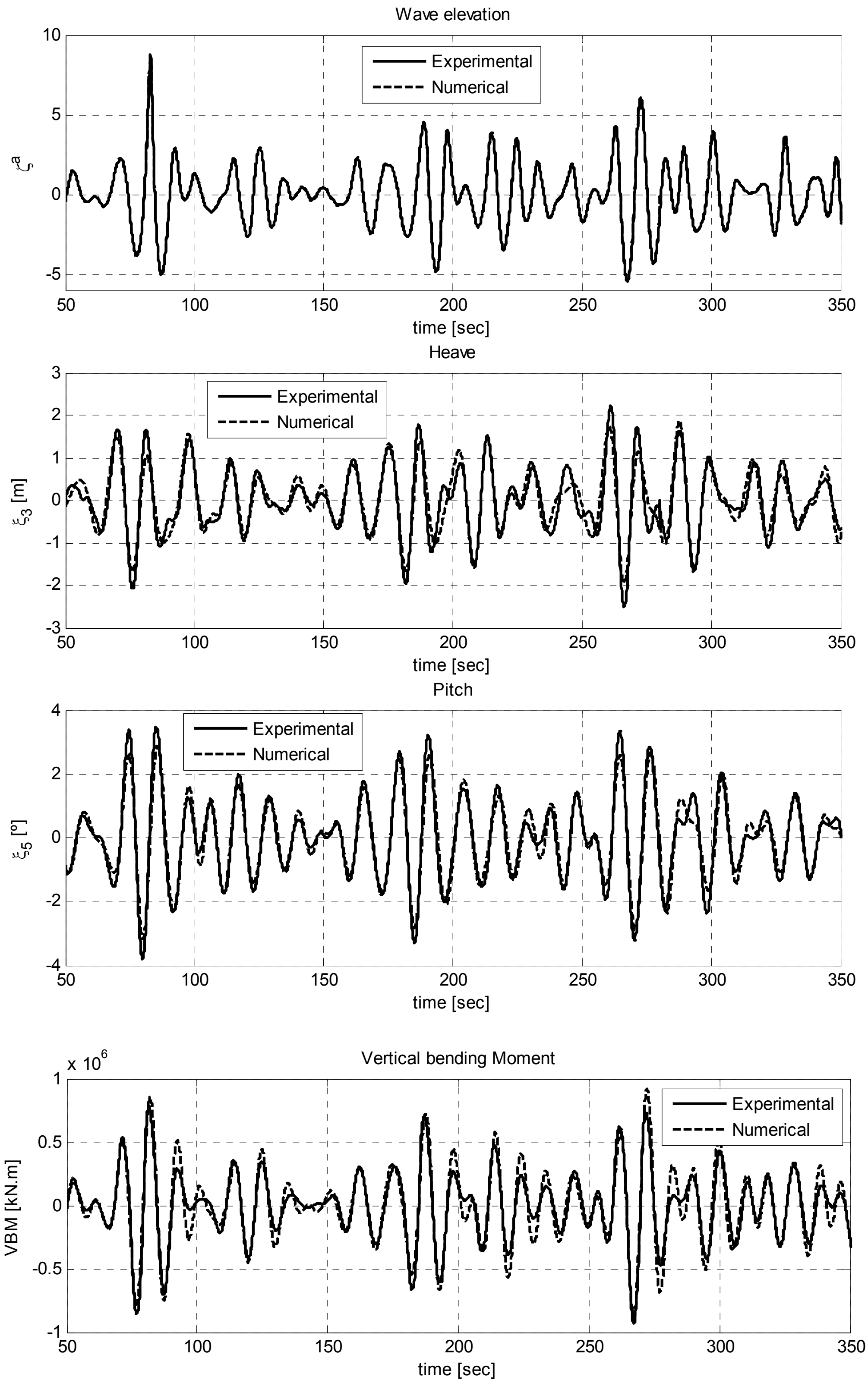

Figure 6: Time series of wave elevation, heave, pitch and vertical bending moment at midship for Fn = 0 and head waves. Direct comparison between experimental data and numerical predictions for Designed Critical Wave Sequence.

The time domain option is used for direct comparison with the experimental time records and the agreement is in fact very good which demonstrates the capability of the seakeeping code. Small discrepancies in the pitch motion and the vertical bending moment at midship are believed to be related to nonlinear effects induced by the large amplitude waves.

Acknowledgements

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