Nonlinear Ship Responses in Head Waves

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June 29, 1993

Abstract

In this study the attention is addressed to the nonlinear behaviour of vertical bending moments in a ship in moderate and severe seas. This effect occurs as a very strong increase of the bending moment in sagging condition and a slight decrease in hogging condition compared to linear predictions. As a result of this phenomenon the stress level in the deck plating becomes much higher than predicted by linear methods.

A new set of experiments has been set up in which the first three harmonic components of the motions, bending moments and shear forces have been analyzed. The experiments have been or will be performed with a standard Wigley hull form as well as with a Wigley hull form with additional bow flare. In this abstract some experimental results have been compared with a large-amplitude strip theory-based simulation model.

It is shown that although the motions can be calculated with a linear approach until quite severe situations, this certainly does not hold for the internal loads, even for a linear hull form such as a Wigley is.

The magnitude of the nonlinear components in the bending moments is strongly related to the amplitude of the relative motion at the bow. This implies that even in very low amplitude waves, a considerable contribution from higher harmonics is experienced if the excitation frequency is close around the peak in the relative motion transfer function.

Additional bow flare appears to increase higher order components in the bending moments especially in the bow region dramatically.

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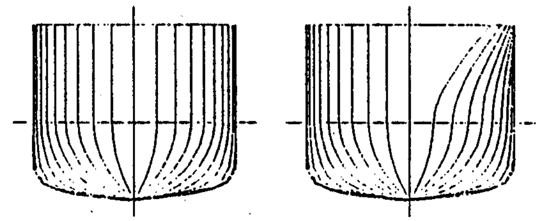

Figure 1: Design ordinates of two Wigley variants (not on scale)

1 Experiments

A lack of published experimental data on the amplitude dependent nonlinearities of bending moments exists. Dalzell [1,2] studied this phenomenon already in 1964 but these experimental results have just been presented in the form of bending moments in sagging and hogging condition, not providing information about the individual harmonic components. The goal of this new set of experiments was to obtain a systematic series of data on the amplitude dependency of vertical ship responses in head waves. The attention was focussed on the first three harmonics of the bending moments and shear forces in the midship cross section and the cross section at a quarter length from the bow as well as of the heave and pitch motion and the force in longitudinal direction. Two hull forms have been tested, i.e. a standard Wigley hull form with main characteristics L = 2.5 m, L/T = 18 and L/B = 7. The second hull form was a Wigley hull form with the same underwater geometry but with additional bow flare, see figure 1. Table 1 shows the test program.

The relevance of taking into account nonlinear effects is clearly shown by looking at the time records resulting from these experiments. Figure 2 shows

Experiment	Model	Performed
Wave force measurements	Original Wigley 8 sections	Yes
Wave force measurements	Wigley with bowflare 8 sections	Not yet
Forced vertical oscillations	Original Wigley 8 sections	Yes
Forced vertical oscillations	Wigley with bowflare 8 sections	Not yet
Measurement of motions, bending moments and shear forces in head waves	Original Wigley 3 sections	Not yet
Wave force measurements		
Measurement of motions, bending moments and shear forces in head waves	Wigley with bowflare 3 sections	Yes

Table 1: Towing tank test program

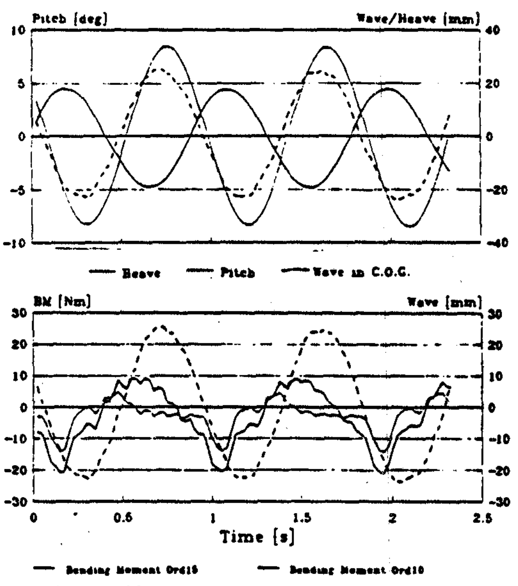

Figure 2: Fragment of recorded signals for (a) motions and wave and (b) vertical bending moments for the Wigley with bow flare

a part of the recorded signals in regular waves at the peak frequency of the relative motion transfer function at the bow in a wave with steepness $H/\lambda \approx 0.014$. The waves and motions show a very regular sine-like response while the bending moments are strongly effected by higher harmonic components.

The relative importance of the nonlinear components in the various recorded signals can be shown by plotting the magnitude of the the nonlinear Fourier components divided by the magnitude of the first harmonic for a certain wave steepness. Figure 3 shows these ratios for the bending moments at midship and at a quarter length from the bow. Similar plots for the motion responses have been prepared too, these plots showed peaks in the curves up to 9% for the pitch motion and only 5% in case of heave.

From these considerations it has to be concluded that it is not allowed to assume the nonlinearities in the bending moments to be weak. The origin of this very strong nonlinear behaviour is the large amplitude relative motion.

2 Mathematical Model

In many 'fully nonlinear' methods a weak nonlinear behaviour is assumed. As was shown by the experimental results, this assumption is certainly not valid in case of the bending moment responses. The aim of the mathematical model described below is to predict the nonlinear loads 'sufficiently accurate enough' in order to be able to make approximations of long term distribution functions or to use the model in probabilistic ship design.

The specific nonlinear phenomenon of interest, i.e. the nonlinear bending moments, especially occurs in slender vessels (experience) sailing in head and bow waves. For those type of vessels the excitation forces are highly dominated by the pressure

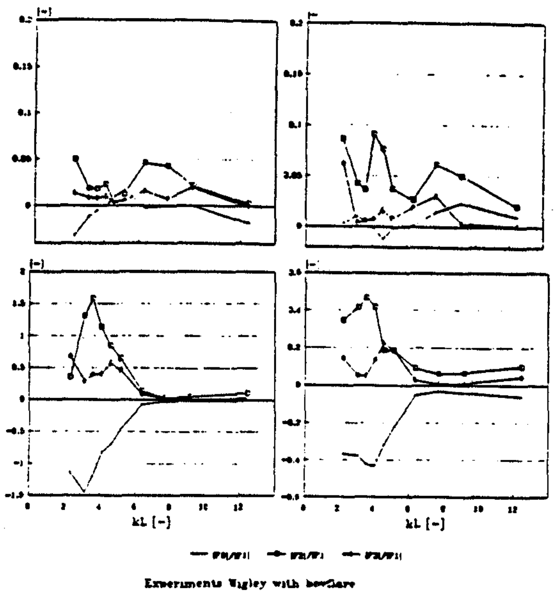

Figure 3: Relative contribution of nonlinear components for $H/\lambda = 0.02$ in (a) heave, (b) pitch, (c) midship bending moment and (d) bending moment at a quarter length from the bow

in the undisturbed waves or the so-called Froude-Kriloff pressure. The magnitude of the pressure due to the diffracted waves will be much smaller than the magnitude of the pressure in the undisturbed waves, which is the result of the incident wave potentials in combination with the hydrostatic pressure. In terms of 'orders', the magnitude of the first order Froude-Kriloff pressure is a first order quantity, while the magnitude of the first order diffracted and radiated wave pressure can be considered as a 'one-and-a-half' order quantity, implying that it is smaller in magnitude than the first order Froude-Kriloff-pressure but larger than the second order Froude-Kriloff pressure.

The easiest way to deal with the main contribution causing the nonlinear effects, i.e. the integral of the pressure in the undisturbed waves over the instantaneous wetted surface, is in a time domain model.

The instantaneous wetted surface is defined by the body in its actual position in the undisturbed waves.

First order contributions from the radiated and diffracted waves have been incorporated in the form

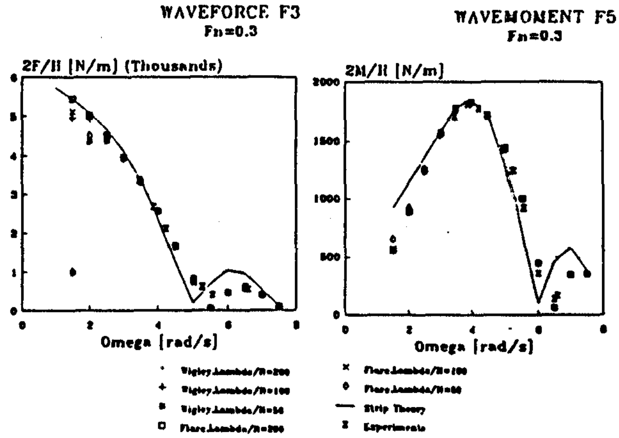

Figure 4: Wave forces and moments from experiments and simulations

of impulse-response functions as was used before in different time domain models [3,4,5]. The frequency domain results have been calculated with a 3D panel program.

The Salvesen-Tuck-Faltinsen-forward speed formulations have been used which has proven to be very valuable in ship motion predictions.

3 Comparison with Experiments

Results of wave force measurements and simulations in steep waves are shown in figure 4. It can be seen that the numerical results hardly show any difference for the Wigley with and without flare. In these figures the response amplitude has been defined as (maximum-minimum)/wave height. The experiments have been performed in the waves with different steepnesses up to the highest possible wave regarding the model's freeboard.

Motion responses for both Wigley hull forms are shown in figure 5. It appeared that the motions are stronly linear in the wave amplitude, in the experiments as well as in the simulations.

An example of a vertical bending moment transferfunction is shown in figure 6. From the simulations a strong nonlinear behaviour is found for the internal loads, especially for the Wigley with bow flare. A comparison between the nonlinear components of the midship bending moments is shown in figure 7.

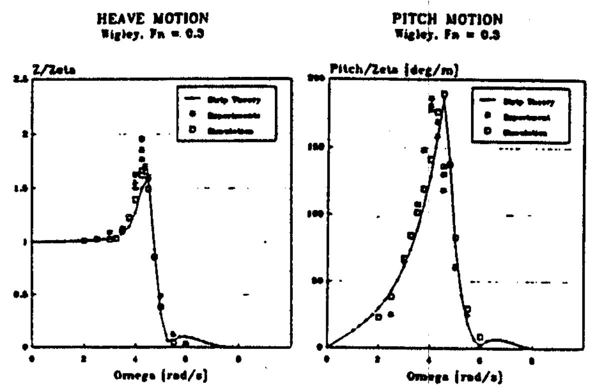

Figure 5: Motion responses from experiments and simulations

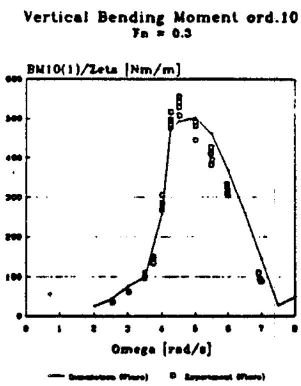

Figure 6: First order midship bending moment

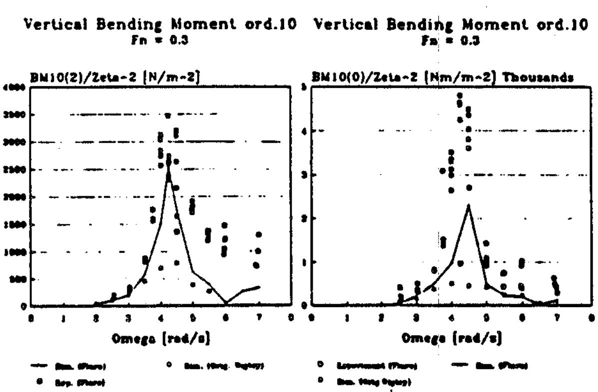

Figure 7: Mean and double-frequency midship bending moment

4 Conclusions

From the experiments it appears that the nonlinearities in the bending moment responses can not considered to be weak. Therefor nonlinear methods have to be used in order to calculate the bending moments, especially when the relative motions are large compared to the draught of the vessel.

The only possible way to solve this problem numerically seems to be in the time domain. In this stadium a large amplitude strip method has been developed, only taking into account the nonlinear Froude-Kriloff force. This approach resulted in satisfactory first order motion and bending moment predictions. An underestimation of the higher harmonics is obtained in case of the internal loads. For that reason the code will be extended with a large amplitude contribution from the radiation and diffraction potentials.

References

[1] J.F. Dalzell. *An investigation of midship bending moments experienced in extreme regular waves by a Mariner-type ship and three variants.* Technical Report SSC-155, Ship Structure Committee, 1964.

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