Some Aspects of Hull-Girder Responses of Ships in Severe Waves

by

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Abstract

Ever since the work of St. Denis and Pierson [1], the superposition technique has been routinely applied to probabilistic predictions of ship motions and wave loads. Strictly speaking, the technique is applicable only for linear, stationary systems. But external forces, restoring forces, damping, and resultant loads on an actual ship all depend on the hull shape and the amplitude of motion, and are therefore generally nonlinear unless the motion amplitudes are sufficiently small. We would expect that the approximate boundary conditions assumed to hold at mean water level in linear theory would become increasingly untenable with increasing motion amplitude. But how severe must the wave conditions be for linear theory to become too inaccurate to be of practical use? The best and perhaps the only way to deal with this question and to determine the fluid- and structural dynamic effects in extreme sea conditions is model testing. Dalzell [2] provides experimental evidence that linear theory provides a good first approximation to extremal events. Nevertheless, evidence such as shown in Fig. 1 [3] throws some doubts on the validity of straightforward application of linear potential theory to steep waves. In linear theory, the gain factor of a transfer function is independent of wave steepness. But the most important consideration for design purposes is the extremal event, which would occur in steep waves. We have therefore decided that more attention needs to be paid to the responses of ships in severe waves.

As part of our investigation, we have conducted a towing-tank test with a frigate model in severe waves. The objective of this paper is to present some notable features of the test data obtained so far, the analysis of which is still on-going. The results should be of interest to the researchers in determining the reasonable limits for the applicability of linear theory.

In our test, the self-propelled 1/20-scale model of a frigate was run in regular head waves with steepness (H/λ) ranging from 1/50 to 1/15, where H is the wave height, and wavelength (λ) from $0.5L$ to $1.6L$ (model length L = 6.225 m). Experimental determination of the transfer function requires that the excitation (i.e. incident waves) be as close to sinusoidal as possible. Herein lies the first difficulty. As Fig. 2 shows, wave forms increasingly deviate from those of sine waves as wave steepness increases. Figure 3 shows the time history of the vertical bending moment (VBM) amidships measured in a run in head waves of Fig. 2. We observed that even at this modest speed of Froude number Fn = 0.12, the model motions were so severe that at every encounter of wave the bow emerged out of water completely and in its subsequent descent, the fore deck submerged completely into a wave crest, resulting in substantial shipment of green water. Note that the whipping seen in Fig. 3 was set off not by bottom slamming but by bow-flare impact: for a particular frigate hull studied, the whipping can be attributed almost entirely to the bow-flare impact (the effect of the bottom slamming is practically nonexistent) and the green water on the foredeck tends to reduce the extreme (sagging) moment: see Fig. 4. This aspect of the theoretical work is dealt in [3]. Some of the transfer functions shown in Fig. 1 were measured in extreme conditions where such nonlinear and nonstationary phenomena as slamming and shipment of green water occurred. When we consider all these facts, the meaning of the comparison such as Fig. 1 appears questionable.

The power spectral densities (PSD's) of the incident wave (Fig. 2) and midship VBM (Fig. 3) are shown in Fig. 5. The frequency of encounter (f_e) is 0.58 Hz. Notice the appearances of the peaks at $2f_e$ and $3f_e$ in the VBM spectra. The PSD at $2f_e$ is 10.4 percent of that at f_e. The peak at 5.3 Hz corresponds to 2-node vibration of the hull girder. Though small, this peak in the PSD represents the prominent high-frequency oscillations superimposed on the low-frequency wave-induced oscillation in Fig. 3. The appearances of the peaks at $2f_e$ and $3f_e$ in the VBM spectra (Fig. 5b) may be construed as an indication of the hull girder behaving as a nonlinear oscillator in this range of strong excitation. Its characteristics are suggestive of the type of nonlinear restoring force represented by Duffing's equation. It appears that the proper treatment of extremal loads on the hull girder would require that we consider the hydroelastic nature of the phenomenon; that is, the mutual interaction of the hull and the fluid motions instead of hydrodynamic loads and structural responses separately.

It therefore appears that simulation of nonlinear systems is better handled in the time domain than in the frequency domain. The surge of interest in recent years in the development of time-domain codes for ship motions and wave loads reflects a logical trend. Even in the time domain, however, modeling of severe ship motions is very difficult. For example, sample output of DREA's two-dimensional time-domain code for nonlinear ship motions and wave loads, is shown in Fig. 6. The code, SLAP1, calculates nonlinear Froude-Krylov forces and nonlinear hydrodynamic inertia and damping forces in each time step for the instantaneous wetted portion of the hull (assumed rigid) below the undisturbed incident wave (the effect of the diffraction on the wave profile is neglected). For regular head waves of steepness 1/30 and wavelength $1.19L$ at $Fn = 0.05$, the power spectra of input incident wave and predicted midship VBM are shown in Fig. 6. As it stands, SLAP1 breaks down when the motion becomes too severe. The wave conditions for Fig. 6 appear to be more or less the limiting conditions. Improvements to SLAP1 is in progress.

The present results only underscore the difficulty of the nonlinear ship-motion and wave-loads problems. The task is so complicated that much work needs to be done.

References

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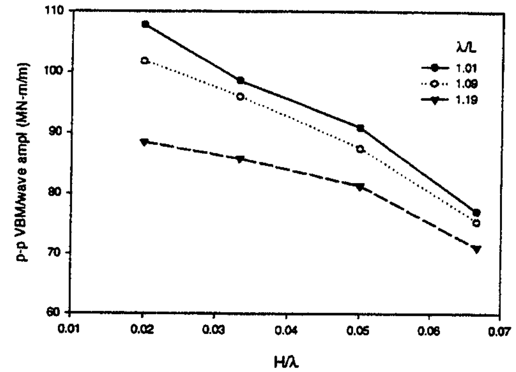

FIG. 1. Ratio of measured peak-to-peak VBM amidships to wave amplitude as a function of wave steepness in head waves. *Fn* = 0.12.

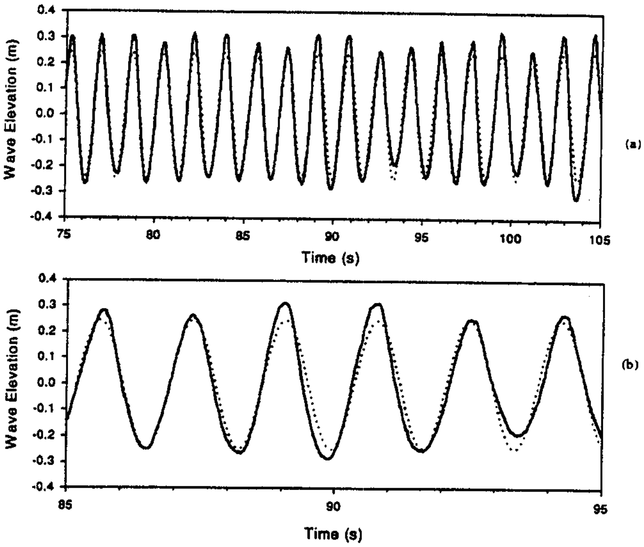

FIG. 2. Wave elevation measured by a probe attached to carriage moving at 0.944 m/s (*Fn* = 0.12).
Legend: —— measured; ..... intended sine wave (nominal frequency 0.459 Hz ($\lambda/L = 1.19$), amplitude 0.247 m, H/λ = 1/15). (b) is an expanded view of (a).

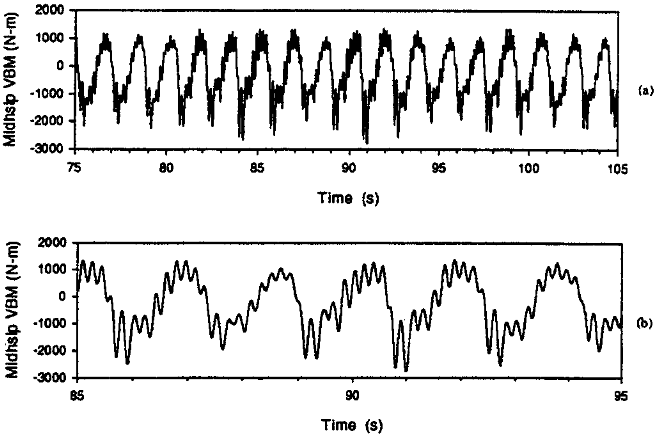

FIG. 3. Time history of measured VBM amidships in head waves of Fig. 2. *Fn* = 0.12: (b) is an expanded view of (a). The negative value indicates sagging moment.

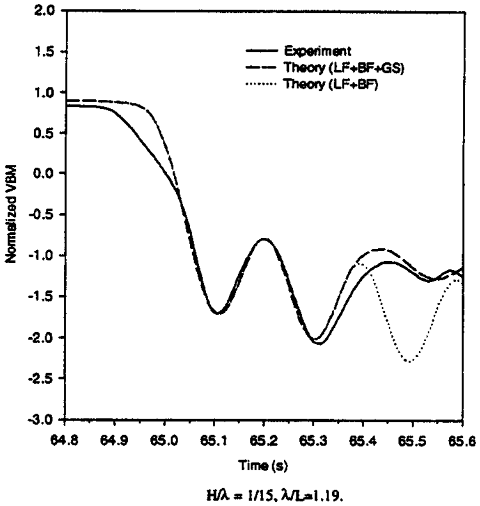

FIG. 4. Predicted and measured midship VBMs related to whipping (after [3]). Legend: (LF) low-frequency wave-induced VBM; (BF) bow-flare impact induced VBM; (GS) green-sea induced VBM.

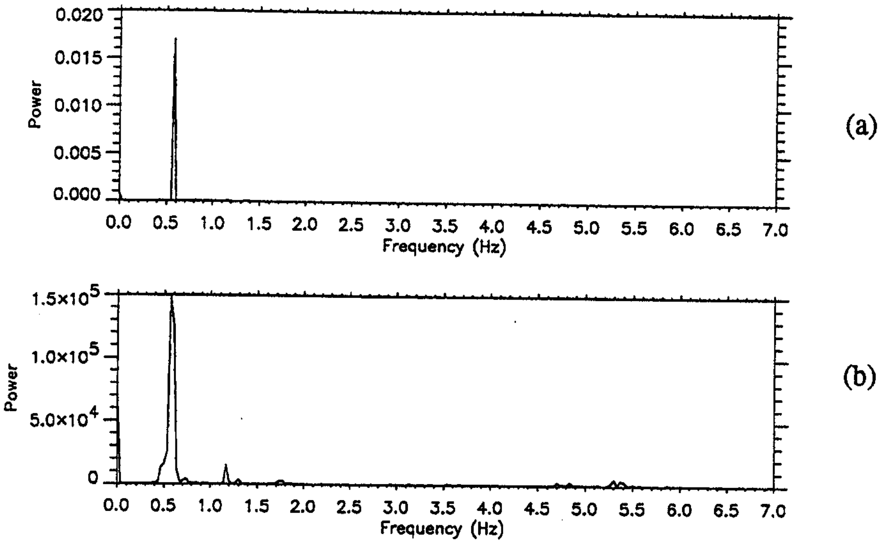

FIG. 5. Power spectral densities of (a) encountered wave and (b) midship VBM: $H / \lambda = 1/15$, $\lambda / L = 1.19$, $Fn = 0.12$.

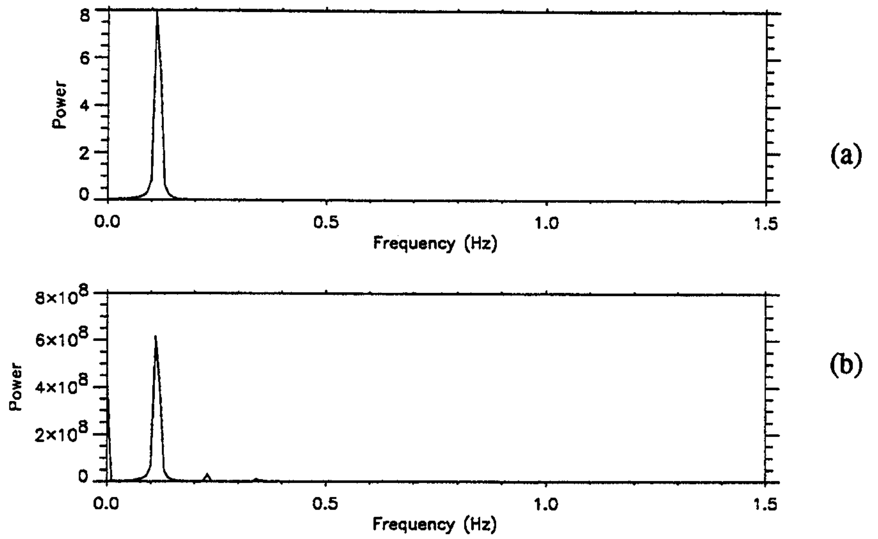

FIG. 6. Power spectral densities of (a) input encountered wave and (b) midship VBM predicted by 2D time-domain code SLAP1: $H / \lambda = 1/30$, $\lambda / L = 1.19$, $Fn = 0.05$.