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TITLE

Applying the TFE Analysis to Validate the Software WAVELOAD

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Applying the TFE Analysis to Validate the Software *WAVELOAD*

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ABSTRACT

A frequency-domain computer program *WAVELOAD* based on the three-dimensional panel-method has been developed to predict ship motions, wave loads, and hydrodynamic pressures. Numerical validation was carried out using the data from model tests of a destroyer and an ore carrier. The total factor error (TFE) was used as an index of correlation of predicted and measured transfer functions. The TFE analysis was also applied to the predictions by other computer programs, *PRECAL* and *SHIPMO7*. The results have shown that *WAVELOAD* is a reliable software package for sea-load predictions.

1. INTRODUCTION

The prediction of ship motions, sea loads, and hydrodynamic pressures over a ship hull is an essential component of ship design. An important use of such data is to provide accurate inputs for the finite-element structural analysis of ship hulls. Based on the three-dimensional panel-method, *WAVELOAD* was developed at Dalhousie University to predict ship motions, sea loads, and hydrodynamic pressure distributions over a ship hull in the frequency domain.

As part of code development, experimental validation based on the total-factor-error (TFE) analysis[1] of *WAVELOAD* was carried out. The TFE analysis was adopted here to overcome the shortcomings of the conventional method of code validation based on visual evaluation. The total factor error is an index of correlation between the predicted and measured transfer functions. This study demonstrated that, by examining TFE values, one could assess not only the degree of correlation between predicted and measured transfer functions quantitatively, but also the reliability of the experimental data as well. The TFE analysis was also applied to the predictions of two other computer programs, *PRECAL*[2] and *SHIPMO7*[3]. Like *WAVELOAD*, *PRECAL* is also a three-dimensional panel-method code in the frequency domain, but *SHIPMO7* is a strip-theory code. Details of the theoretical background are in references [4] and [5].

The analysis in this study was limited to the case of a destroyer model advancing in regular head waves because no other sets of comprehensive experimental data for hull-pressure transfer functions were available. The analysis was also applied to an ore carrier. However, not enough test data of the ore carrier is available for the TFE analysis. The results have demonstrated that *WAVELOAD* is a reliable software package for predicting ship motions and sea loads.

2. TOTAL FACTOR ERROR

The correlation of predicted and measured transfer functions for ship motions and wave loads can be expressed by the total factor error (TFE) to eliminate the shortcomings inherent in the conventional method of code validation. In contrast to the conventional method, which is based on the visual evaluation and qualitative judgement, the TFE analysis affords an efficient, as well as objective, means of evaluating the reliability of the computer-predicted transfer functions for ship responses. A brief explanation of TFE is given below, for details please see Ref. [1].

Under the assumption of a linear relationship between ocean waves and the ship's response, the power spectral density (PSD) functions are related by:

$$S_{resp}(\omega) = |H(\omega)|^2 S(\omega) \tag{13}$$

where $S(\omega)$ and $S_{resp}(\omega)$ are the PSD's of the wave and the ship's response, respectively, and $H(\omega)$ is the transfer function for the ship's response. The wave spectral density $S(\omega)$ can be either a mathematical model (e.g. Pierson-Moskowitz, ITTC, JONSWAP, Ochi-Hubble spectra) or an actual ocean spectrum.

The following expression is used as the first step in defining the total factor error:

$$\int_0^\infty \{|\hat{H}(\omega)| - |H(\omega)|\}^2 S(\omega) d\omega \tag{14}$$

where $\hat{H}(\omega)$ is the predicted value of the transfer function and $H(\omega)$ is the experimental value. The expression (14) may be regarded as the mean square error (MSE) of the predicted transfer function relative to the wave spectrum $S(\omega)$. It gives the weighted deviation between prediction and experiment. The amount of difference is weighted by a measure of its importance in terms of the harmonic content of the wave spectrum $S(\omega)$.

For a prescribed wave spectrum and a particular set of experiment data, the values of (14) can be used to rate the relative merits of two or more sets of predictions. Since the area under the power spectrum is an important parameter in the spectral analysis, the ratio of the MSE to the area under the reference response spectrum,

$$\frac{\int_0^\infty \{|\hat{H}(\omega)| - |H(\omega)|\}^2 S(\omega) d\omega}{\int_0^\infty |H(\omega)|^2 S(\omega) d\omega} \tag{15}$$

provides a more meaningful measure of importance to the error associated with the predicted transfer function. In (15), ω ranges from 0 to infinity. The experimental values of ω, however, are limited by physical constraints: its lowest value by the water depth of the tank and the highest by the power of the wavemaker. Moreover, transfer functions are measured in experiments only at a finite set of frequencies: $\{H(\omega_i)\}$ for $\omega \in \{\omega_i\}$ and $i = 1, 2, \ldots, N$, say. So the total factor error is defined by the square root of the following expression,

$$\varepsilon^2 = \frac{\sum_{i=1}^{N} \{|\hat{H}(\omega_i)| - |H(\omega_i)|\}^2 S(\omega_i)}{\sum_{i=1}^{N} |H(\omega_i)|^2 S(\omega_i)} \tag{16}$$

as a measurement of error of the predicted transfer function. Since ε is usually a small number, it is multiplied by 100 and expressed as percentage. Obviously, the value of ε is dependent upon the number and the composition of a particular data set.

3. VALIDATION

3.1 Experimental Data for a Destroyer

The experimental data[6] are from model tests of the IROQUOIS Class destroyer. The tests were conducted at the Institute for Marine Dynamics (IMD), St. John's, Nfld. The self-propelled 9-m model was run in regular head waves of $0.25 \le \lambda / L \le 1.5$ at Froude numbers *Fn*=0.0, 0.1, 0.2, 0.29, 0.37 and 0.39. The model was free to pitch and heave, but constrained in other modes. The model was equipped with a rudder and A-brackets, but without other appendages (such as bilge keels and fins). Figure 1 shows the body plan and locations of pressure transducers. Transducers #1, #4, #6, #8, #11, #14 and #16 are located along the keel at Stations 17, 15, 13, 10, 7, 5, and 3, respectively.

3.2 Result of Calculations for the Destroyer

In this study, the model with 150 panels on the port side of the hull below the waterline was used for computation.

To examine the overall patterns of predictions and their correlation with experiments, the responses were calculated at 60 wavelengths between $0.025 \leq \lambda / L \leq 2.0$ at *Fn*=0.29. Figures 2 to 6 show typical results. In Figures 2 and 3, the predicted and measured nondimensional heave and pitch motion amplitudes and phase angles at *Fn*=0.29 are shown. The heave and pitch transfer functions predicted by *WAVELOAD* agree well with test data and those predicted by *PRECAL* and *SHIPMO7*. Figures 4 through 6 show the predicted and measured hydrodynamic pressures at three transducer locations (#2, #8 and #14). Only the predictions by *WAVELOAD* and *PRECAL* are shown since *SHIPMO7* does not compute hydrodynamic pressures. The pressures were nondimensionalized by $\rho g a$, where ρ is the density of water and g is the gravitational acceleration.

The correlation of predicted and measured responses is summarized in Tables 1 and 2 in terms of TFE's which were calculated using ITTC wave spectra at frequencies corresponding to experimental data. The numbers of data points available for the TFE analysis were 10, 12 and 12 for *Fn*=0.0, 0.29 and 0.39, respectively. In Tables 1 and 2, heave motions predicted by the three computer programs are seen to be roughly of equal accuracy, but TFE's for pitch motions are somewhat greater for *SHIPMO7* than for *WAVELOAD* and *PRECAL*. The TFE's for pressure transfer functions are generally greater than those for motion transfer functions. This is understandable, since ship motions represent an integrated effect of hydrodynamic pressures acting on the hull and so they are relatively insensitive to variations of pressures over small hull-surface areas. The fact that such exceptionally large magnitudes of TFE's as those for transducer #14 (P14) at *Fn*=0.29 and 0.39 occur for both *WAVELOAD* and *PRECAL* suggests that they are likely to be caused by the anomaly of the data rather than by the inaccuracy of the predictions per se. The TFE's calculated using ITTC wave spectra ($H_s = 3.26m$, $T_p = 9.7s$) and JONSWAP wave spectra ($H_s = 5.0m$, $T_p = 12.4s$) at *Fn*=0.20 and *Fn*=0.37 for 16 transducers are shown in Figure 7 and Figure 8, respectively.

3.3 Pressures over the Hull of an Ore Carrier Model

WAVELOAD was also applied to predict the pressure distribution over the entire hull of the ore carrier KASAGISAN-MARU[7]. The computed results were compared with the experimental data and with those based on strip theory by Kim[7]. Since there are not enough test data available, the TFE analysis is not applicable. Figure 9 shows the locations of calculated pressures at the midship section. Figures 10 to 12 present the comparison of pressures between the predictions by *WAVELOAD* and by Kim for the experimental data in bow seas at wave heading 135^0.

4. CONCLUDING REMARKS

Comparing with the experimental data obtained for a destroyer model and an ore carrier model, it has shown that *WAVELOAD* is a reliable computer program for the predictions of ship motions and hydrodynamic pressure distributions over the wetted hull. For more thorough validation of the code, the predictions for other hull forms and different wave headings need to be examined. No comprehensive measurements of hull pressures other than those used in this study are available at present. The need to conduct more model tests is apparent. This study exemplified the usefulness of the total factor error as a quantitative, objective measure of correlation between predicted and measured ship-response transfer functions. Moreover, the TFE analysis could be a useful means of providing a check on the reliability not only for theoretical predictions but also for experimental data, since an exceptionally large value of TFE may indicate possible data anomalies.

ACKNOWLEDGEMENT

The authors are grateful for the research support from the Defence Research Establishment Atlantic.

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Table 1. Total factor errors of motions and pressures based on ITTC spectrum: Sea State 4 $(H_s = 1.88m, T_p = 8.8s)$

Speed	Motions	Sea State 4		
	Pressures	WAVELOAD	PRECAL	SHIPMO7
Fn=0.0	Heave	14.2	13.9	17.1
	Pitch	8.8	7.7	13.5
	P-2	11.6	14.7	
	P-8	17.3	17.1	
	P-14	38.2	38.5	
Fn=0.29	Heave	26	23.2	20.9
	Pitch	5.9	5.3	8.7
	P-2	13.7	15.2	
	P-8	66.2	13.8	
	P-14	472.5	125.7	
Fn=0.39	Heave	13	15.1	10.5
	Pitch	10.9	11.3	10.9
	P-2	22.1	29	
	P-8	98.3	58.3	
	P-14	328.2	284.1	

Table 2. Total factor errors of motions and pressures based on ITTC wave spectrum: Sea State 7 $(H_s = 7.5m, T_p = 15s)$

Speed	Motions	Sea State 7		
	Pressures	WAVELOAD	PRECAL	SHIPMO7
Fn=0.0	Heave	8.8	8.6	11.6
	Pitch	6	4.3	11.3
	P-2	13.6	17.9	
	P-8	28.5	27.4	
	P-14	62.1	63.2	
Fn=0.29	Heave	25.2	23.3	20.4
	Pitch	5.5	3.6	8.4
	P-2	19.9	21.7	
	P-8	47.2	20.4	
	P-14	320.8	109	
Fn=0.39	Heave	14.5	16.2	11.4
	Pitch	7.8	7.6	11
	P-2	22.2	32.5	
	P-8	77.6	45.5	
	P-14	264.8	195.4	

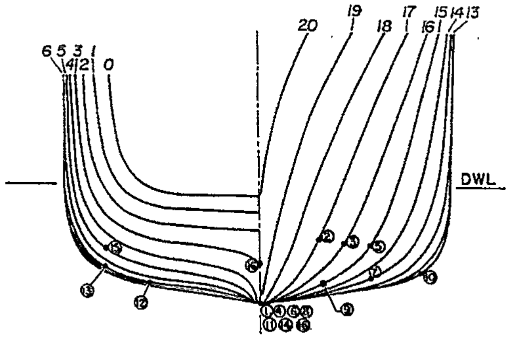

Figure 1. Body plan and locations of pressure transducers

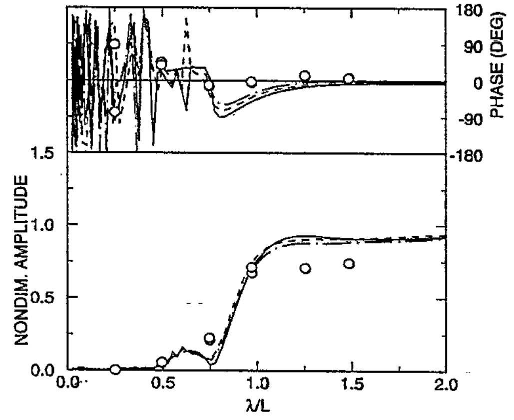

Figure 2. Comparison of measured and predicted heave motions at Fn=0.29. Symbols:
(— WAVELOAD; --- PRECAL;
—·— SHIPMO7; o experiment)

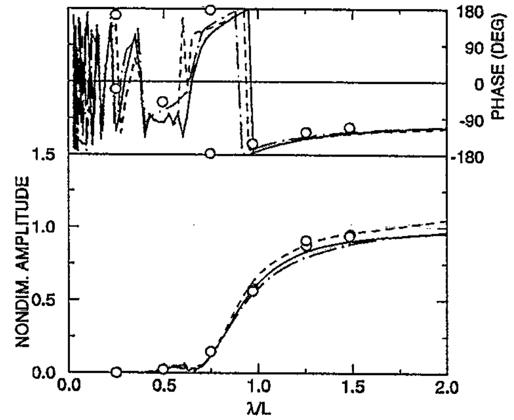

Figure 3. Comparison of measured and predicted pitch motions at Fn=0.29. For symbols, see Fig. 2

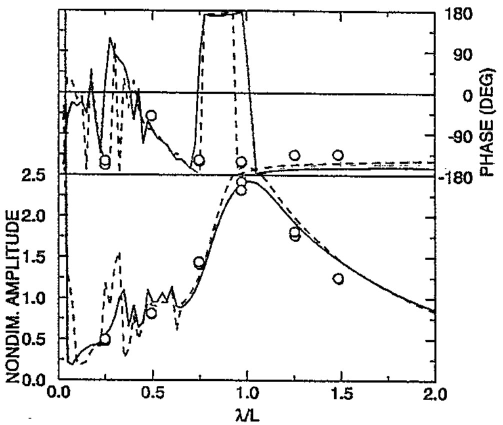

Figure 4. Comparison of measured and predicted hydrodynamic pressure on transducer #2 at Fn=0.29. Symbols: (— WAVELOAD; --- PRECAL; o experiment)

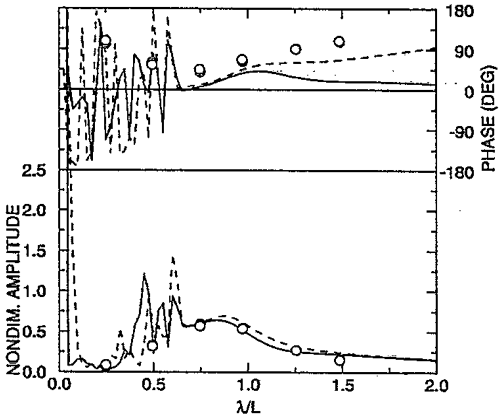

Figure 5. Comparison of measured and predicted hydrodynamic pressure on transducer #8 at Fn=0.29. For symbols, see Fig. 4.

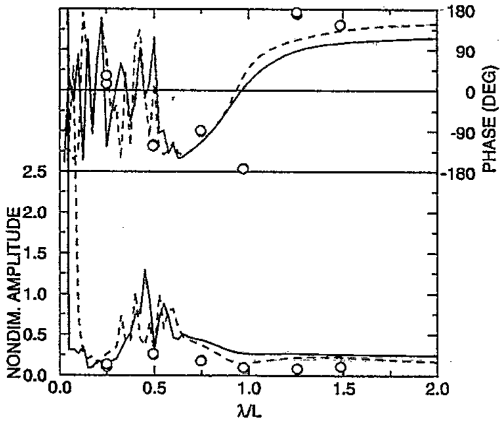

Figure 6. Comparison of measured and predicted hydrodynamic pressure on transducer #14 at Fn=0.29. For symbols, see Fig. 4.

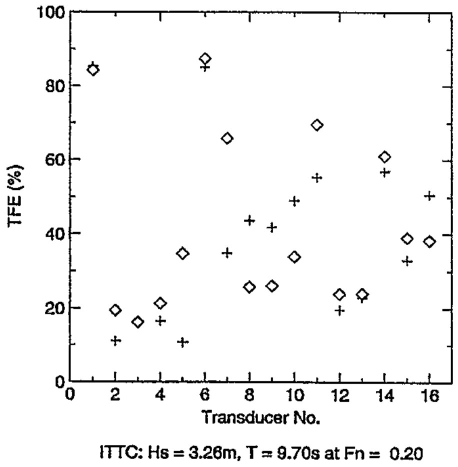

Figure 7. TFE's of WAVELOAD (◊) and PRECAL (+) at 16 transducer locations by using ITTC wave spectra

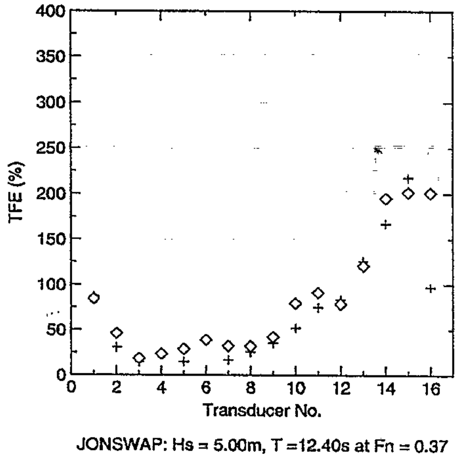

Figure 8. TFE's of WAVELOAD (◊) and PRECAL (+) at 16 transducer locations by using JONSWAP wave spectra

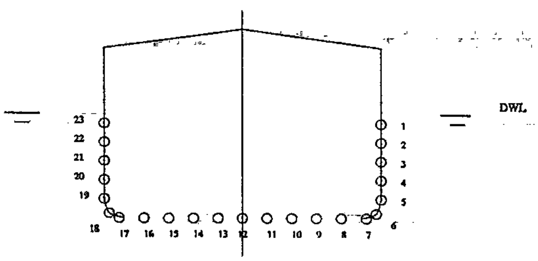

Figure 9. Locations of computed pressures for the ore-carrier

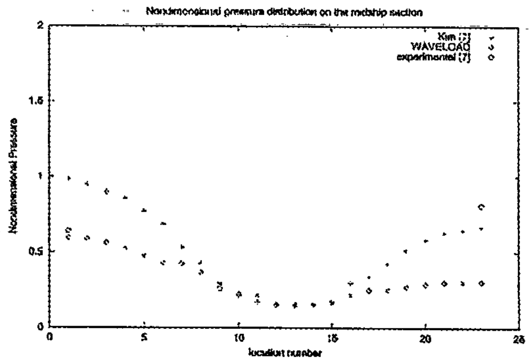

Figure 10. Comparison of pressures at 23 locations on midship section of the ore-carrier at $\lambda / L = 1.25$, Fn=0.0792 and heading 135^0

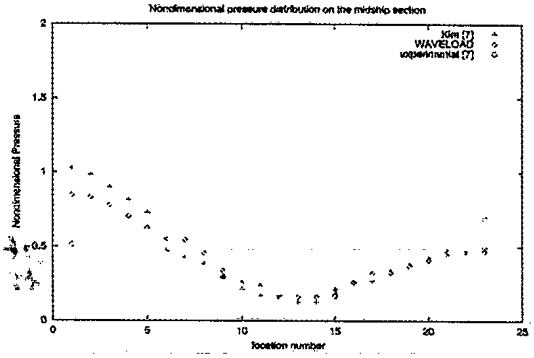

Figure 11. Comparison of pressures at 23 locations on midship section of the ore-carrier at $\lambda / L = 1.0$, Fn=0.0643 and heading 135^0

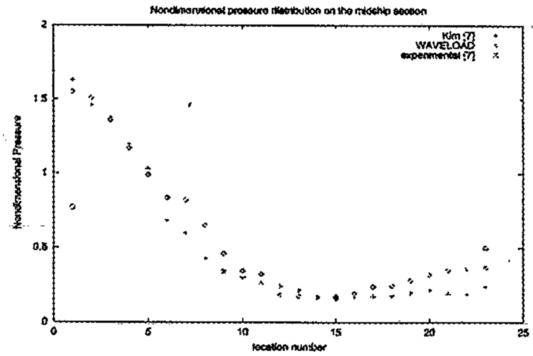

Figure 12. Comparison of pressures at 23 locations on midship section of the ore-carrier at $\lambda / L = 0.75$, Fn=0.0414 and heading 135^0

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