TITLE

Validation of WAVELOAD, a 3-D Frequency-Domain Computer Program for Ship Motions and Hull Pressures

Validation of WAVELOAD, a 3-D Frequency-Domain Computer Program for Ship Motions and Hull Pressures

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ABSTRACT

The prediction of ship motions, sea loads, and hydrodynamic pressure distributions over a ship hull is an essential component of ship structural design. The immediate goal is to provide accurate hull pressure input for the finite-element structural analysis. To this end, 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. The purpose of this paper is to describe the theoretical background of WAVELOAD and its experimental validation using the data from model tests with a destroyer model in head seas. The total factor error (TFE) was used as an index of correlation of predicted and measured transfer functions. The TFE analysis was applied to the predictions by the other computer programs, PRECAL and SHIPMO7, as well as to those by WAVELOAD. The results showed 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 the Center for Marine Vessel Development and Research (CMVDR) 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 analysis[1] of WAVELOAD was carried out. Total-factor-error analysis was adopted here to overcome the shortcomings of the conventional method of code validation based on the visual evaluation. The total factor error (TFE) 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. SHIPMO7 is a strip-theory code. 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 results have demonstrated that WAVELOAD is a reliable software package for predicting ship motions and sea loads.

In this paper, the theoretical background of WAVELOAD is first described briefly. The total factor error analysis is then outlined. The experimental validation and comparison with the other two programs are presented.

2. THEORETIC BACKGROUND

It is assumed that the fluid is inviscid and incompressible and the flow is irrotational, and that the ship is a rigid body with steady forward speed in regular waves and it oscillates harmonically in time about its mean position. The free-surface condition has been linearized to the calm water surface. Based on the linear potential theory, the flow field will be a superposition of steady flow, incident waves, diffracted waves and radiated waves. The total velocity potential in the flow field can be expressed as

$$\Phi_T(x,y,z;t) = -Ux + \phi_s(x,y,z) + \Phi(x,y,z;t) \qquad (1)$$

where $-Ux$ is the velocity potential of uniform flow; $\phi_s(x,y,z)$ is the steady disturbance potential. The steady flow potential can be expressed as

$$\Phi_s = -Ux + \phi_s(x,y,z) \qquad (2)$$

$\Phi(x,y,z;t)$ is the unsteady velocity potential which can be written as

$$\begin{aligned}\Phi(x,y,z;t) &= \Phi_I + \Phi_D + \Phi_R \\ &= (\phi_I(x,y,z) + \phi_D(x,y,z) + \phi_R(x,y,z))e^{-i\omega_e t}\end{aligned} \qquad (3)$$

where Φ_I, Φ_D and Φ_R are the velocity potential of incident waves, diffracted waves and radiated waves, respectively. The steady flow potential is solved by the double-body flow method. The radiated and diffracted potentials are obtained by employing the zero-speed Green's function.

The steady flow effect to the radiated waves can be represented by m-terms[4], which are defined as

$$\begin{aligned}(m_1,m_2,m_3) &= -(\vec{n}\cdot\nabla)\vec{W} = -(\vec{n}\cdot\nabla)\nabla\Phi_s \\ &= -(n_1\Phi_{sxx} + n_2\Phi_{sxy} + n_3\Phi_{sxz}, \\ &\qquad n_1\Phi_{syx} + n_2\Phi_{syy} + n_3\Phi_{syz}, \\ &\qquad n_1\Phi_{szx} + n_2\Phi_{szy} + n_3\Phi_{szz}) \\ (m_4,m_5,m_6) &= \vec{r}_g \times (m_1,m_2,m_3) - \vec{n}\times\nabla\Phi_s \\ &= \vec{r}_g \times (m_1,m_2,m_3) + (n_3\Phi_{sy} - n_2\Phi_{sz}, \\ &\qquad n_1\Phi_{sz} - n_3\Phi_{sx}, n_2\Phi_{sx} - n_1\Phi_{sy})\end{aligned} \qquad (4)$$

where $\vec{r}_g = (x-x_g, y-y_g, z-z_g)$ is the position vector from the center of gravity of the ship to a point (x,y,z) on the hull surface, and

$$\vec{W} = \nabla\Phi_s \qquad (5)$$

The m-terms can be computed directly from the computed Φ_s[5]. A special numerical scheme is devised to compute m-terms. Based on the rational Gaussian surface theory [6], the disturbance potential at any point of the hull can be written as

$$\Phi_s(x,y,z) = \sum_{i=1}^{n} V_i g_i(x,y,z) \qquad (6)$$

where n is the number of panels, V_i is the interpolation parameter for the ith point, and the interpolation function $g_i(x,y,z)$ is given by

$$g_i(x,y,z) = \frac{w_i \bar{g}_i(x,y,z)}{\sum_{j=1}^{n} w_j \bar{g}_j(x,y,z)} \qquad (7)$$

with

$$\begin{aligned}\bar{g}_i(x,y,z) = \exp\{-[(x-x_i)^2 + (y-y_i)^2 \\ + (z-z_i)^2]/(2\sigma^2)\}\end{aligned} \qquad (8)$$

In (7) and (8), w and σ are the weighting factor and deviation, respectively. Since $g_i(x,y,z)$ is differentiable, the first- and second-order derivatives of $\Phi_s(x,y,z)$ can be obtained accurately from the computed potential on each panel.

The hydrodynamic forces acting on a ship can be obtained from

$$F_j = \iint_S p n_j ds, \text{ for } j=1,2,\ldots 6 \qquad (9)$$

where S is the mean wetted hull surface, n_j is the generalized unit normal, and p is the hydrodynamic pressure acting on the ship hull,

$$p = -\rho\left(\frac{\partial\Phi}{\partial t} + \vec{W}\cdot\nabla\Phi\right) \qquad (10)$$

The ship motion equations can be set up as

$$\sum_{k=1}^{6}[-\omega_e^2(m_{jk}+\mu_{jk}) + (-i\omega_e\lambda_{jk}) + C_{jk}]\bar{x}_k = f_j \qquad (11)$$

where ω_e is the frequency of encounter, $\bar{x}_k$ is the complex motion amplitude of the kth mode, m_{jk} is the mass matrix, μ_{jk} is the added mass matrix, λ_{jk} is the damping matrix, C_{jk} is the restoring force coefficient matrix, and f_j is the wave exciting force.

The hydrodynamic pressure due to the incident, diffracted and radiated waves is obtained as

$$\begin{aligned} p_{hd} = \rho[& i\omega_e(\phi_I+\phi_D) + \vec{W}\cdot\nabla(\phi_I+\phi_D) + \\ & \omega_e^2\sum_{k=1}^{6}\bar{x}_k\phi_k - i\omega_e\sum_{k=1}^{6}\bar{x}_k(\vec{W}\cdot\nabla\phi_k)] \end{aligned} \qquad (12)$$

As the ship oscillatory motions cause hydrostatic pressure fluctuation, the complex amplitude of the fluctuation is also considered here. The wave loads on a specified cross-section X_C can be obtained by direct integration of the hydrodynamic pressure and hydrostatic pressure increment over the wetted hull surface forward of the cross-section X_C plus the inertial forces of ship mass forward of X_C [5].

3. TOTAL-FACTOR-ERROR ANALYSIS

The correlation of predicted and measured transfer functions for ship motions and wave loads can be expressed by the total factor error (TFE)[1] to eliminate the shortcomings inherent in the conventional method of code validation. In contrast to the latter, which is based on the visual evaluation and qualitative judgement, the total-factor-error 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, see [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:

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

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 square of the absolute value of the transfer function, $|H(\omega)|^2$, is often called the response amplitude operator (RAO). The wave spectral density $S(\omega)$ can be either a mathematical model (the Pierson-Moskowitz, ITTC, JONSWAP, Ochi-Hubble, etc.) or an actual ocean spectrum.

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

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

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,

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

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 $i = 1, 2, ..., N$, say. So the total factor error is defined by the square root of the following expression,

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

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.

4. VALIDATION

4.1 Experimental Data

The experimental data[7] are from model tests with a model 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 no other appendages (such as bilge keels, fins). Table 1 gives the particulars of the ship and the model. 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.

4.2 Result of Calculations

Reference [5] shows that the predicted heave and pitch transfer functions are essentially independent on the number of panels. In addition, it shows that merely increasing the number of panels in a geometric model does not necessarily lead to more accurate predictions of hydrodynamic pressures. In this study, the geometry model with 150 panels on the port side of the hull below the waterline was used for computation.

To examine the overall patterns of the predictions and their correlation with experiments, the responses were calculated at 60 wavelengths between $0.025 \le \lambda / L \le 2.0$ at *Fn*=0.0, 0.29 and 0.39. Figures 2 to 8 show the typical results. In Figs. 2, 3 and 4, predicted and measured heave and pitch motion amplitudes and the phase angles at *Fn*=0.29 and 0.39 are shown. Amplitudes of the heave- and pitch-motions were nondimensionalized by the amplitude a of the incident wave and the wave slope $k_0 a$, respectively, where $k_0 = \omega_0^2 / g$ is the wavenumber, and ω_0 is the incident wave frequency. The heave and pitch transfer functions predicted by WAVELOAD agree well with test data and those predicted by PRECAL and SHIPMO7. Figures 5 through 8 show predicted and measured hydrodynamic pressures at three transducer locations (#2, #8 and #14) for the two speeds. Only the predictions by WAVELOAD and PRECAL are shown; SHIPMO7 cannot predict 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 2 and 3 in terms of the total factor errors. TFE's in these tables were calculated using an ITTC wave spectrum at frequencies corresponding to experimental data. The numbers of data points available for the total-factor-error analysis were 10, 12 and 12 for *Fn*=0.0, 0.29 and 0.39, respectively. For the spectral parameters, the following values were used as representatives of two sea states: $H_S = 1.88\,\text{m}$, $T_P = 8.8\,\text{s}$ (Sea State 4) and $H_S = 7.5\,\text{m}$, $T_P = 15\,\text{s}$ (Sea State 7). In Tables 2 and 3, heave motions predicted by the three computer programs are seen to be roughly of equal accuracy, but TFE's for pitch motions are somewhat larger for SHIPMO7 than for WAVELOAD and PRECAL. The TFE's for pressure transfer functions are generally larger 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.

5. CONCLUDING REMARKS

Comparisons with the experimental data obtained with a destroyer model in head seas in this study showed 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 wave directions need to be examined; nevertheless, 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 (TFE) as a quantitative, objective measure of correlation between predicted and measured ship-response transfer functions. Moreover, the TFE was shown to be a useful means of providing a check on the reliability, not only of theoretical predictions, but also of experimental data. since an exceptionally large value of TFE can indicate possible data anomalies.

ACKNOWLEDGEMENT

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REFERENCES

1. Ando, S., "Quantification of Correlation of Predicted and Measured Transfer Functions for Ship Motions and Wave Loads", *RINA Int'l Conf. on Ship Motions & Maneuverability*, Feb. 18-19, 1998, London.
2. Huijsmans, R. *et al.*, "PRECAL V2.0, User's Manual", Maritime Research Institute, Netherlands, May 1997.
3. McTaggart, K. A., "SHIPMO7 – An Updated Strip Theory Program for Predicting Ship Motions and Sea Loads in Waves", DREA Technical Memorandum 96/243, March 1997.
4. Newman, J. N., "The Theory of Ship Motion", *Advances in Applied Mechanics*, Vol. 18, 1978.
5. Qiu, W. and Hsiung, C. C., "Theoretical Manual for WAVELOAD version 1.0 - a Computer Program for Predictions of Ship Motions and Hydrodynamic Pressure Distribution and Sea Loads", CMVDR Technical Report NAP-1999-01, January 1999.
6. Goshtasby, A., "Design and Recovery of 2-D and 3-D Shapes Using Rational Gaussian Curves and Surfaces", *Int. J. of Computer Vision*, Vol. 10, No.3, 1993.
7. Ando, S. and Cumming, D., "Measurement of Motions and Hydrodynamic Pressures on the Hull of a Model of a Destroyer in Regular Head Waves", DREA Technical Memorandum 92/210, March 1992.
8. Qiu, W. and Hsiung, C. C., "Validation of WAVELOAD Version 1.0 for the Case of a Destroyer in Regular Head Waves", CMVDR Technical Report, December 1998.

Table 1. Particulars of ship and model

	Ship	Model
Scale ratio	1	1/13.479
Length, Lpp	121.3 m	900 cm
Beam, B	15.22 m	112.9 cm
Draft,T	4.73 m	35.1 cm
Volume of displacement	4552 m^3	1.859 m^3
Block coefficient	0.52	0.52

Table 2. Total factor errors of motions and pressures based on ITTC spectrum: Sea State 4

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 3. Total factor errors of motions and pressures based on ITTC wave spectrum: Sea State 7

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	

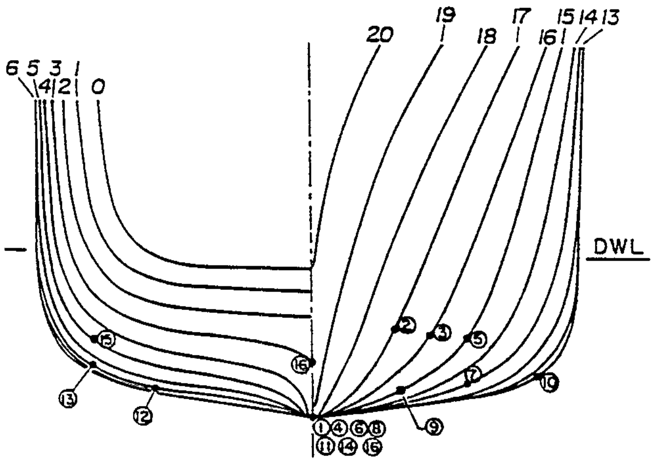

Figure 1. Body plan and locations of pressure transducers

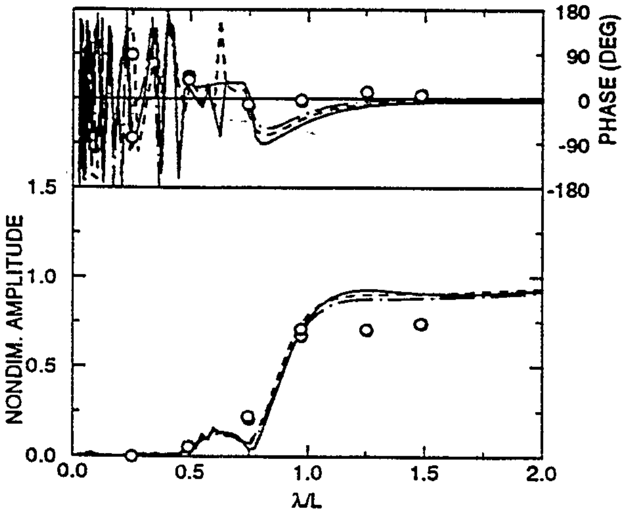

Figure 2. Comparison of measured and predicted heave motions at Fn=0.29. Symbols:
(— WAVELOAD; — PRECAL;
—·— SHIPMO7; o experiment)

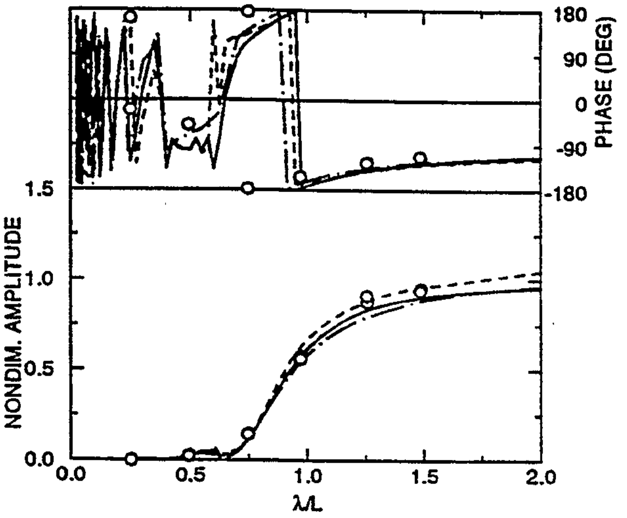

Figure 3. Comparison of measured and predicted pitch motions at Fn=0.29. For symbols, see Fig. 2.

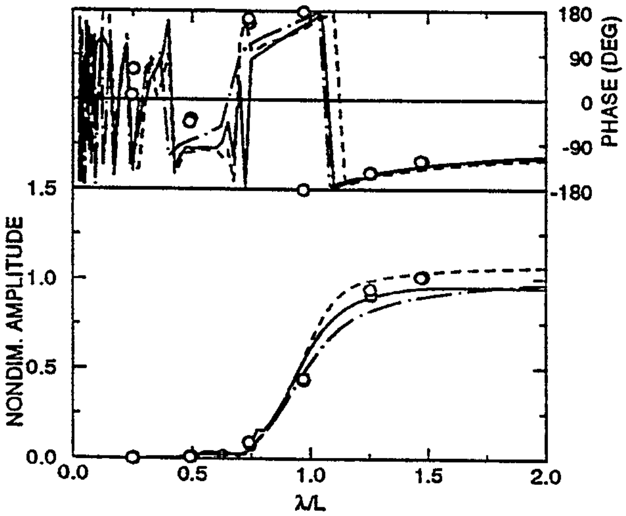

Figure 4. Comparison of measured and predicted pitch motions at Fn=0.39. For symbols, see Fig. 2.

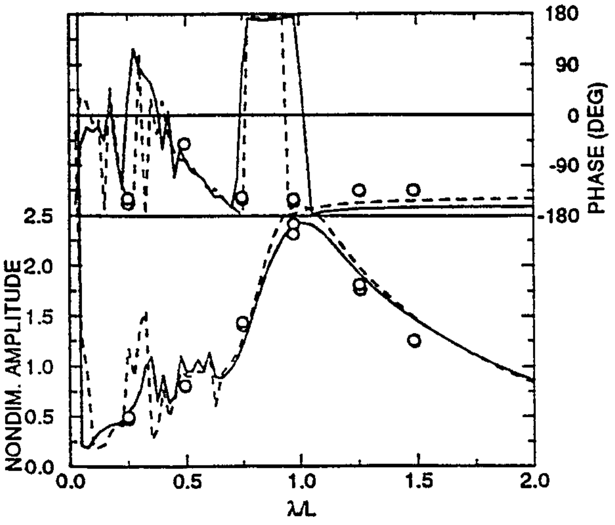

Figure 5. Comparison of measured and predicted hydrodynamic pressure on transducer #2 at Fn=0.29. Symbols: (— WAVELOAD; — PRECAL; o experiment)

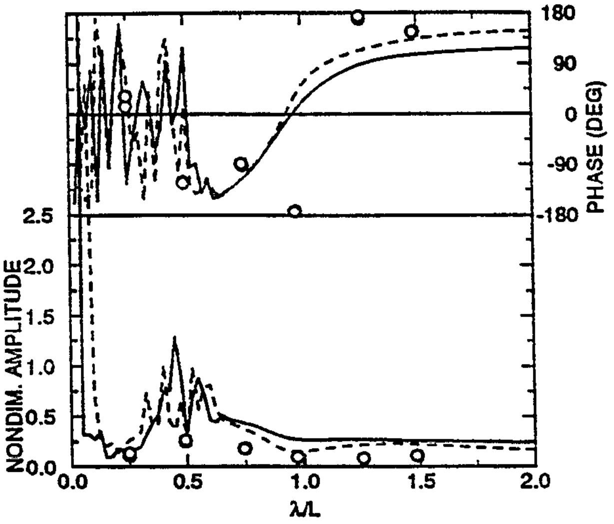

Figure 7. Comparison of measured and predicted hydrodynamic pressure on transducer #14 at Fn=0.29. For symbols, see Fig. 5.

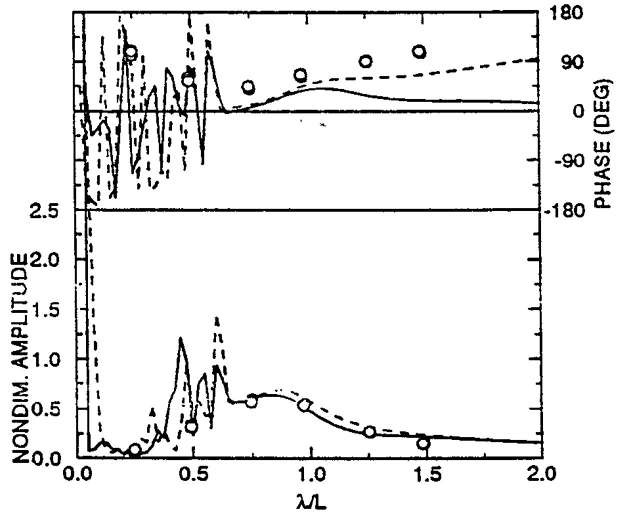

Figure 6. Comparison of measured and predicted hydrodynamic pressure on transducer #8 at Fn=0.29. For symbols, see Fig. 5.

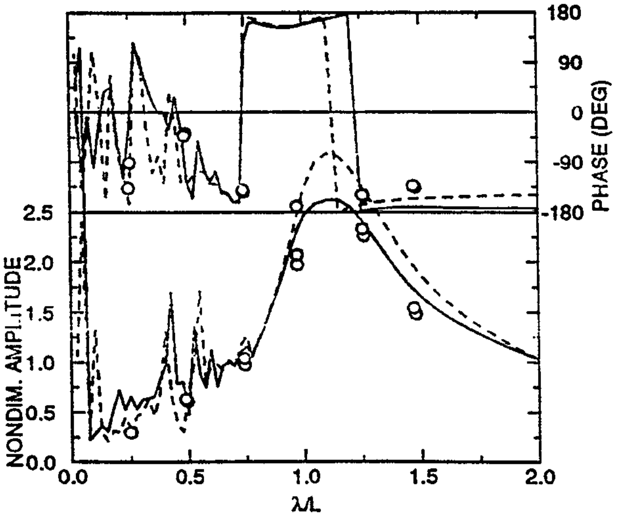

Figure 8. Comparison of measured and predicted hydrodynamic pressure on transducer #2 at Fn=0.39. For symbols, see Fig. 5.

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