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L'APPROXIMATION DU NAVIRE ELANCE: COMPARAISON DE MESURES EXPERIMENTALES ET DE PREDICTIONS NUMERIQUES

F. Noblesse, D. Hendrix et A. Barnell

David Taylor Research Center
Bethesda, MD 20084-5000 U.S.A.

RESUME

Des resultats de calculs numeriques de resistance de vagues, fonction spectre, ligne d'eau et champ de vagues sont presentes pour quatre coques de navire pour lesquelles existent des valeurs experimentales. Des applications numeriques effectuees precedemment par d'autres auteurs sont egalement examinees. L'approximation du navire elance donne des predictions numeriques comparables a celles qui peuvent etre obtenues au moyen de methodes numeriques considerablement plus complexes.

SUMMARY

THE SLENDER-SHIP APPROXIMATION: COMPARISON BETWEEN EXPERIMENTAL DATA AND NUMERICAL PREDICTIONS

Numerical predictions of wave resistance, wave spectrum, wave profiles and wave patterns obtained using the slender ship approximation are presented for four hull forms for which experimental data are available. Previous numerical applications of the slender-ship approximation by other authors are also reviewed. The slender-ship approximation yields numerical predictions that are comparable to those which can be obtained using considerably more complex numerical methods.

INTRODUCTION

Near-field potential-flow calculations about ships advancing at constant speeds in calm water are routinely required for evaluating their hydrodynamic characteristics, in calm water and in waves, and for determining the required propulsion and control devices. Calculations of far-field wave patterns are also important in connection with wave-resistance predictions and remote sensing of ship wakes.

Alternative numerical methods have been developed for evaluating near-field flow about a ship, that is, flow at the hull surface and in its vicinity. These include finite-difference methods, e.g. Coleman [2] and Miyata and Nishimura [3], and the more widely used boundary integral equation methods, also known as panel methods. The latter methods can be divided into two main groups, according to the Green function that is used. These two groups of methods are the Rankine-source method and the Neumann-Kelvin method, which are based on the simple Rankine (free-space) fundamental solution and the more complex Green function satisfying the linearized free-surface boundary condition, respectively.

The Rankine-source method was initiated by Gadd [4], Dawson [5] and Daube [6], and has since been adopted by many authors. The Neumann-Kelvin approach has a long history. A survey of recent numerical predictions obtained by a number of authors on the basis of the Neumann-Kelvin method may be found in Baar [7]. This study and that by Andrew, Baar and Price [8] also contain extensive comparisons of the authors' own Neumann-Kelvin numerical predictions with experimental data. An approximate solution, defined explicitly in terms of the value of the Froude number and the hull shape, to the Neumann-Kelvin problem was proposed in Noblesse [9]. Several numerical applications of this slender-ship approximation, by the present authors and by others, are reviewed further on in this paper.

The aforementioned alternative numerical methods for predicting flow in the vicinity of a ship are not all directly suitable for predicting the wave pattern of a ship at large, or even moderate, distances. More precisely, the finite-difference method and the Rankine-source panel method require truncating the flow domain at some relatively-small distance away from the ship and therefore can only be used for near-field flow calculations. (However, these near-field flow predictions can be used as input to a far-field Neumann-Kelvin flow representation).

On the other hand, the Neumann-Kelvin theoretical framework is equally suitable for near-field and far-field flow predictions. Indeed, the far-field Neumann-Kelvin flow representation is a simplified special case of the corresponding near-field representation. In particular, the slender-ship approximation provides an explicit representation of the flow due to a ship valid both in the near field and in the far field. More generally, a modified mathematical expression for the wave-spectrum function in the Neumann-Kelvin representation of the steady wave pattern of a ship was recently obtained in Noblesse and Lin [10]. This new expression is considerably better suited for accurate numerical evaluation than the well-known usual expression given in [9] and elsewhere.

THE SLENDER-SHIP APPROXIMATION

A hierarchy of slender-ship approximations is defined in [9]. At the simplest level is the zeroth-order approximation, which provides an explicit expression for the wave-spectrum function (and hence the wave resistance) in terms of the hull speed, length and shape. This approximation is extremely simple and may be regarded as a generalization of the classical thin-ship approximation of Michell [11]. More precisely, the zeroth-order slender-ship approximation is obtained by merely neglecting the near-field flow disturbance caused by the ship in the expression for the far-field wave-spectrum function. Thus, no integral equation is solved and no Green function is evaluated in this approximation, which is conceptually and numerically very simple.

The zeroth-order approximation can nevertheless be useful for some practical ship-design applications if properly applied, in the manner explained by Scragg et al. [12] and Letcher et al. [13]. More precisely, Scragg found that the zeroth-order approximation was inadequate for predicting the wave resistance of a given hull form but nevertheless provided quite accurate predictions of the relative differences in resistance due to hull-form modifications.

The next level of approximation is the first-order approximation, which provides an expression for the flow about a ship defined explicitly in terms of the value of the Froude number and the hull shape. This expression is valid at any point in the flow field and thus provides an approximation for the near-field flow and the far-field waves. The first-order slender-ship approximation is obtained by merely neglecting the unknown doublet-distribution term in the modified integro-differential equation for the velocity potential given in [9] and hence is defined in terms of a source-distribution alone, with density explicitly related to the hull shape; the expression for the first-order slender-ship approximation thus only involves the Green function (not its gradient), which represents a significant simplification for numerical calculations. Partial theoretical justification for this slender-ship approximation is presented in [9] and in Noblesse and Triantafyllou [14] and Noblesse [15].

The first-order slender-ship approximation can be used to determine the wave resistance by integrating the pressure on the hull as is done in [7] and [8] or by using the Havelock formula for evaluating the wave energy radiated via the trailing wave pattern, as is recommended in [9] and is done in Figure 1 in the present paper. As one would naturally expect, either of these two methods for evaluating the wave resistance using the first-order slender-ship approximation provides more realistic predictions than the extremely-simple zeroth-order approximation. In particular, Figure 1 shows that the large humps and hollows in the zeroth-order approximation are greatly attenuated in the first-order approximation.

Numerical predictions of wave resistance, sectional vertical force, sinkage and trim and pressure signature obtained using the first-order slender-ship approximation and the Neumann-Kelvin theory are presented in [7,8] for five hull forms (submerged prolate spheroid, Wigley parabolic hull, HSVA tanker, Friesland class destroyer, cruiser) for which experimental data are available. Good agreement is found among the experimental data and the numerical predictions based on the Neumann-Kelvin theory and the slender-ship approximation. In particular, the predictions obtained in [7,8] using the Neumann-Kelvin theory and the considerably simpler slender-ship approximation are consistently close to one another.

Numerical predictions obtained using twelve computer codes (five codes based on the Neumann-Kelvin theory and seven Rankine-source codes) were compared to data from model experiments for two ship hulls (a high speed destroyer-type hull with a transom stern and a tug boat) at three Froude numbers each at the Workshop on Kelvin Wake Computations [16]. Three complementary aspects of the Kelvin wake were considered for evaluating the numerical predictions, namely the wave profile along a specified longitudinal wave cut, the wave spectrum function and surface contours for the wave elevation in an area extending three ship lengths behind the sterns of the ship models. The numerical predictions were made without prior knowledge of the experimental results. The numerical predictions obtained using the first-order slender-ship approximation were found "consistently superior for both models at all speeds and in the three evaluation categories" [16, pg.13], namely wave cuts, wave spectra and contour plots. This finding is especially interesting because the slender-ship approximation is considerably simpler than the alternative calculation methods (Neumann-Kelvin and Rankine-source codes) used at the Workshop. Contour plots of the wave elevations computed using the first-order slender-ship approximation for the two specified ship models and the three specified Froude numbers are shown in Figure 5 in this present paper.

Numerical predictions obtained using the first-order slender-ship approximation are presented and compared in Figures 1, 2a-c, 3 and 4a,b in this paper for the Wigley hull and the Series 60 $C_B = 0.60$ ship model. More precisely, Figure 1 depicts the wave resistance of the Wigley hull predicted by both the zeroth-order and the first-order approximations. Figures 2a-c depict the far-field wave spectrum function $|A(\theta)|^2$ and its real and imaginary parts $C(\theta)$ and $S(\theta)$ predicted by both the zeroth- and first-order approximations for the Wigley hull at six values of the Froude number. Finally, Figures 3 and 4a,b depict the wave profiles along the Wigley hull at six values of the Froude number and along the Series 60 $C_B = 0.60$ model at twelve values of the Froude number, respectively.

Figure 1 shows that the zeroth-order and the first-order approximations to the wave resistance differ significantly. More precisely, the pronounced humps and hollows in the zeroth-order wave-resistance curve are greatly reduced in the first-order approximation, as was already noted. This attenuation of the humps and hollows in the wave-resistance curve is in accordance with the experimental data. It may be seen from Figure 2a that differences between the zeroth-order and the first-order approximations to the wave-spectrum function $|A(\theta)|^2$ are relatively insignificant for small and moderate values of θ, say for values of θ smaller than about 40°, corresponding to the long waves in the spectrum; however, the first-order approximation is significantly larger than the zeroth-order approximation for larger values of θ, corresponding to the shorter waves in the spectrum, in accordance with the experimental data. The numerical predictions and the experimental data for small and moderate values of θ are in relatively good agreement for some values of the Froude number (notably for $F = 0.250$ and $F = 0.316$) but significant discrepancies exist for other values of the Froude number; thus, there is a lack of consistency. Discrepancies between the numerical predictions and the experimental data are significantly larger in Figures 2b,c corresponding to the imaginary and real parts of the function $A(\theta)$ than in Figure 2a corresponding to the function $|A(\theta)|^2$.

The first-order slender-ship approximation to the wave profile is in better agreement with the experimental data in Figures 4a,b than in Figure 3 corresponding to the Series 60 $C_B = 0.60$ ship model and the Wigley hull, respectively. Discrepancies between the numerical predictions and the experimental data are fairly important for the Wigley hull, including a significant underprediction of the amplitude of the bow wave and an appreciable phase shift. It is interesting that Figures 6.6, 6.7 and 6.8 in Jensen [17] show similar discrepancies between the experimental wave profile along the Wigley hull and the profile computed using a Rankine-source method in which the nonlinear free-surface boundary condition is used. Figures 6.17, 6.18, 6.19 and 6.20 in [17] also show better agreement between the experimental and predicted wave profiles for the Series 60 $C_B = 0.60$ model than for the Wigley hull. The wave profiles for the Wigley hull and the Series 60 $C_B = 0.60$ model computed in [17] do not appear to be in significantly better agreement with the experimental data than those predicted using the considerably simpler slender-ship approximation and depicted in Figures 3 and 4a,b in the present paper.

CONCLUSION

A major recommendation of the first-order slender-ship approximation resides in its great simplicity. More precisely, this approximation defines the velocity potential explicitly in terms of the value of the Froude number (that is, the ship speed and length) and the hull shape. This expression for the potential is valid at any point on the hull surface and in the fluid and thus provides an explicit approximation to the near-field flow and the far-field waves. The expression for the first-order slender-ship approximation is defined in terms of a source-distribution alone, with density explicitly related to the hull shape, and thus only involves the Green function (not its gradient), which represents a significant simplification for numerical calculations.

Another important recommendation of the first-order slender-ship approximation is that it yields numerical predictions which are not necessarily inferior to those provided by considerably more complex numerical methods. Thus, the discrepancies between the experimental wave profiles along the Wigley hull and the Series 60 $C_B = 0.60$ model and the numerical profiles reported in [17] and in Figures 3 and 4a,b in the present paper are comparable. As a matter of fact, the numerical predictions obtained using the first-order slender-ship approximation were found in [16] to be consistently superior to the corresponding predictions obtained using both Neumann-Kelvin codes and Rankine-source codes. This surprising finding is likely to be due to the considerable difficulties of obtaining reliable numerical predictions using complex numerical methods. For instance, it was recently shown by Scragg and Talcott [18] that their Neumann-Kelvin numerical predictions do not converge with decreasing panel size for a hull form having flare.

The first-order slender-ship approximation thus provides a simple and efficient design tool which may be useful for a broad range of practical applications. It may also be valuable as a research tool for performing systematic numerical calculations aimed at investigating various aspects of steady free-surface flow about a ship. Finally, the slender-ship approximation provides a solid starting point for developing a more refined numerical method in which the boundary conditions at the hull surface and at the free surface are satisfied more accurately.

ACKNOWLEDGMENTS

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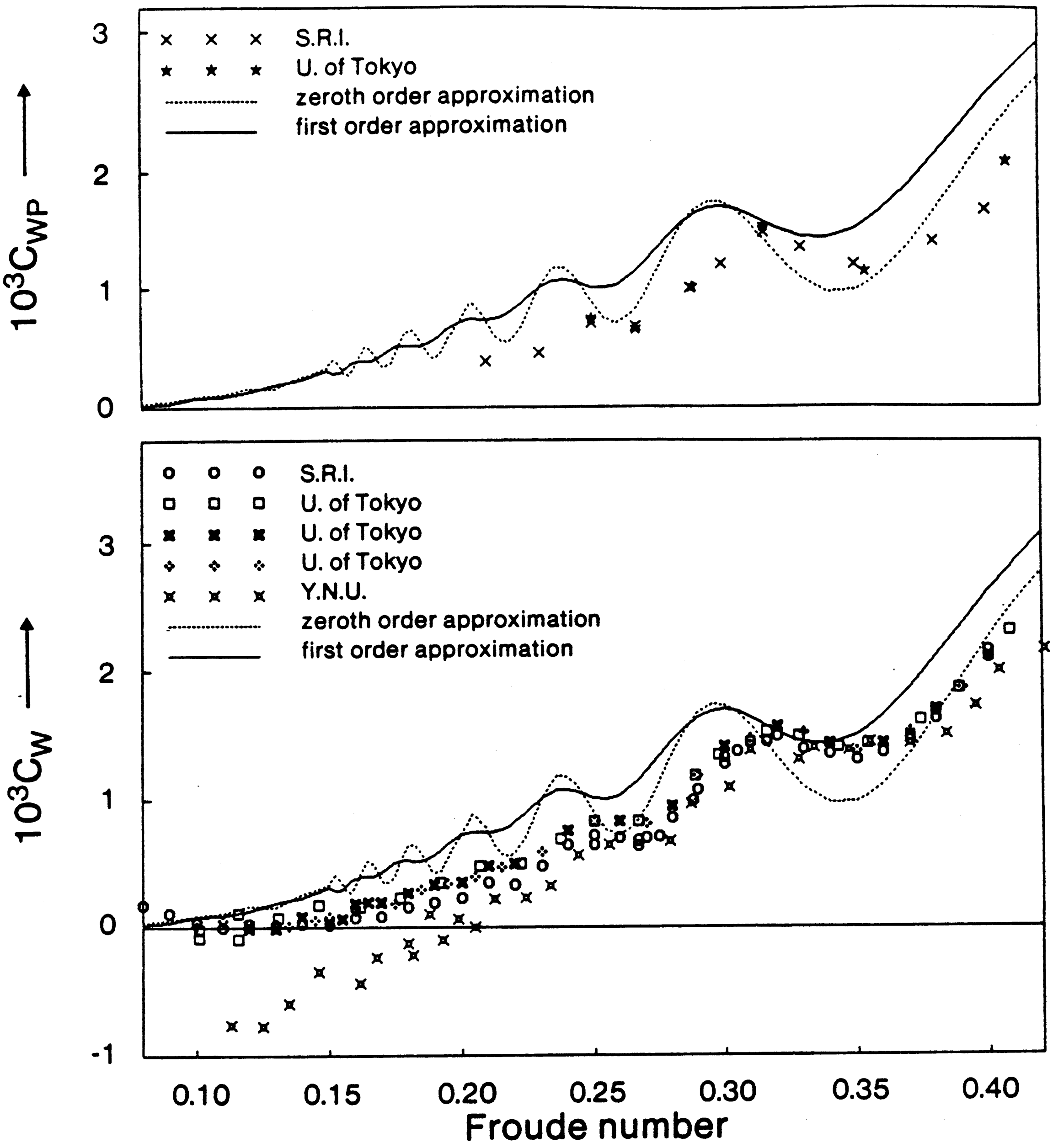


Figure 1 - Wave-resistance coefficients C_W (residuary resistance) and C_{WP} (wave pattern analysis) for the Wigley hull. The hull is held fixed (no sinkage and trim). The experimental data are those collected under the Cooperative Experimental Program of the Resistance Committee of the International Towing Tank Conference and reported in [1]. The numerical predictions correspond to the zeroth-order (dotted line) and the first-order (solid line) slender-ship approximations. The strong humps and hollows in the zeroth-order approximation are greatly attenuated in the first-order approximation.

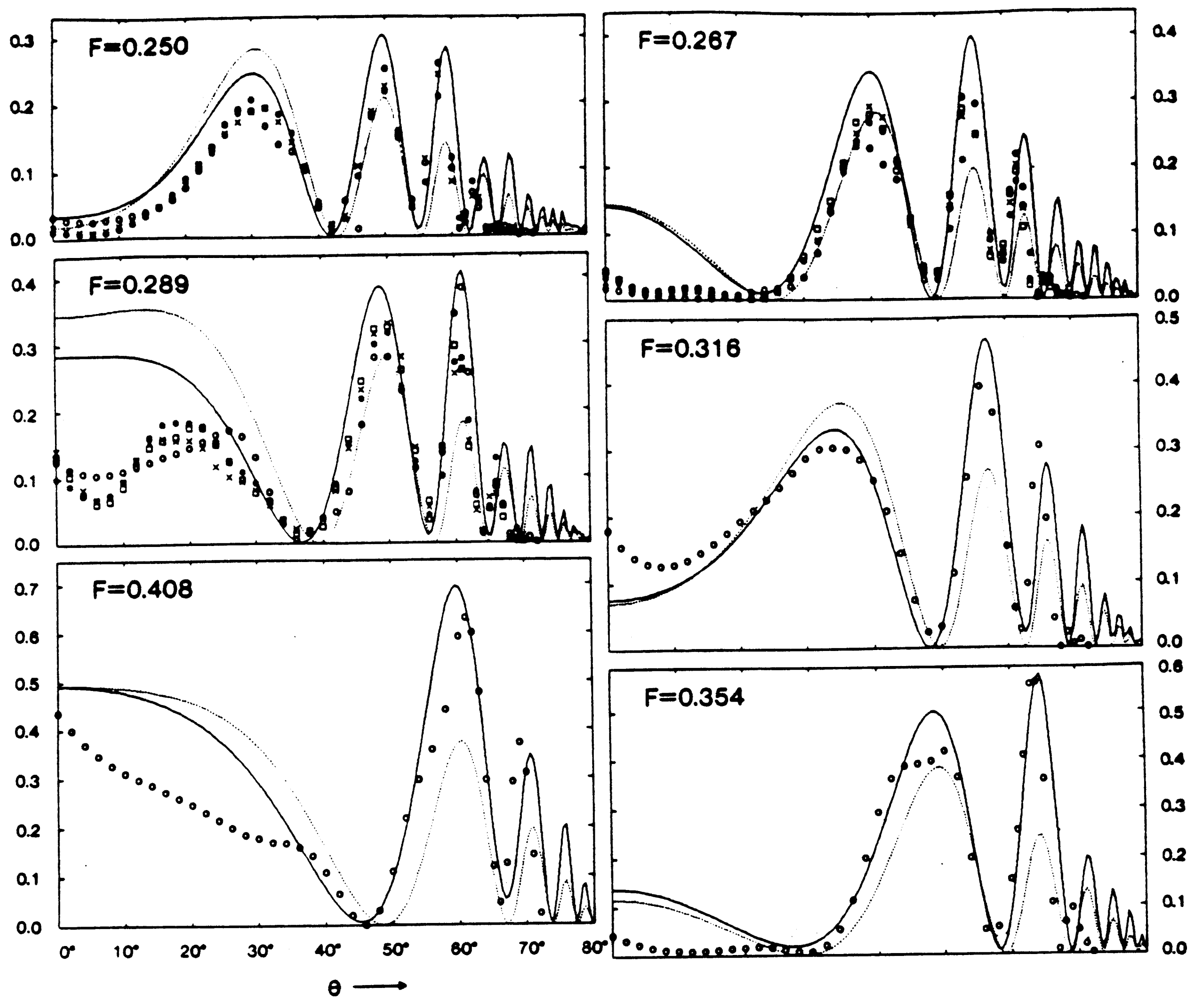
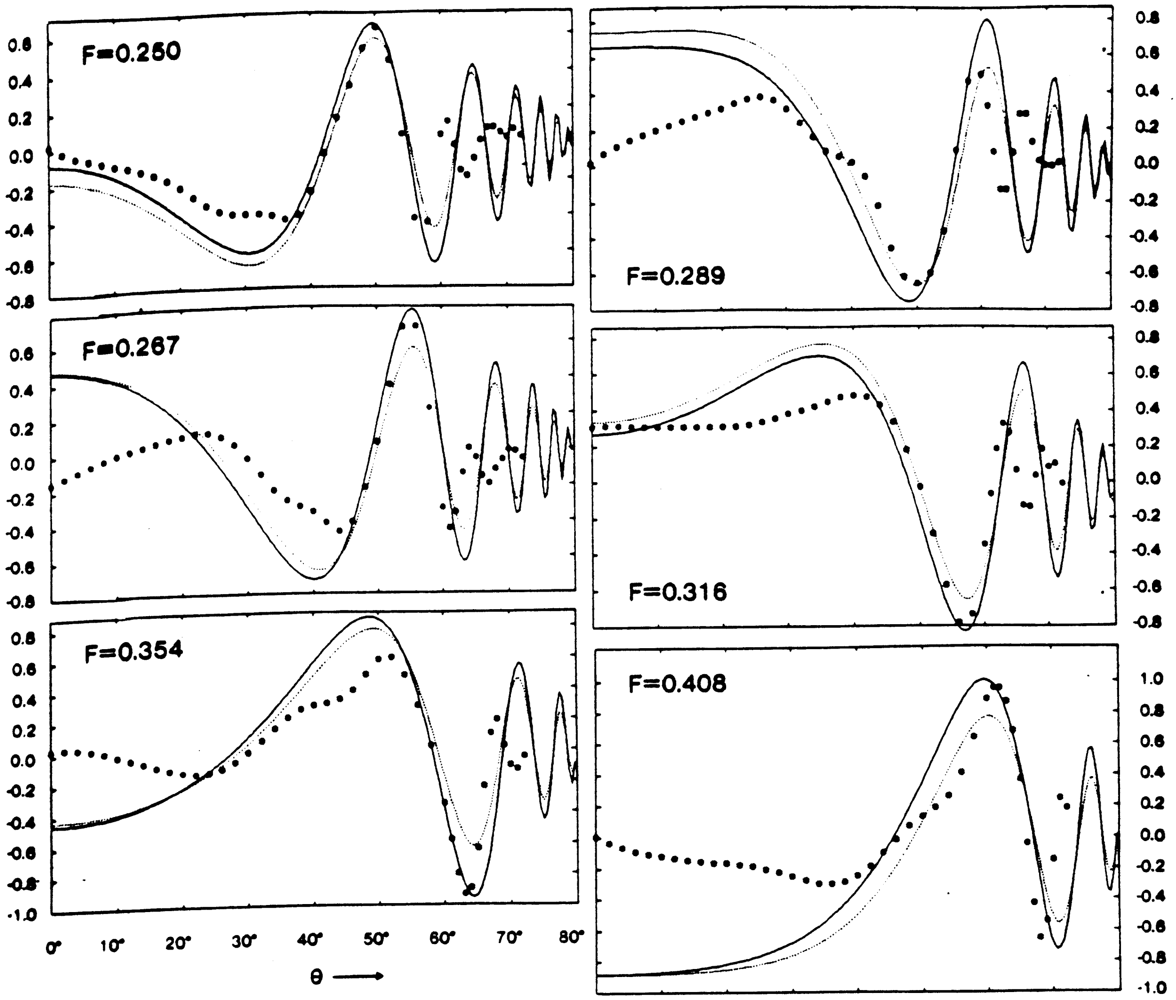


Figure 2a - The far-field wave-amplitude (spectrum) function $10^3 \mid A(\theta) \mid^2$ for the Wigley hull at 6 values of the Froude number between 0.25 and 0.408 and for values of θ between 0 and 80°.

Figure 2b - (top part of next page) - The imaginary part 10^2 S(θ) of the wave-amplitude function.

Figure 2c - (bottom of next page) - The real part 10^2 C(θ) of the wave-**amplitude** function.

In **these** three figures, the Wigley hull is held fixed (no sinkage and trim), the experimental data are those obtained at the University of Tokyo and the Ship Research Institute and reported in [1]. The numerical predictions correspond to the zeroth-order (dotted line) and first-order (solid line) slender-ship approximations. Agreement between the experimental data and the numerical predictions is significantly better for the function $\mid A(\theta) \mid^2$ than for its real and imaginary parts C(θ) and S(θ).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F=0.289
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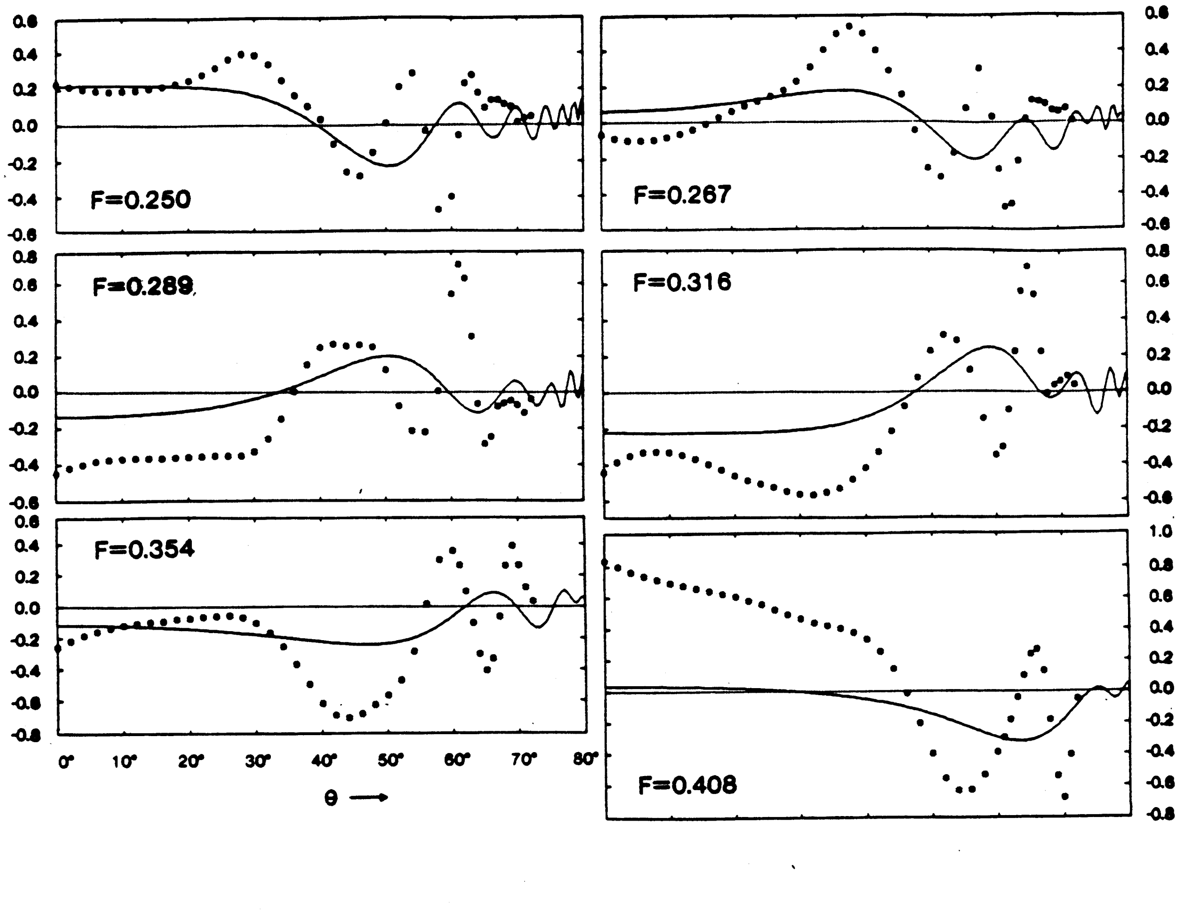
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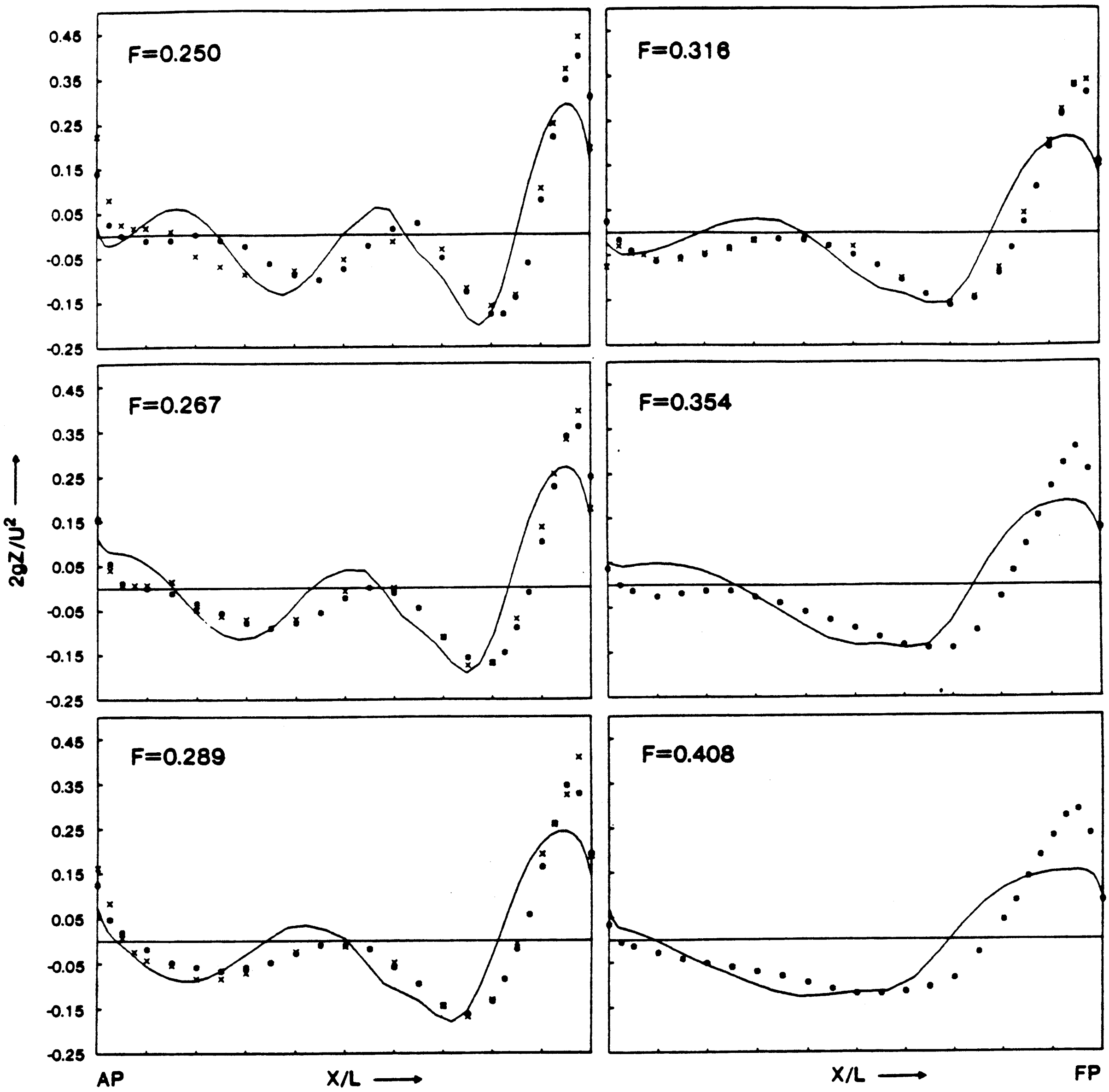

Figure 3 - Wave profiles along the Wigley hull for 6 values of the Froude number between 0.250 and 0.408. The hull is held fixed (no sinkage and trim). The experimental data are those obtained at the University of Tokyo (*) and the Ship Research Institute (x) and reported in [1]. The numerical predictions (solid line) correspond to the first-order slender ship approximation. The amplitude of the bow wave is significantly underpredicted and there is an appreciable phase shift between the experimental and theoretical wave profiles.

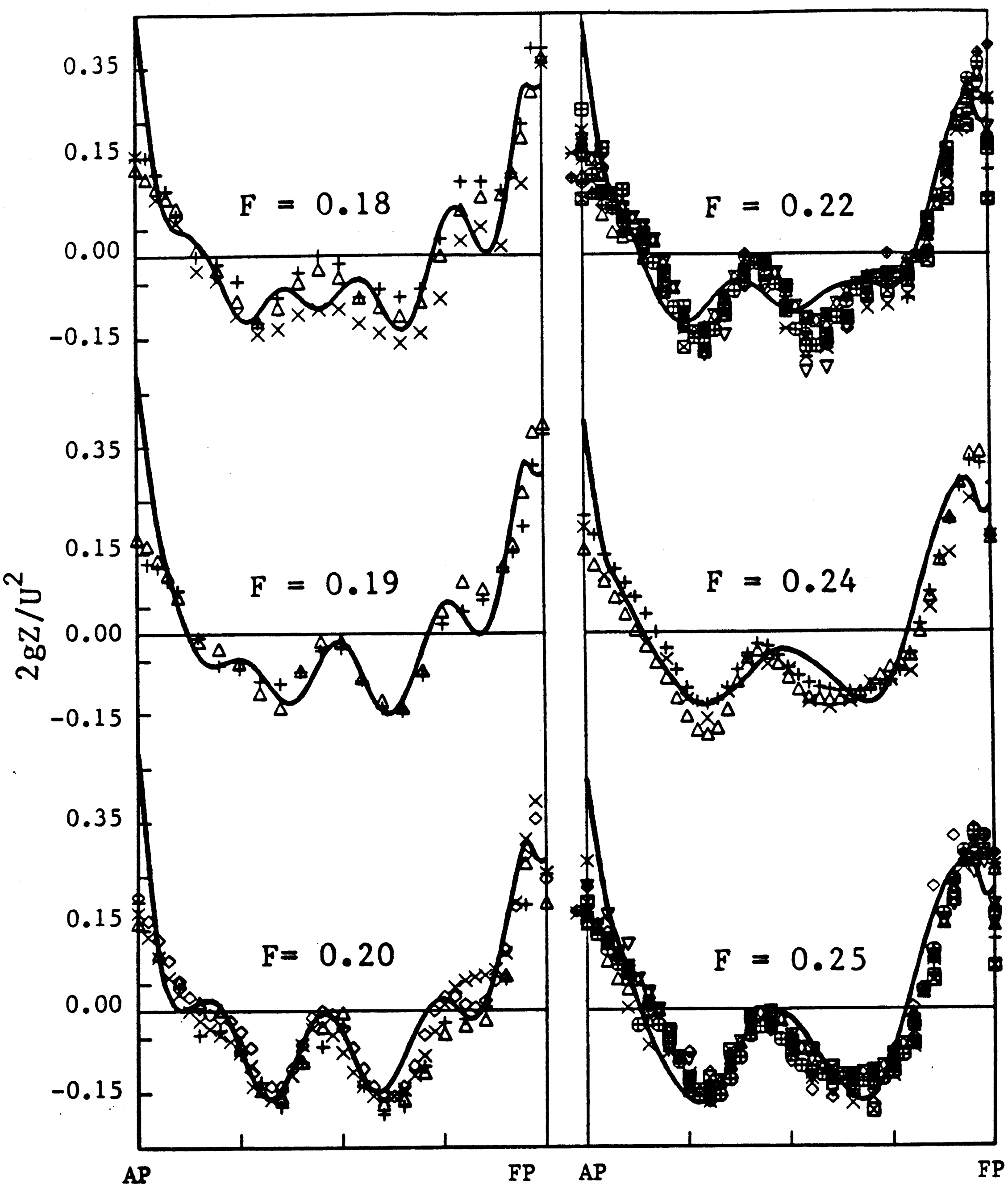

Figure 4a - Wave profiles along the Series 60 $C_B = 0.60$ hull form for 6 values of the Froude number between 0.18 and 0.25. The hull is held fixed (no sinkage and trim). The experimental data are those collected under the Cooperative Experimental Program of the Resistance Committee of the International Towing Tank Conference and reported in [1]. The numerical predictions (solid line) correspond to the first-order slender-ship approximation. Agreement between the experimental data and the numerical predictions is better for the Series 60 model than for the Wigley hull.

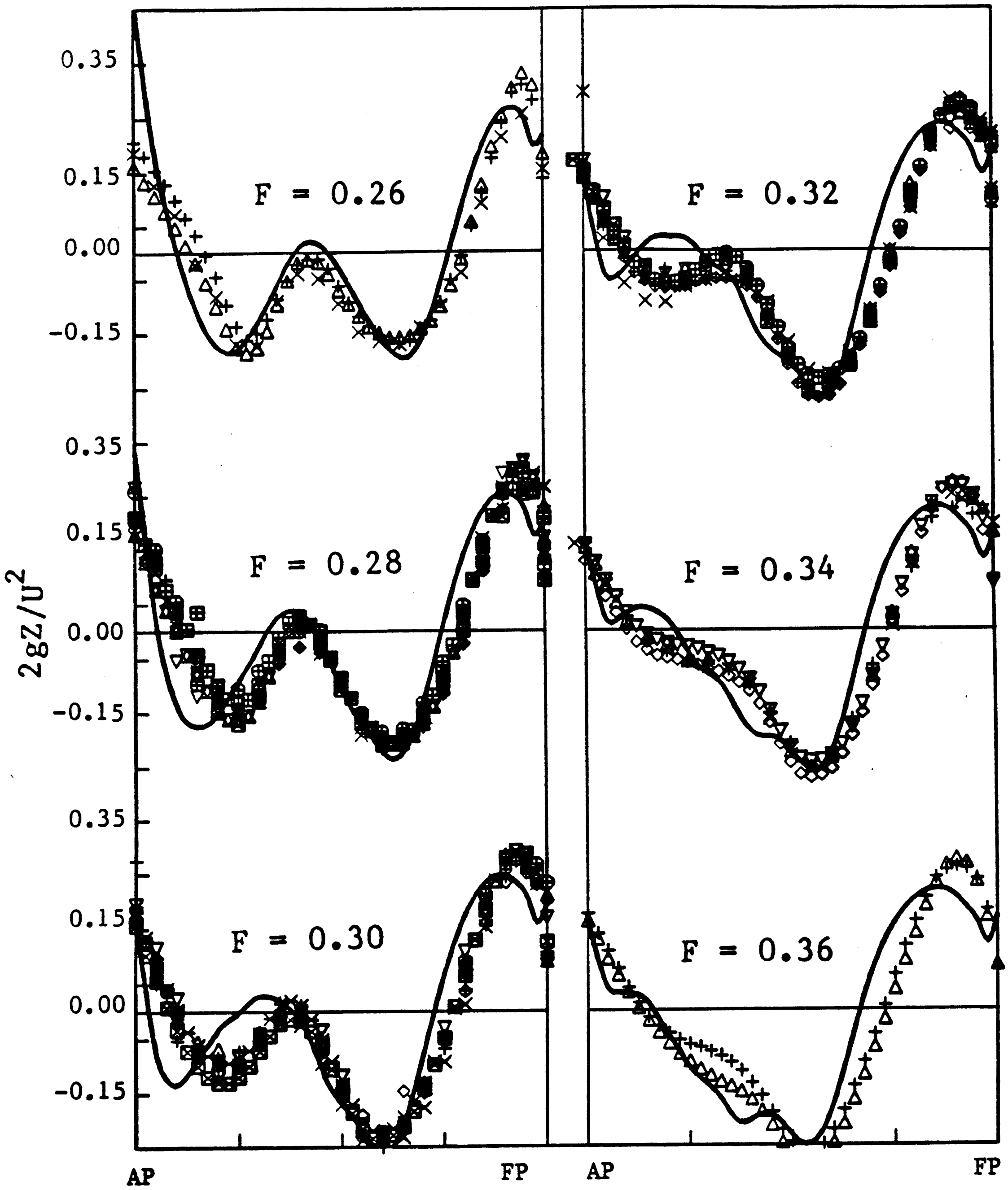

Figure 4b - Wave profiles along the Series 60 C_B = 0.60 hull form for 6 values of the Froude number between 0.26 and 0.36. See Figure 4a for further explanations.

Figure 5 - (next page) - Wave patterns computed using the first-order slender-ship approximation for the two ship models and the three values of the Froude considered at the Workshop on Kelvin Wake Computations held at DTRC in January 1988.

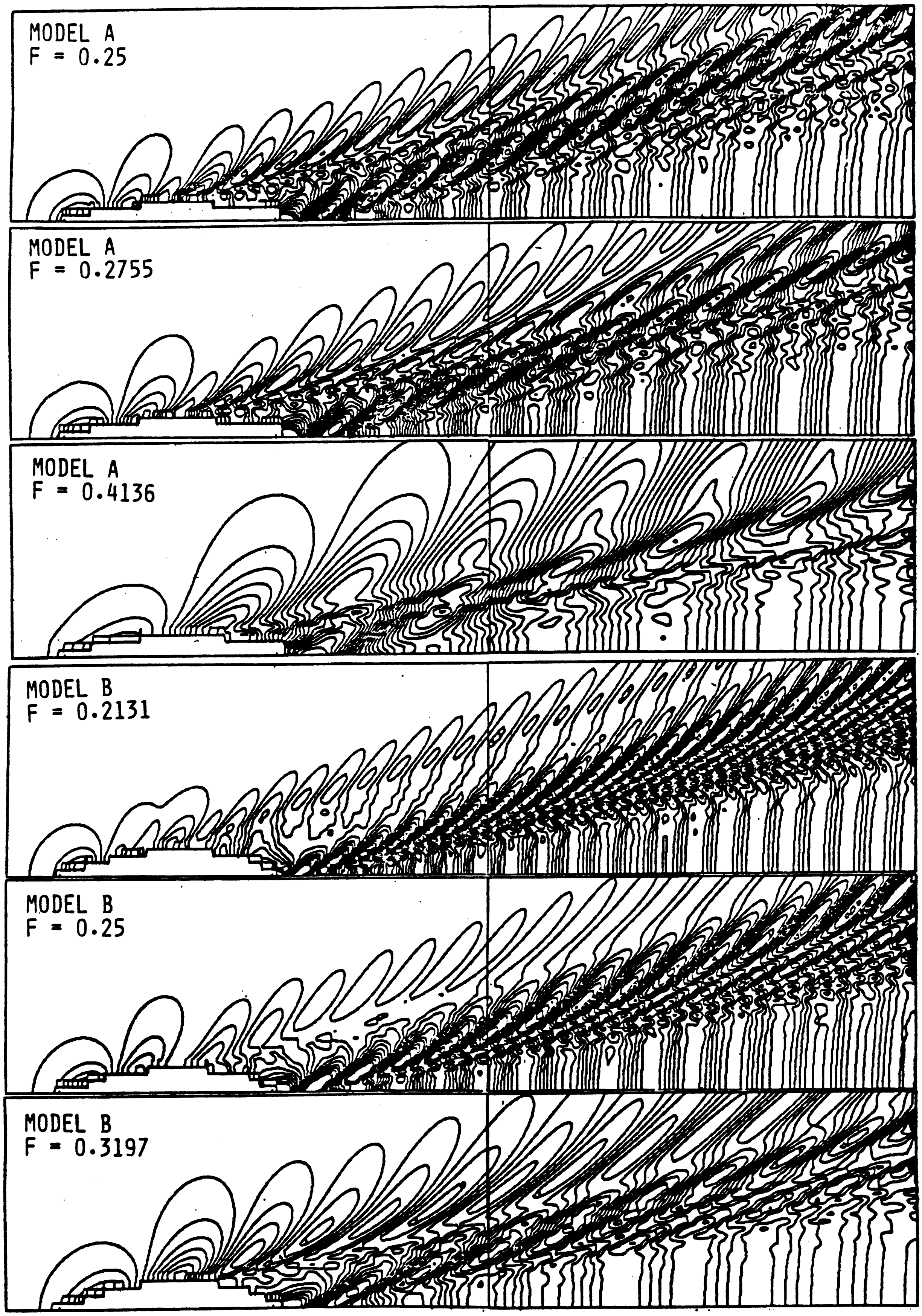

Figure 5 - See previous page.