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SURFACE-WAVE INTERACTION BETWEEN ADJACENT SLENDER BODIES

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Predicting the wave-induced motions of a twin-hull ship is a practical problem involving wave interaction between adjacent slender bodies. Closely related situations include two ships transferring cargo at sea or a conventional ship operating near a harbor boundary. The objective of the present study is to develop an approximate theory for the first-order hydrodynamic forces on these geometric configurations. Thus we neglect viscous effects, linearize the boundary conditions and decompose the flow into incident, radiated and diffracted wave components.

The slenderness of a mono-hull ship justifies approximating the flow near it by a sequence of two-dimensional problems. A simplified view of the flow near adjacent slender bodies would therefore suggest that interaction occurs only between sections which lie in the same transverse plane. This approach, known as "strip theory", has been applied to mono-hull ships, but is strictly only valid for short wavelengths comparable to the ship's beam. It has also been applied to twin-hull ships, but it exaggerates interaction effects near the resonant frequencies because it only allows wave energy to flow in the transverse direction. Two distinct types of resonance can be identified between adjacent slender bodies. The first occurs at intermediate frequencies, right in the middle of the practical range of interest, when the enclosed free surface behaves like a water column. At higher-frequencies, there is resonance due to the presence of standing waves between the bodies. Clearly, three-dimensional effects, in particular longitudinal interaction, must play an important role in dissipating the energy trapped between the bodies.

The high-frequency restriction on strip theory has been removed in the "unified theory" derived by Newman (1978) and Sclavounos (1984) where the strip-theory solution near the ship is supplemented by a homogeneous component which accounts for longitudinal hydrodynamic interaction. Approximate treatments of three-dimensional wave interaction among non-slender (in the horizontal direction) bodies separated by sufficiently large distances have been presented by Ohkusu (1974), Greenhow (1980), Simon (1982), and Kagemoto and Yue (1985). Typically, the multiple-body problem is reduced to a set of radiation-diffraction problems for each body separately, the solutions of which are then combined analytically to approximate the wave interaction effects. Unified theory is applied in the present study to solve the zero-speed mono-hull problem and is extended, following an approach typified by that of Simon, to include wave interaction between adjacent slender bodies with no forward speed.

To simplify the derivation, we consider two identical bodies which are symmetric about their own centerplanes and rigidly connected in a catamaran configuration. Generalizations to cases where the bodies do not satisfy some or all of these conditions present no additional fundamental difficulties. The bodies or hulls are assumed to be separated by a distance on the order of their length, hence the theory will be called the "far-field approximation". This assumption proves not to be restrictive as the approximation performs well even when the hulls are one beam apart.

For the twin-hull radiation problem, the far-field approximation regards the total disturbance in the vicinity of each hull as being composed of a radiation component resulting from its own forced oscillation, an "incident wave" representing the influence of the other hull, and an "interaction" component created by diffraction of that incident wave. Unlike a conventional diffraction problem however, the complex amplitude of the incident wave is permitted to vary slowly along the length of the hull and is determined as follows. The radiation and interaction components associated with each hull are represented in the far field by distributions of oscillatory wave sources and dipoles along its longitudinal axis. This axis is appropriately defined by the intersection of the hull's centerplane and the mean free surface. The sources and dipoles (which are oriented perpendicularly to the centerplane) account for the parts of the disturbance which are symmetric and anti-symmetric respectively with respect to the centerplane. The source strength and dipole moment associated with the single-body radiation disturbance are known from solving the unified-theory integral equation for each hull, but the interaction singularity distributions are initially unknown. The technique of matched asymptotic expansions is applied to obtain a pair of coupled integral equations for these distributions. Once solved, the longitudinal distributions of the incident wave amplitude and phase are given explicitly. Thus the far-field approximation accounts for longitudinal interactions among the sections of each body, as in unified theory, and interactions of all sections of one body with all sections of the other.

It is worth noting that non-wavelike terms are retained in the final coupled integral equations. If these terms are omitted and the body length is allowed to become infinite while the frequency is kept constant, the two-dimensional approximation derived by Okhusu (1974) is recovered. Versions of this two-dimensional approximation with and without the non-wavelike terms have been compared with an "exact" numerical solution. The improved accuracy at low frequencies when they are included suggests that a similar improvement can be expected by including them in the far-field approximation.

The far-field approximation has been thoroughly tested for the case of twin semi-submerged spheroids with beam-to-length ratios of one eighth. Values of the heave added-mass and damping coefficients from the far-field approximation, strip theory and a three-dimensional numerical method are shown in Figure 1 for a separation distance of one quarter the hull length. This case is actually a fairly severe test of the far-field approximation for two reasons. First, the bodies are close together; the distance between their surfaces at the mid-section is only one diameter. Second, a spheroid has blunt ends which violate an initial assumption that both the source strength and its longitudinal derivative be smooth at the ends. Nevertheless, the far-field approximation is in excellent agreement with the independent three-dimensional numerical calulations over the entire frequency range while strip theory displays large discrepancies at low frequencies and in the regime of water-column resonance ($KB/2 \simeq .5$). The far-field approximation is equally reliable for the pitch mode where the differences between the far-field approximation and strip theory are even more dramatic.

Heave-mode results for a separation distance of one half the hull length are shown in Figure 2. The apparent accuracy of strip theory near the standing-wave resonance ($KB/2 \simeq \pi/3$) is deceptive because these are integrated results; the longitudinal distribution of hydrodynamic forces predicted by strip theory varies rapidly near the section where standing-wave resonance is strongest whereas the far-field approximation predicts a smooth distribution even in the resonant regime.

A far-field reciprocity relation for the exciting forces and moments has also been derived on the basis of the far-field approximation. It has been used to evaluate the heave and pitch exciting forces for three wave directions. Both the moduli and phases of these quantities are in good agreement with a three-dimensional numerical solution of the diffraction problem.

To summarize, the far-field approximation has been found to be very robust for all tested frequencies and for moderate separation distances. This is surprising because the initial assumption that the bodies are in the far-field of each other appears to be invalid in this case. At higher frequencies where resonance occurs, the far-field approximation appears to be physically realistic while strip theory does not. The reciprocity relations for the exciting forces appear to be equally reliable.

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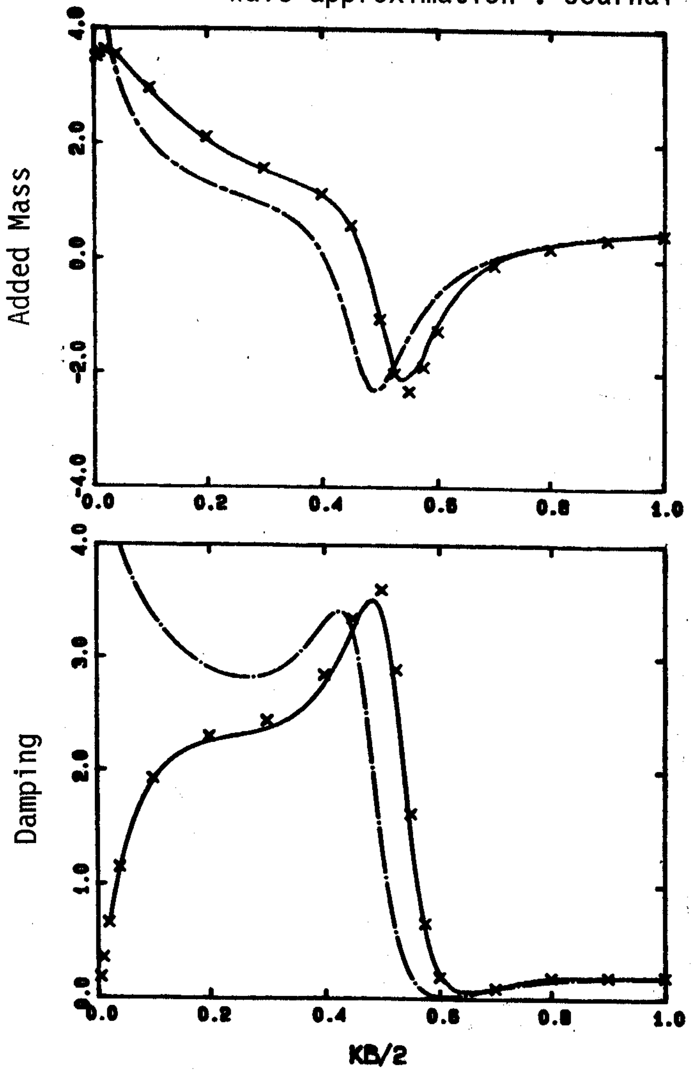

Fig 1: Heave added mass and damping coefficients of twin semi-submerged spheroids with diameter-to-length ratio 1/8 and separation-to-length ratio 1/4; according to far-field approximation (————), strip theory (—·———·—) and three-dimensional numerical method (x). Coefficients are normalized by displaced mass of both spheroids and wavenumber K is normalized by radius of one spheroid.

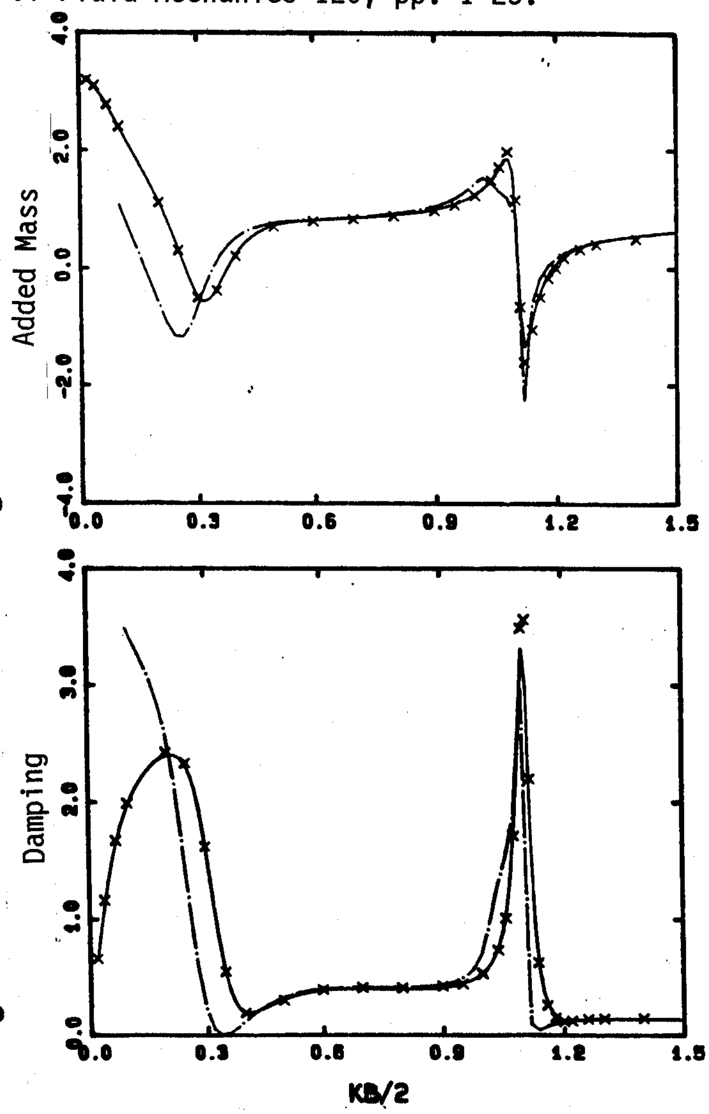

Fig. 2: Heave added mass and damping coefficients of twin spheroids with separation-to-length ratio 1/2.

Discussion

Kleinman: Have these resonances in the added mass and damping coefficients been observed? Is there experimental data to confirm them?

It is strange that different methods which give very different results for the potential on the hull nevertheless produce similar results for added mass.

Breit: Ohkusu (1971) presents some experimental results for two-dimensional sections. He reported that the very high standing waves between the sections at the resonant frequencies were so large that they broke over the sections.

Papankolaou: How about the effects of oblique seas? Did you calculate exciting forces? The physical situation is different from a mono-hull body.

Breit: I have calculated the exciting force from a far-field reciprocity relation. This was first derived by Sclavounos, "Forward Speed Exciting Forces on Ships in Waves", J. Ship Research 29, No. 2, 1985, pp. 105-111, in the context of a single slender body. These relations have been extended to twin slender bodies at zero speed and are very accurate for all wave headings.

A direct solution of the diffraction problem by this approach is also feasible. I believe it would be a straight-forward extension of the unified-theory solution of diffraction by a single slender body, derived by Sclavounos, "The Diffraction of Free-Surface Waves by a Slender Ship", J. Ship Research 28, No. 1, 1984, pp. 29-47.

Evans: It is well-known that negative added mass occurs for single submerged bodies. Ogilvie showed this as being an excess of potential over kinetic energy of the fluid which seems reasonable for submerged bodies. Do you have any physical understanding of this phenomenon for two surface piercing bodies as you have shown here.

Breit: The added-mass does become negative in the three-dimensional as well as the two-dimensional results. I share your curiosity about this problem, but I cannot contribute any further physical insight.

P. Martin: Can you handle non-parallel slender bodies?

Yes, non-parallel bodies could be analyzed by this approach, but it depends how far one is willing to stretch the assumptions that the flow is slowly varying along the length, and that it can be approximated locally by a plane wave.

X.-J. Wu

This is very interesting work. The asymptotic matching method has now been successfully extended to twin hulls. As we know, many researchers, such as Newman, Ogilvie, Faltinsen, Troesch, Sclavounos, etc. have applied such a method in mono-hull cases and reported satisfactory results in spite of different treatments. We may ask a question why such an approximation works. In the zero forward speed case, the ordinary strip theory mainly depends on two basic assumptions: (i) the end effects are negligible and (ii) the structure is long enough in comparison with the beam which is the same order as the incident waves. Between them, which one is more important? In our field, perhaps no one has answered this question. For this purpose, an incomplete model is designated to yield numerical evidence ("An Incomplete Model for Numerical Investigation of the Ends Effect", to be submitted). It showed that for sway, heave and roll, the end effects may be small and the influence of finite length is dominant. Therefore, as long as the finite length is taken into account, reasonable predictions for sway, heave and roll may be obtained. This investigation has led to a rational 2D Green's function expression which takes care of finite length effect without use of the asymptotic matching procedure (Ref. X. J. Wu, "A rational two dimensional Green's function expression", to be submitted). For the case of surge motion and head (following) waves, however, end effects are particularly significant. Therefore, I suggest that further development of the strip theory for obtaining all the necessary information should be towards a 3D-2D combination concept (Ref.: X.J. Wu, "A Hydrid 3D Strip Method for Evaluating Surging Coefficients of Full-Shaped Ships", 7th Int. Conf on Boundary Element Method, Como, Italy, Sept. 1985).

Breit:

It is correct to say that unified theory does not account for end effects. Based on the good agreement between unified theory and "exact" three-dimensional numerical methods, it seems that finite-length effects are more important than end effects, at least at zero speed.