Wave effects on vessels with internal tanks

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The motions of fluid in internal tanks have important effects on the dynamic response of vessels in waves, particularly during loading and unloading operations when the tanks are partially filled. This topic is of special interest for LNG tankers and FPSO vessels. Coupled tank/ship motions have been studied by Kim (2001) and Rognebakke & Faltinsen (2001, 2003), with nonlinear analyses of the interior flow in the tanks, and by Molin *et al* (2002) and Malenica *et al* (2003) with linear analyses. In these works the tank dynamics are analysed separately from the exterior radiation and diffraction problems. The solution of the coupled equations of motion follows by combining the hydrodynamic forces for the tanks with the vessel's added-mass, damping, and exciting forces. When the tank motions are linearized, their only effect on the vessel's motions is to modify the added mass.

Recently we have extended the panel code WAMIT to analyse coupled tank/ship motions, following a unified approach where the interior wetted surfaces of the tanks are included as an extension of the conventional computational domain defined by the exterior wetted surface of the body. All of the tank and hull wetted surfaces form one large global boundary surface. The principal modification is to impose the condition that the separate fluid domains are independent. This is achieved trivially, by setting equal to zero all coefficients of the linear system for the potential where the source and field points are in different fluid domains. This is equivalent to forming separate linear equations for each domain, and concatenating these into one global system in a block-diagonal manner. The exterior free-surface Green function is used for each domain, with vertical shifts of the coordinates corresponding to the free-surface elevation in each tank.

The principal advantage of this approach is that the exterior panel code can be extended to include internal tanks with relatively few modifications. All of the usual hydrodynamic parameters can be evaluated in a similar manner as for vessels without tanks, including the added-mass and damping coefficients, exciting forces, RAO's, and the mean second-order drift forces and moments. Local values of the free-surface elevation, pressure and velocity can be evaluated both inside and outside the tanks. The geometry of the tanks can be described in the same manner as the exterior hull surface. Disadvantages include the larger size of the linear system, which implies some loss of computational efficiency, and the need to re-run the complete interior/exterior analysis in situations where only one or the other is changed, e.g. when the tank depths are modified. Since the entire analysis is linearized, nonlinear sloshing effects are not included.

It is not obvious that a conventional exterior panel code can be applied to an internal problem. We have found the higher-order method to be robust in this respect, with B-spline representation of the solution and accurate definitions of the geometry. The low-order panel method also appears to work for tanks, although with somewhat slower convergence. Computations have been made for various vessels, including the barge model studied by Molin *et al* (2002) where experimental and computational data are available for comparison. Some of these results are shown by Newman (2004).

Results are presented here for the hemispheroid shown in Figure 1. This vessel has three internal tanks, with the same depth of fluid in each tank. The tank lengths are the same, but the widths and elevations are different. Figure 2 shows the first-order motions and drift force in beam waves, for three relative densities of the tank fluid (ρ=0, 0.5, 1.0). The total displacement and waterline plane are fixed as the tank density is varied. The results with zero density are equivalent to the conventional case without internal tanks. All results are normalized by the exterior fluid density, gravity, wave amplitude, and a characteristic length scale of 1m, and plotted vs. the nondimensional wavenumber $Ka = \omega^2 a/g$, where ω is the radian frequency and a=1m is the maximum radius of the spheroid. The vertical center of gravity is in the waterplane, and the radii of gyration are k_x=50cm, and $k_y = k_z$=3m.

Figure 3 shows the six principal added-mass coefficients, normalized by the mass of fluid displaced by the hull. Since the added mass is the sum of the separate pressure forces on the hull and tanks, the coefficients in Figure 3 are linear functions of the tank density.

Most of the added-mass coefficients are singular at the resonant periods of antisymmetric sloshing modes. The surge resonance at Ka=1.184 is the same for all three tanks. In sway there are two resonant frequencies (Ka=1.653, 2.427) due to the different widths. The first singularity in yaw corresponds to the sway mode of the outer tanks (Ka=2.427); the second smaller singularity is associated with the diagonal sloshing mode of the center tank (Ka=2.922).

At resonance the added-mass coefficients tend to $\pm\infty$. This explains the rapid fluctuations of the RAO's shown in Figure 2. The sway RAO approaches zero at the resonant frequencies, where the added mass is infinite. At slightly higher frequencies, where the negative added mass cancels the body mass, the RAO is large. Since the hull is axisymmetric there is no moment from the external pressure, but the tanks induce roll motions when the density is nonzero.

For heave the tank fluid translates uniformly and the RAO is not affected. The frequency-dependence of the tank component of the heave added mass is an interesting feature in Figure 3. The velocity potential in each tank is $\phi = (z_t - 1/K)$, per unit heave velocity, where z_t is the local vertical coordinate above the tank free surface and the constant $1/K$ is required by the free-surface condition. Thus, for a tank with volume V_t and waterplane area S_t, the added mass is $\rho_t(V_t - S_t/K)$. In the equations of motion the contribution from the term S_t/K is canceled by the hydrostatic restoring force.

The most surprising results are the sharp reductions in the sway drift force, which coincide with the peak sway response. From momentum conservation the tanks only affect the horizontal drift force indirectly, by modifying the motions of the hull. Since roll has no effect, the reduced drift force is associated primarily with the sway RAO.

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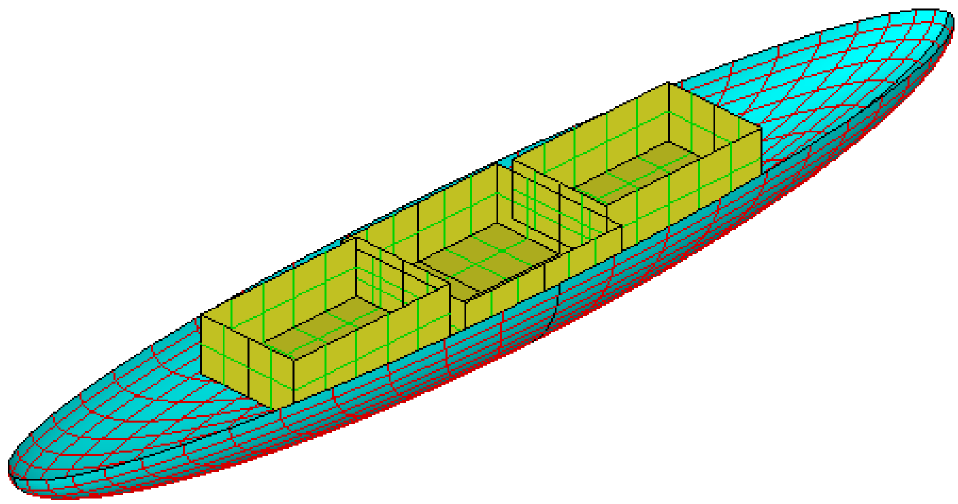

Figure 1: Perspective view of the spheroidal hull. The length is 12m and the midship section is a semi-circle of radius 1m. Each tank is 2m long, and 62.5cm deep. The tank widths are 120cm, 160cm, and 120cm. The free surfaces are at $z=$ 25cm, 12.5cm, and 25cm above the exterior waterplane.

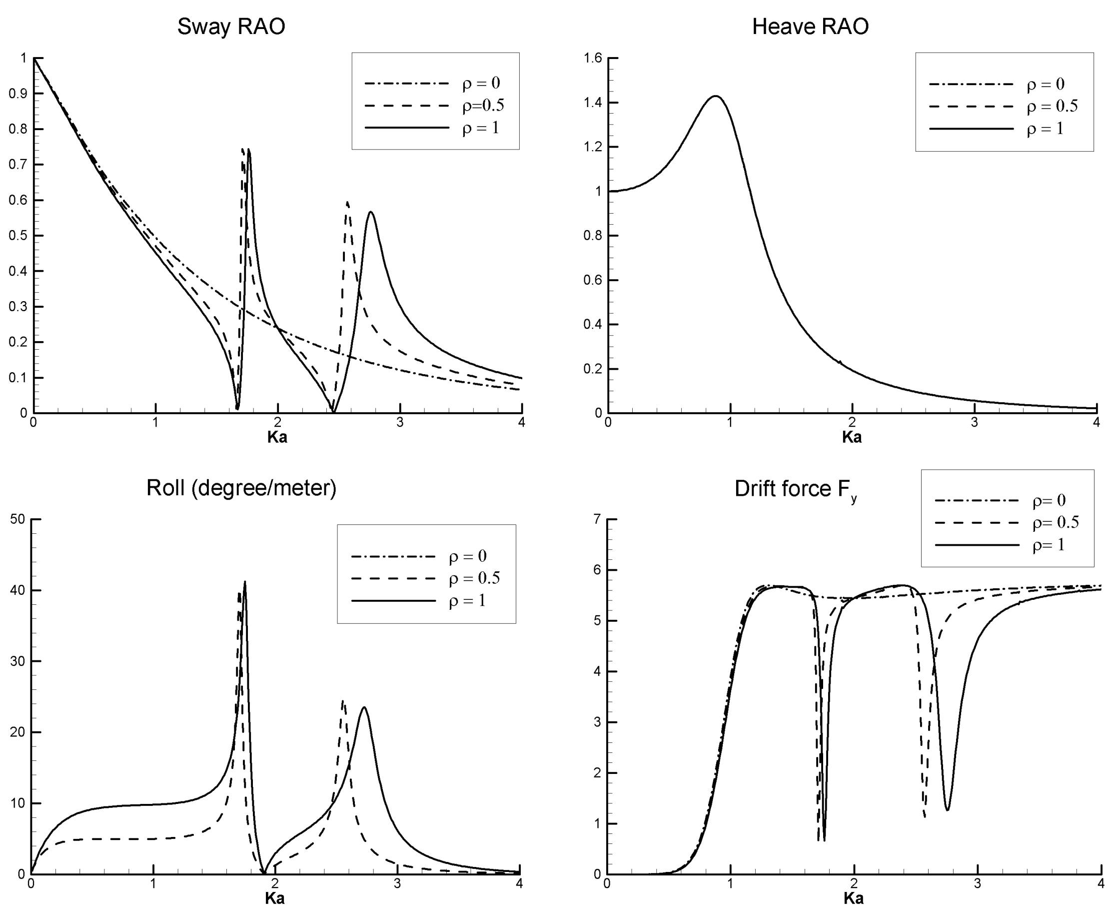

Figure 2: RAO's and drift force for the spheroidal hull in beam waves.

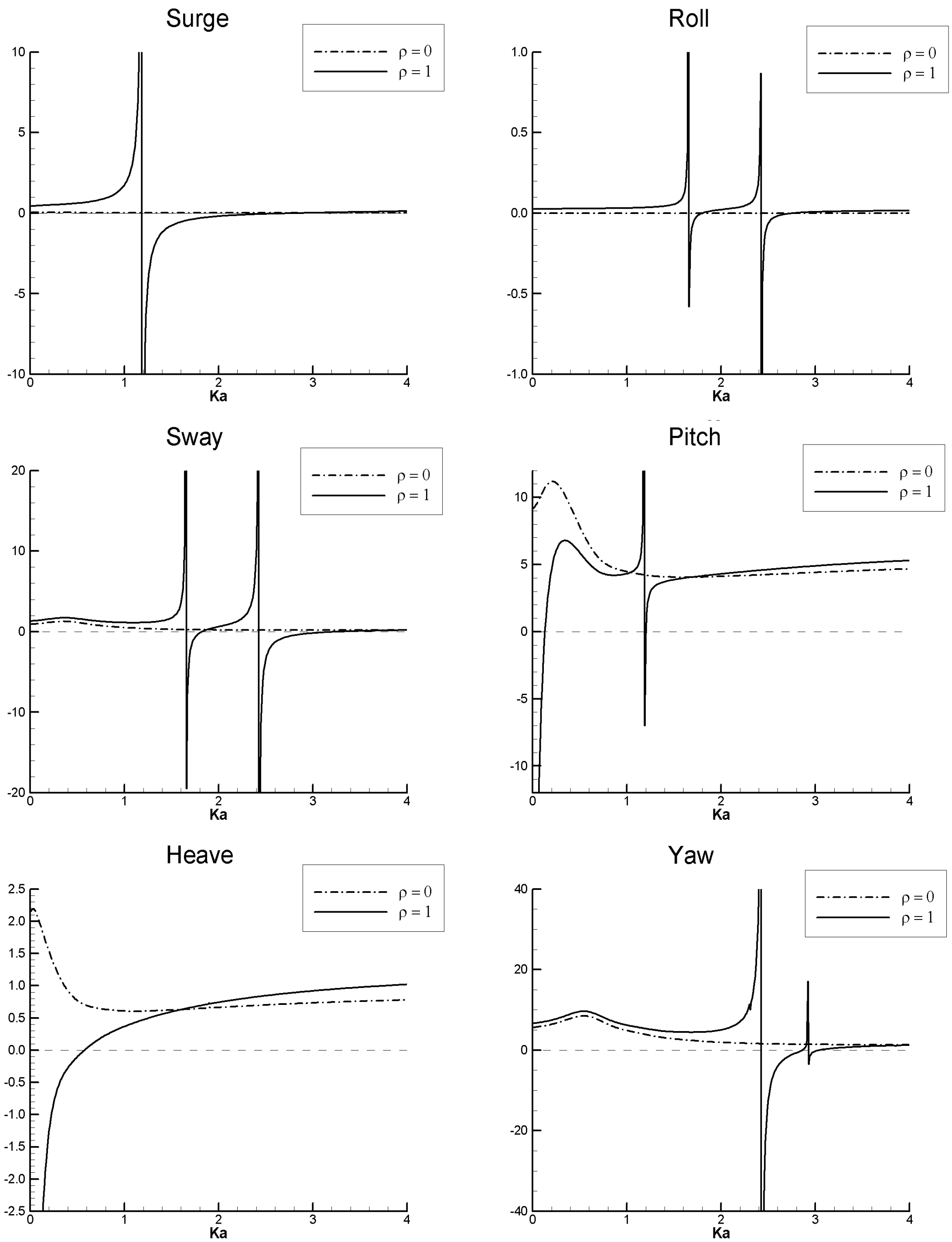

Figure 3: Added-mass coefficients of the spheroidal hull. All coefficients are normalized by the displaced mass and a length of 1m.