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NUMERICAL SIMULATION
OF
PROPELLANT SLOSHING FOR SPACECRAFT

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INTRODUCTION

There are numerous advantages to the use of liquid propellants in maneuvering spacecraft. However, the motion of the liquid propellant can result in forces that tend to disturb the motion of the spacecraft. These forces can be modified by tank design, or accounted for by the active spacecraft-control system. Under some circumstances, fluid dynamic forces can even lead to unstable motion of the spacecraft (1).

The motion of the fluid, and therefore the resulting forces, can rarely be predicted by analytic methods, particularly when the tank geometry is complex, the fluid is bounded by a free surface, or realistic tank motions are considered. It is, however, currently practical to predict these fluid motions, forces, and moments by numerical simulation.

Building on the two-dimensional SOLA-VOF program (2), we have written a three-dimensional computer simulation program, HYDR-3D (3), that handles a wide variety of fluid dynamic problems.

In this paper we shall briefly describe HYDR-3D and summarize its applications to propellant slosh problems.

METHODOLOGY

HYDR-3D is an extension of the well known SOLA (4) algorithm to flows in three dimensions containing free surfaces. The Navier-Stokes equations with variable viscosity are solved by a semi-implicit, finite-difference algorithm. First order space and time differencing were used in all the calculations presented in this paper, although a second order option is available. The calculations were performed in Cartesian geometry using variable-size mesh cells and partial area and volume blockages to model curved tanks and internal baffles. Arbitrary motion of the computational grid is easily specified in HYDR-3D, allowing analysis of spinning, coning, and accelerating spacecraft. The VOF (5) algorithm is used to track the motion of arbitrary free surfaces

Including bubbles, droplets and breaking waves.

APPLICATIONS

We describe three applications of HYDR-3D to sloshing problems: a spherical tank in a gravitational field, a spin-stabilized spherical tank in coning motion, and a 90° turning maneuver of an odd-shaped tank containing a complex set of baffles.

SHAKING SPHERE

The accuracy of HYDR-3D for sloshing problems has been investigated by comparison with a linear analytic result for small amplitude sloshing in a spherical tank shaken in a gravitational field (6). A sphere, which is 50 cm in radius, is half filled with fluid and shakes horizontally in a normal gravitational field with the acceleration

$$\dot{u}(t) = 0.792 \sin(5.385t)$$

Although this frequency is near resonance, the flow remains in excellent agreement with linear theory as seen in Fig. 1. The calculated results presented in the figure were obtained using the partial area/volume blockages in a Cartesian mesh of rectangular cells to define the sphere.

SPIN-STABILIZED APPLICATION

HYDR-3D was applied to the analysis of a spin-stabilized system with spherical propellant tanks (7). Because the angular momentum of the spacecraft will not be in exact alignment with the principal axis of inertia, its motion will consist of a precession, or "coning" about the angular momentum vector, as well as spinning about the principal axis. Coning has two critical effects. First, it can lead to unstable spacecraft motion if the fluid-generated forces tend to increase the angle between the angular-momentum vector and the principal axis. Second, energy dissipation is enhanced by the fluid motion induced in propellant tanks. Both of these effects require control system action (through thrusters). Thrust requirements must be analyzed to estimate control

