FED - Vol. 15

Forum on Unsteady Flow

presented at

THE WINTER ANNUAL MEETING OF
THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
NEW ORLEANS, LOUISIANA
DECEMBER 9-14, 1984

sponsored by

THE FLUIDS ENGINEERING DIVISION, ASME

edited by

P. H. ROTHE
CREARE R & D, INC.

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
United Engineering Center 345 East 47th Street New York, N.Y. 10017

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

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

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

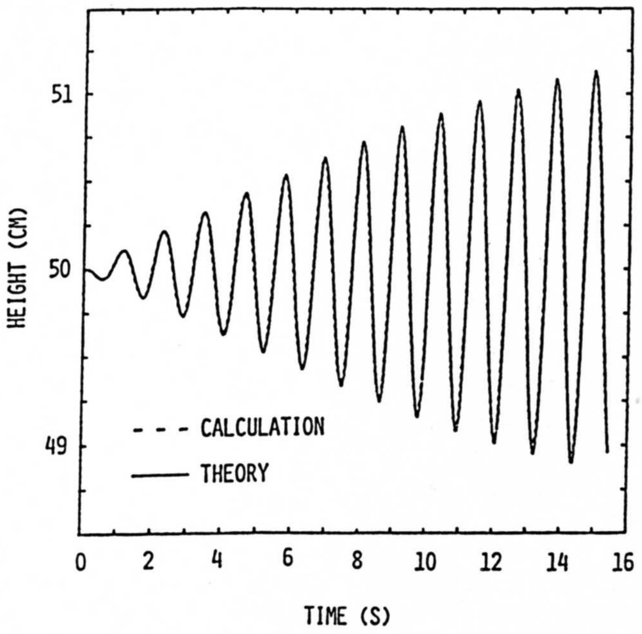

Fig. 1. Spherical Tank Surface Height Comparison

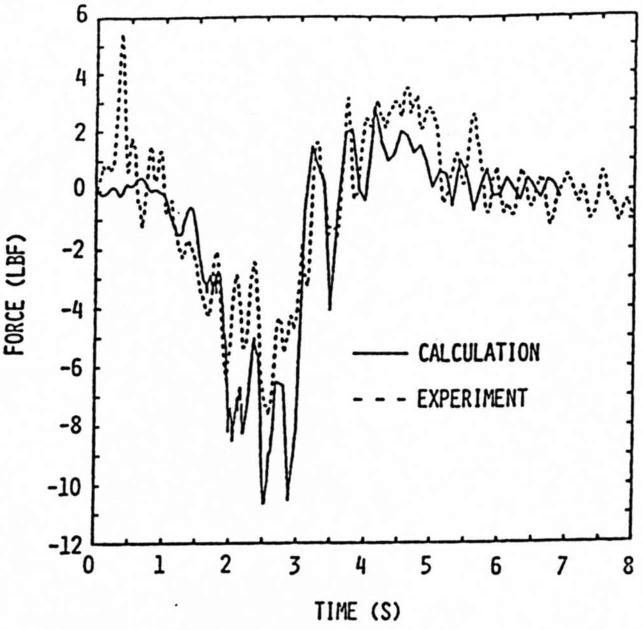

Fig. 2. Three-Axis Stabilized Circumferential Force Comparison

system fuel consumption.

Because the spacecraft contains four propellant tanks, direct use of calculated forces for a single tank is difficult. Therefore, calculations were used to parameterize an equivalent mechanical model (consisting of two simple pendulums) for propellant sloshing forces. Four mechanical models can then be coupled with the control system algorithm to study system stability and propellant consumption.

Centrifugal force tends to keep the propellant surface smooth for spin-stabilized spacecraft, therefore a simpler free surface treatment (4) was used for these calculations. Calculations showed that two modes of propellant sloshing require different pendulum parameters. This occurs because the equilibrium surface generated under the influence of centrifugal force is a cylinder centered at the axis of rotation. Therefore, disturbances along the axis of the cylinder behave differently from disturbances in the perpendicular direction, as can be seen in Table I. Both pendulum modes also differ somewhat from that observed in a spherical tank in a gravitational field. The resonance slosh predicted, based on this mechanical model, was also observed calculationally and experimentally (8).

TABLE I

	NON SPINNING SPHERES		FIRST PENDULUM		SECOND PENDULUM	
FILL FRACTIONS	ℓ/D	m/m_T	ℓ/D	m/m_T	ℓ/D	m/m_T
0.25	0.38	0.74	0.44	0.55	0.45	0.55
0.50	0.30	0.57	0.41	0.32	0.44	0.29
0.75	0.24	0.38	0.33	0.20	0.35	0.11
0.93	0.14	0.18	0.24	0.12	0.26	0.06

THREE-AXIS STABILIZED APPLICATION

Three-axis stabilized spacecraft do not have effective gravitational forces to limit the motion of propellants during maneuvers; their analysis, therefore, requires the full capabilities of HYDR-3D. Low gravity tests made in an aircraft in a parabolic trajectory were simulated using HYDR-3D (9). The test tank was of complex shape with several internal baffles. In nearly zero-gravity conditions, the test tank was rotated by 90° in 3 seconds and the forces exerted on the tank were recorded. Figure 2 compares the measured and calculated force in the circumferential direction. (The large amplitude oscillations in the measured force are thought to be a result of structural vibrations in the test apparatus.) Coupled calculations of HYDR-3D and a rigid-body spacecraft model are now being performed at Rockwell International to determine the efficacy of internal baffles.

ACKNOWLEDGEMENTS

This work was supported in part by the Naval Research Laboratory (contract #N00014-83-C-2082) and the Rocketdyne Division of Rockwell International (contract #R34 PMK-147875).

NOMENCLATURE

D	Sphere Diameter
ℓ	Effective Pendulum Length
m	Effective Pendulum Mass
m_T	Actual Fluid Mass
t	Time
u	Acceleration in the x-direction

REFERENCES

1. Abramson, H.N., Editor, "The Dynamic Behavior of Liquids in Moving Containers," National Aeronautics and Space Administration report, NASA SP-106 (1966).

2. Nichols, B.D., Hirt, C.W., and Hotchkiss, R.S., "SOLA-VOF: A Solution ALgorithm for Transient Flow with Multiple Free Boundaries," Los Alamos Scientific Laboratory report LA-8355 (1980).

3. Sicilian, J.M. and Hirt, C.W., "HYDR-3D: A Solution Algorithm for Transient 3D Flows," Flow Science User's Manual, FSI-84-18-1 (1984).

4. Hirt, C.W., Nichols, B.D., and Romero, N.C., "SOLA-SURF: Basic Solution Algorithm for Flows Bounded by Curved Surfaces," in SOLA: A Numerical Solution Algorithm for Transient Fluid Flows, Los Alamos Scientific Laboratory report LA-5852 (1975).

5. Hirt, C.W. and Nichols, B.D., "Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries," Journal of Computational Physics, Vol. 39, No. 1, January 1981.

6. Budiansky, B., "Sloshing of Liquids in Circular Canals and Spherical Tanks," Journal of the Aero/Space Sciences, Vol. 27, No. 3, March 1960.

7. "Application of SOLA-3D/FSI to Fluid Slosh," Flow Science, Inc. report, FSI-84-17-1, May 1984.

8. Zedd, M.F. and Dodge, F.T., "Energy Dissipation of Liquids in Nutating Spherical Tanks Measured by a Forced Motion Spin Table," AIAA Guidance and Control Conf., August 1984.

9. Sicilian, J.M. and Hirt, C.W., "Development and Testing of the SOLA-SLOSH Computer Program," Flow Science Inc. report FSI-84-18-2, May 1984.