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D. J. NORTON
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PROPELLANT TANK FORCES RESULTING FROM FLUID MOTION IN A LOW-GRAVITY FIELD

J. Navickas[1], C. R. Cross[2], D. D. Van Winkle[3]
McDonnell Douglas Astronautics Company
Huntington Beach, California

BSTRACT

\n accurate prediction of forces exerted by propellant motion on the torage container is required for many space vehicles under a wide ange of dynamic environments. Most approximate methods fail al-ogether or give overly conservative results. A finite difference tech-ique to solve the equations of motion offers a substantial improvement ver the approximate methods. One such program, HYDR-3D, de-eloped by Flow Science, Inc., was chosen to conduct propellant mo-on analysis under some typical space dynamic environments. A artially filled spherical tank was subjected to rotational motion about n axis of rotation outside of the tank to determine the tank sidewall rces and moments caused by such a maneuver. The same tank was ubjected to accelerations parallel to the tank axis in order to determine ne acceptable acceleration levels to settle the propellant before the ngine restart. The program was able to track the propellant config-ration through large displacements and provide useful design data. omputed results also compared well with cylindrical container test ata at a relatively low Bond number with large liquid surface eformations.

OMENCLATURE

A	=	fractional area open to flow
a	=	acceleration
b	=	loss across a porous baffle
F	=	volume fraction occupied by fluid
f	=	viscous acceleration
p	=	pressure
t	=	time
u	=	x-velocity
V	=	fractional volume open to flow
v	=	y-velocity
		z-velocity
wsx	=	wall shear stress
wsy	=	wall shear stress
wsz	=	wall shear stress
x	=	coordinate axis
y	=	coordinate axis
z	=	coordinate axis
μ	=	viscosity
ρ	=	density
τ	=	shear stress

Subscripts

r	=	radial
x	=	x-direction
y	=	y-direction
z	=	z-direction

INTRODUCTION

Propellant response to dynamic excitations in a low-gravity field has always been an area of concern in the design of space systems. These concerns are amplified as the performance requirements for many space-operating systems become quite demanding. Since many vehicles are launched from the Shuttle payload bay, forces and moments applied to the vehicle during the ejection stage must be determined to evaluate clearance and vehicle control requirements. The unbalanced moments are caused by an unsymmetric propellant configuration, where the liquid-vapor interface can assume a minimum energy configuration and be located anywhere in the tank before vehicle ejection from the payload bay. As the mission progresses, it is frequently necessary to position the propellant at a particular location within the tank for engine restart or other purposes. Therefore, the optimum acceleration levels and durations to accomplish this task with a minimum of vehicle and propellant disturbances have to be determined. Forces and moments during such settling maneuvers must be determined in order to establish the vehicle control requirements. Additionally, if a stable platform must be maintained after a vehicle maneuver, the force and moment calculations must be continued after the maneuver is completed.

Many techniques have been developed to determine propellant dynamics in a low-gravity field. An equivalent pendulum method, described by Abramson (1), has been used extensively in control system analysis. However, this method is not applicable at very low gravity levels or at large liquid surface deformations. NASA has used a KC-135A aircraft flying a parabolic trajectory to provide approximately 30 sec of zero-g environment, to experimentally evaluate fluid response to dynamic disturbances. Orbital experiments provide excellent means to evaluate low-gravity fluid dynamic behavior. However, such experiments are expensive, require a long lead time and do not allow

[1]Principal Engineer/Scientist
[2]Engineer Scientist/Specialist
(presently with Astronautics Technology Center)
[3]Manager

continuous changes as the system design evolves. Numerical techniques have been undergoing intense development for a number of years. It appears that a point has been reached in this development to permit propellant response chasracteristics to be calculated for rather general dynamic environments. The present analysis was conducted to predict liquid dynamic response to a number of possible dynamic disturbances of a spherical propellant tank and to give some insight into the capabilities and limitations of the HYDR-3D (2) code.

COMPUTATIONAL METHOD

The HYDR-3D code is a result of many years of development of numerical techniques started with the Marker-and-Cell Program (3). The initial program evolved into many variations, some rather general, some oriented towards a specific task. The SOLA-SURF Program (4) is a two-dimensional program that has been used extensively. It accommodates liquid surface configurations of limited slope, hence it cannot be used where excessive surface deformations are encountered. The SOLA-VOF Program (5) is a two-dimensional program that can accommodate multi-valued liquid surface configurations, including breaking surfaces. This program has also been used in a variety of applications.

The HYDR-3D program is a three-dimensional program that can accommodate extensive surface deformations, including separation of liquid volumes from the liquid bulk. General initial fluid surface configurations and container geometries are represented by analytical expressions. Both liquid and vapor can be treated as either compressible or incompressible media. Surface tension and viscosity are also included. General vehicle motions are entered through a special routine that relates motion of a separate mesh coordinate system to an inertial reference system. Motion of rotating and translating systems can, therefore, be readily represented.

A fully compressibile continuity equation and the Navier-Stokes equations of motion are solved by the program. The Cartesian form of the equations, taken from Reference (2), follows.

The fully compressible continuity equation is:

$$V \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u A_x) + \frac{\partial}{\partial y}(\rho v A_y) + \frac{\partial}{\partial z}(\rho w A_z) = 0$$

The equations of motion are:

$$\frac{\partial u}{\partial t} + \frac{1}{V}\left[uA_x \frac{\partial u}{\partial x} + vA_y \frac{\partial u}{\partial y} + wA_z \frac{\partial u}{\partial z}\right] = -\frac{1}{\rho}\frac{\partial p}{\partial x} + g_x + f_x - b_x$$

$$\frac{\partial v}{\partial t} + \frac{1}{V}\left[uA_x \frac{\partial v}{\partial x} + vA_y \frac{\partial v}{\partial y} + wA_z \frac{\partial v}{\partial z}\right] = -\frac{1}{\rho}\frac{\partial p}{\partial x} + g_y + f_y - b_y$$

$$\frac{\partial w}{\partial t} + \frac{1}{V}\left[uA_x \frac{\partial w}{\partial x} + vA_y \frac{\partial w}{\partial y} + wA_z \frac{\partial w}{\partial z}\right] = -\frac{1}{\rho}\frac{\partial p}{\partial z} + g_z + f_z - b_z$$

The viscous accelerations are:

$$\rho V f_x = wsx - \left\{\frac{\partial}{\partial x}(A_x \tau_{xx}) + \frac{\partial}{\partial y}(A_y \tau_{xy}) + \frac{\partial}{\partial z}(A_z \tau_{xz})\right\}$$

$$\rho V f_y = wsy - \left\{\frac{\partial}{\partial x}(A_x \tau_{xy}) + \frac{\partial}{\partial y}(A_y \tau_{yy}) + \frac{\partial}{\partial z}(A_z \tau_{yz})\right\}$$

$$\rho V f_z = wsz - \left\{\frac{\partial}{\partial x}(A_x \tau_{xz}) + \frac{\partial}{\partial y}(A_y \tau_{yz}) + \frac{\partial}{\partial z}(A_z \tau_{zz})\right\}$$

where

$$\tau_{xx} = -2\mu\left\{\frac{\partial u}{\partial x} - \frac{1}{3}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)\right\}$$

$$\tau_{yy} = -2\mu\left\{\frac{\partial v}{\partial y} - \frac{1}{3}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)\right\}$$

$$\tau_{zz} = -2\mu\left\{\frac{\partial w}{\partial z} - \frac{1}{3}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)\right\}$$

$$\tau_{xy} = -\mu\left\{\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right\}$$

$$\tau_{xz} = -\mu\left\{\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right\}$$

$$\tau_{yz} = -\mu\left\{\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right\}$$

Fluid configurations are defined in terms of volume of fluid function. This function represents the volume of fluid 1 per unit volume and satisfies the equation

$$\frac{\partial F}{\partial t} + \frac{1}{V}\left[\frac{\partial}{\partial x}(FA_x u) + \frac{\partial}{\partial y}(FA_y v) + \frac{\partial}{\partial z}(FA_z w)\right] = 0$$

Either no-slip or free-slip boundary conditions can be input at solid boundaries. These conditions are imposed after each pass through the mesh during the pressure iteration.

Surface tension effects are input in an explicit fashion by adjusting the pressure component in the equations of motion.

The computational scheme normally employed is a modified donor-cell method which is first-order accurate in space and time. Although a second-order method is available as an option in the program, the first-order method is adequate for most solutions.

COMPUTATIONAL RESULTS

Limited comparisons of computed results to test data indicate that the program can predict fluid dynamic behavior under a wide range of conditions. The program has been used to calculate liquid surface displacement and liquid forces in a sinusoidally excited spherical tank (2). Results compare well to test data. However, the solution represents linear range with a well-behaved single-value liquid surface. Estes et al. (6) predicted with fair accuracy propellant-induced forces and moments in a KC-135 test using a predecessor of the HYDR-3D program. Torrey (7) used the SOLA-VOF program to compute low-gravity liquid settling including surface tension. Results compare well to test data, although the resolution of the test data is rather limited, since liquid configuration in a drop tower test was obtained from a movie film. In the experiment, acceleration was applied to settle liquid from the top to the bottom of a cylindrical tube with hemispherical