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EFFECTS OF TRANSIENT PROPELLANT DYNAMICS ON DEPLOYMENT OF LARGE LIQUID STAGES IN ZERO-GRAVITY WITH APPLICATION TO SHUTTLE/CENTAUR

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ABSTRACT

A common requirement of the space station era will be deployment and docking of orbit transfer vehicles with large quantities of liquid propellants. The maneuver will typically start at zero gravity with short, transient accelerations applied to provide accurate vehicle positioning for clearance during deployment or engagement during docking. Since the propellant tanks are not always full and the initial zero-g position of liquid and ullage may not be known, transient fluid forces can have a major influence on vehicle motion. Until recently, this fluid dynamics problem could not be analyzed adequately. This paper describes the application of a recently developed computational fluid dynamics (CFD) program, HYDR-3D, to the analysis of separation of the Centaur G-Prime vehicle from the Space Shuttle Orbiter. The typical application presented illustrates a particularly difficult design task - deployment of a large, liquid-filled, densely packaged vehicle from a manned vehicle. Since it represents a potential catastrophic hazard, a vast number of conditions and parameters must be analyzed to ensure tolerance of at least two credible failures. Validation of the HYDR-3D program against zero- and low-gravity experimental data is also presented. Using the fluid dynamics program, this approach can be used confidently to analyze and determine design requirements for a variety of orbit transfer vehicle/space station deployment and docking problems.

KEYWORDS

Space vehicle deployment; upper stage separation; zero-gravity fluid dynamics; computational fluid dynamics; Shuttle/Centaur.

CENTAUR/ORBITER SEPARATION SYSTEM

The Centaur G-Prime is a modification of the LO_2/LH_2 fueled Centaur that has flown as an upper stage on Atlas and Titan launch vehicles since 1962. Designed for full use of the Orbiter payload bay volume, it provides maximum possible synchronous orbit and planetary mission performance with state-of-the art propulsion. A schematic of its separation from the Orbiter is shown in Fig. 1. Until cancelled in the wake of the Challenger accident, the G-Prime had been the first large liquid stage scheduled to fly from the Shuttle in May 1986. A version of G-Prime is now planned as an upper stage for Titan for use on high energy missions. The first two missions, planned for the Shuttle, Galileo and Ulysses, are used in this paper to illustrate effects of propellant dynamics on deployment of a large liquid stage in zero-g and the methodology for analyzing the problem this presents. On Ulysses, for example, the LO_2 weight of 37,500 lb. is 71 percent of the total separated weight of 52,600 lb. It is obvious that LO_2 motion and forces on the tank must be accurately predicted in order to determine vehicle motion.

For separation, the Centaur is rotated 45 degrees out of the Orbiter bay by a rotation system driving the deployment adapter (DA). Separation is initiated by a Super*Zip ring, which circumferentially severs the Centaur aft adapter from the DA. Separation force is provided by 12 compressed coil springs plus a number of spring-loaded disconnects. The springs have a 4-inch stroke; the disconnects have 2.2 inches or less. Maximum axial acceleration is about 0.1g, with a minimum relative separation velocity of 1 ft/sec. Four 11-inch-long guides alleviate angular motion resulting from any imbalances in the separation forces, but are not long enough to control all residual effects of propellant motion. The critical clearance is that between the engine bell and the DA. The aft end of the bell must travel 93 inches before it clears the DA and about 60 feet before it clears the Orbiter cabin.

HYDR-3D PROPELLANT DYNAMICS ANALYSIS APPROACH

The most difficult aspect of ensuring adequate clearance is determining the transient propellant forces on the tanks resulting from impulsive separation and guide forces. Because of its weight, LO_2 is the largest factor. The 45-degree deployment and the Orbiter attitude control create tank accelerations of about 10^{-6}g, even before separation. This causes the spherical zero-g ullage bubble to become ellipsoidal and to be located almost any place in the tank at the instant of separation. Scale-model drop-tower tests by the NASA/Lewis Research Center (Carney, 1985) showed that a stable, centered ullage location existed only for low-liquid-fill levels of less than about 40%. Above 80% fill, the ullage bubbles were small enough to be accommodated anywhere within the container boundaries. As bubble diameter increased for fills less than 80%, the tendency for the bubble to attach to the desired wall with largest radius of curvature increased.

Most missions desire maximum propellant fill, which is about 96%. This has the most uncertainty of ullage location but the least effect from it. However, several factors (e.g., trajectory, energy, Shuttle lift capability, stay-time before deployment) result in fill levels in the 65 to 96% range. The lower the fill, the larger the effect on separation, and the ullage location is still uncertain. Most likely, then, the propellant center of mass will be offset from the axial centerline and the axial separation acceleration will cause rotation of the propellants. The resulting moments and lateral forces have a major effect on vehicle motion and DA clearance.

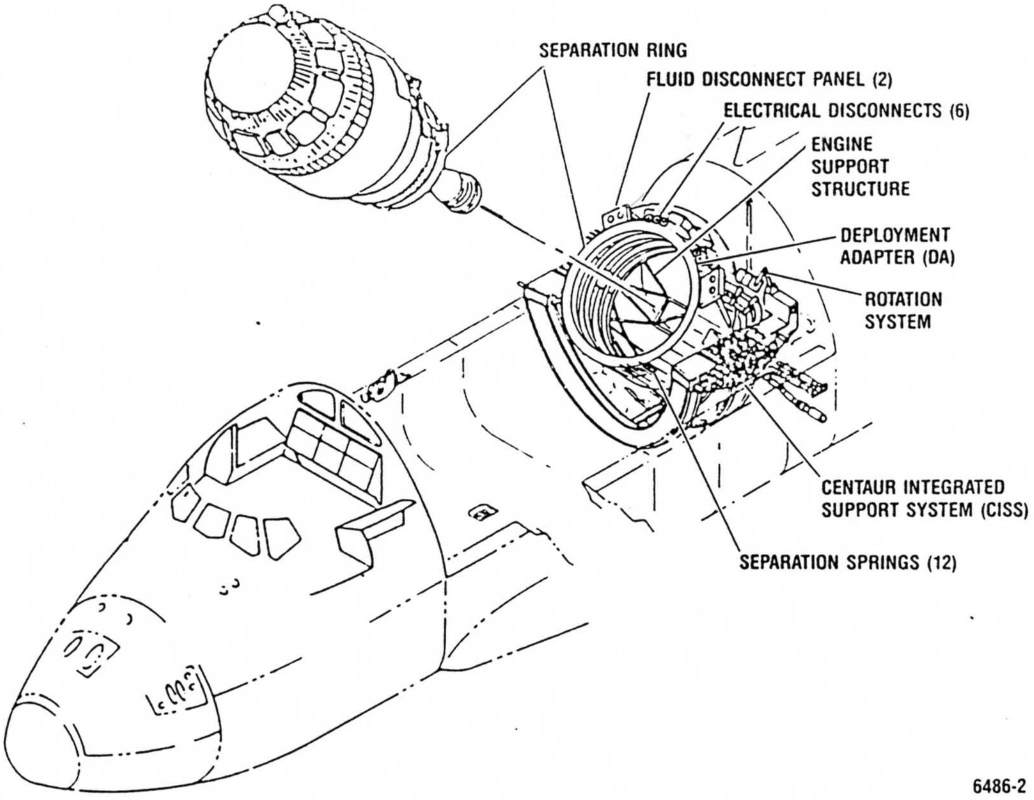

Fig. 1. Shuttle/Centaur separation system.

A recently available large-scale CFD computer program, HYDR-3D, developed by Flow Science, Inc., was the only method found to determine propellant dynamic forces for the conditions imposed. Key features of the program are listed in Table 1 and a full description and user instructions are furnished by Hirt and Sicilian (1985a). HYDR-3D has evolved from the well-known Marker-and-Cell finite difference technique which uses pressure and velocity as primary dependent variables. It is a general, three-dimensional hydrodynamics code which solves the Navier-Stokes equations of an incompressible (or slightly compressible) fluid with multiple free surfaces. Forces and moments are calculated by summing the pressure-area product for each cell in the computational mesh. General tank geometry may be modelled, including internal parts that may be modelled as either solid obstructions or porous baffles.

Table 1. HYDR-3D program description.

- General-purpose, finite-difference, large-scale computational fluid dynamics program developed by Flow Science, Inc.
- 3D Navier-Stokes dynamics including surface tension, wall viscous forces & limited compressibility
- Fractional area/volume method for obstacles
- General free surface configurations
- Multiple boundary conditions
- Variable mesh
- Automatic time-step (stability) controls
- General non-inertial accelerations
- Mesh, fluid region, baffle & obstacle generators
- Extensive graphics output of flow velocity patterns, net fluid forces & moments on tank walls

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This capability for handling three-dimensional, real-vehicle, complex geometry and general liquid/ullage interface geometry is believed to be unique. It eliminates the need for gross idealization of fluid dynamics in real tank shapes, similarly to what large-scale finite-element programs have done for structural analysis. Hirt and Sicilian (1985b) present, in detail, the variable porosity technique for obstacles in the flow path, Fractional Area Volume Obstacle Representation (FAVOR). They also discuss methods of avoiding grid distortion and numerical instability and accuracy problems and reasons for using a finite difference rather than a finite element approach.

The mesh can be varied to use small cells in areas of high dynamic activity and large cells in less active areas. Typical cell distributions mesh for the G-Prime LO_2 tank is shown in Fig. 7 and 9. The tank is an oblate spheroid with a cylindrical midsection. It contains a midsection solid ring and a porous, internal thrust barrel at the aft end which are important to internal tank fluid motion. The direction and magnitude of velocity for each cell containing liquid are portrayed by the arrows. Any cross-section in any direction may be displayed, as well as three-dimensional representations. Pressure distributions may also be displayed.