EFFECT OF PROPELLANT SLOSHING ON THE DESIGN OF SPACE VEHICLE PROPELLANT STORAGE SYSTEMS

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ABSTRACT

Propellant sloshing in many of the presently planned space vehicles, such as the single-stage-to orbit (SSTO), and the Lunar-Mars missions, can affect the vehicle design in a number of ways. The FLOW-3D program, a general three-dimensional fluid flow program with a free-surface capability was used to investigate some of the critical propellant sloshing effects on the vehicle design in generic SSTO vehicle oxygen and hydrogen tanks. Areas investigated were: 1. Propellant motion and liquid impact on the tank structure caused by dynamic disturbances in cavitating and non-cavitating oxygen tanks. 2. Propellant response to dynamic disturbances in a hydrogen tank undergoing a direct-to-orbit trajectory. Results indicate that propellant sloshing can result in significant disturbing forces and impact pressures.

INTRODUCTION

Propellant dynamic behavior in some of the space transportation vehicles that are presently planned or are already in the design stages can significantly affect the vehicle design. This is mainly due to the complex nature of the missions, requiring, in some instances, a high degree of vehicle maneuverability with large quantities of propellant on-board. Such systems can undergo highly nonlinear propellant sloshing modes, with large propellant surface displacements. This can cause large disturbing forces and moments, disturb the propellant thermodynamic balance, and result in significant impact pressures.

Studies have been conducted to determine the effects of the cargo sloshing on the stability of ground transportation systems (1) and petroleum ships (2). Numerous methods have been developed to predict the liquid impact loads. Experimentally determined pressures caused by a metal pipe impact on water surface have been compared to pressures determined by a number of computational methods (3) and methods have been investigated that could be used to determine the cargo impact pressures in liquefied natural gas tankers (4). In general, studies of nonlinear fluid sloshing and impact on the container structure have been conducted by the nuclear and the petroleum transportation industries. This technology in presently being acquired by the aerospace industry and applied to the design of a variety of space-oriented systems. Large amplitude low-gravity propellant motion has been compared to numerical results (5), experimentally determined low-gravity force and moment measurements have also been compared to numerical calculations (6).

In the present analysis the FLOW-3D program (7) was used to determine the sloshing characteristics in generic oxygen and hydrogen tanks for a SSTO vehicle. The FLOW-3D program is a general three-dimensional fluid flow program with compressible and incompressible options. It is especially well-suited to predict propellant motion in tanks with a free liquid surface and complicated tank geometries with internal obstructions such as baffles. The program was also modified to allow the formation of large voids when the local pressure in the liquid bulk decreases below the saturation pressure. The SSTO vehicle was chosen because of the variety of dynamic environments such a vehicle can experience.

COMPUTATIONAL MODELS

Since oxygen and hydrogen are the likely propellants for the SSTO vehicles and many other proposed systems, an oxygen tank and a hydrogen tank in a generic SSTO vehicle were chosen to investigate the potential problem areas that may be caused by propellant sloshing. The two fluids have very different properties, can be contained in tanks of different configurations and be subjected to different dynamic environments which would depend, primarily, on the tank location in the vehicle. Because of such differences, the severity of the potential design problems in the two tanks can be quite different.

The oxygen tank configuration if shown in Figure 1. It is a tank with a rather large moment arm between the tank and the vehicle center of gravity, a typical condition for a tank located in the forward section of the vehicle. The hydrogen tank configuration is shown in Figure 2. It is a tank located closer to the vehicle center of gravity. The tank shape is typical of tanks designed to fit within the contour of the vehicle. Both the oxygen tank and the hydrogen tank models are two-dimensional one-ft thick slices. This is done to conserve computer time. The actual vehicle design may require fully three-dimensional models.

OXYGEN TANK ANALYSIS

The oxygen tank, because of a high liquid density and a long moment arm, represents the highest potential for disturbing forces and moments and liquid impact loads. The vehicle is assumed to be in level flight, with g_Z = 1.0 g's, excited by a ± 2.0 degree rotation at 1.0 Hz frequency about the vehicle center of gravity. A cavitating and a non-cavitating liquid conditions are considered. In a non-cavitating case the liquid is not allowed to separate from a solid surface by forming a void, a condition characteristic of a highly subcooled liquid. This condition is assumed in the FLOW-3D fluid motion analysis. In a cavitating liquid it is assumed that a pressure within the liquid bulk can decrease below the saturation pressure, thus forming a vapor void. This is typical for a saturated or slightly subcoolded liquid. The FLOW-3D program has been modified to permit the analysis of this condition (8) It has been shown (4) that the liquid impact characteristics depend greatly on the vapor pressure within the collapsing void. Hence, liquid collapsing around a void with a noncondensable gas or vapor at high pressure will result in lower impact pressure than liquid collapsing around a low-pressure void formed by cavitation. This was the motivation behind the FLOW-3D program modification. The limiting impact pressure can be expressed as:

$$p=\rho vc$$

Where p is the impact pressure, ρ is the fluid density and c is the speed of sound in the liquid. It is quite apparent that large liquid velocities approaching a tank surface through a void of low pressure can result in rather large impact pressures. In the cavitating case analysis it is assumed that all voids are at zero pressure, thus offering no resistance to fluid flow. This is a limiting case designed to generate the maximum impact velocities. Fluids have to develop some degree of superheat to induce cavitation. The degree of required superheat depends on the fluid properties, suface roughness, presence of impurities and the rate of pressure decrease. Each design must, therefore, be considered individually. The present analysis was conducted to show the limiting case, or the maximum potential for damage. In most cases some of the pertinent parameters affecting cavitation will have to be determined experimentally, then used as imputs into the computational models.

Liquid motion for the non-cavitating case is shown in Figure 3. Liquid motion for one void collapse sequence is shown in Figure 4. Liquid motions for these two cases are quite different, with the liquid in the cavitating case separating from the tank surface at one point and impacting the tank surface at another point at frequent intervals, which is not the case with the non-cavitation fluid.

Liquid impact velocities for cavitating and non-cavitating cases at a point close to the tank bottom are compared in Figure 5. Here the positive velocity represents liquid moving away from the tank wall and the negative velocity represents liquid impact. The cavitating case shows one large impact velocity, whereas the non-cavitating case shows none. The impact velocities close to the tank top are compared in Figure 6. Here the positive velocities represent liquid impact. The cavitating case shows larger and more frequent impact velocities than the non-cavitating case.

Propellant sloshing can result in significant destabilizing moments, the seriousness of the problem depending on the vehicle aerodynamic design characteristics. A comparison of rigid-body moments to those generated by a sloshing fluid is shown in Figure 7. The sloshing fluid causes rather large moment variations, which must be considered in the vehicle design.

HYDROGEN TANK ANALYSIS

The hydrogen tank was analyzed in a direct-to orbit flight mode. Highly simplified load factors for such a trajectory are shown in Figure 8. It is assumed that the tank starts draining at 690 seconds after liftoff. Two external dynamic environments were considered. In one case, the vehicle is assumed to be excited by a ± 2.0 degree rotation at I.0 Hz frequency about the vehicle center of gravity. Propellant dynamic analysis was conducted at the 690 second time point, prior to the start of propellant draining. In the second case the propellant is assumed to be draining as it undergoes the flight trajectory. At 180 seconds from the start of propellant draining a ± 2.0 degree rotation at I.0 Hz frequency is applied to the vehicle.

In the first case considered, a computational model consisting of the forward 11-ft portion of the tank was constructed. Since sloshing is essentially a surface phenomenon, exclusion of the liquid that does not display any significant motion does not degrade the accuracy of the results. Results of analysis are shown in Figure 9. Large ullage volume deformations imply that such systems as the tank pressurization will be influenced by this phenomenon. For instance, it may not be possible to maintain a higher ullage vapor temperature than that of liquid.

The liquid resonant frequency was also approximated by applying the linear sloshing analysis in a rectangular tank (9), where the period of the first harmonic can be calculated as follows:

$$T = \frac{2\pi}{\sqrt{\frac{\pi g}{\ell} \tanh \frac{\pi h}{\ell}}}$$

where ℓ is the tank width, g is the acceleration level, and h is the tank depth.

In the present analysis the length of the liquid surface was used for the tank width ℓ. A resonant frequency of f=0.848 Hz was calculated. This partially explains the large computed liquid surface deformations - the chosen exciting frequency is close to the resonant frequency. An exciting frequency of 0.5 Hz, a point further away from resonance, resulted in smaller surface deformations. It is interesting to note that the rather approximate calculation gave a fairly good indication of the resonant frequency.

Liquid surface configuration for the second case considered is shown in Figure 10, beginning at 180 seconds after start of tank draining, where a 1.0 Hz periodic disturbance has been added to the baseline acceleration. Liquid surface deformation for this case is substantially smaller than the deformation for the first case considered. Two reasons can be readily identified to explain the difference: the rotational moment arm is decreased as the propellant surface recedes, thus resulting in lower forces due to rotational disturbances, and the resonant frequency is reduced due to changes in the acceleration level and the characteristic surface length. Propellant behavior at this stage of the mission suggests that, unlike at the beginning of the tank draining, warm vapor pressurization is feasible.

CONCLUSIONS AND RECOMMENDATIONS

Propellant sloshing can cause significant destabilizing forces and moments in space transportation systems with large quantities of on-board propellant. This is especially true in highly maneuverable systems, such as the SSTO vehicles presently under development in a variety of configurations. In such systems the dynamic environment of the vehicle must be accurately established and used as an input to the propellant dynamic analysis. In some instances it may be necessary to couple the vehicle flight dynamics programs to the fluid dynamics programs to obtain an implicit solution of the vehicle dynamic behavior.

Liquid impact on the tank structure must also be considered in the vehicle structural design. This is especially true for lightweight high-performance systems. To accurately predict the liquid impact loads, further development of fluid dynamics codes is necessary. Vapor cushioning effects and structural flexibility have to be included. Experimental verification of computed results is also necessary.

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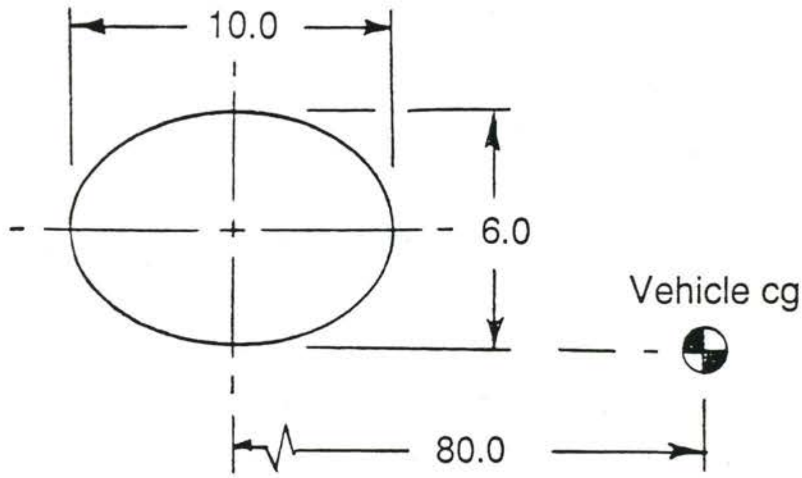

Figure 1. Oxygen Tank Configuration

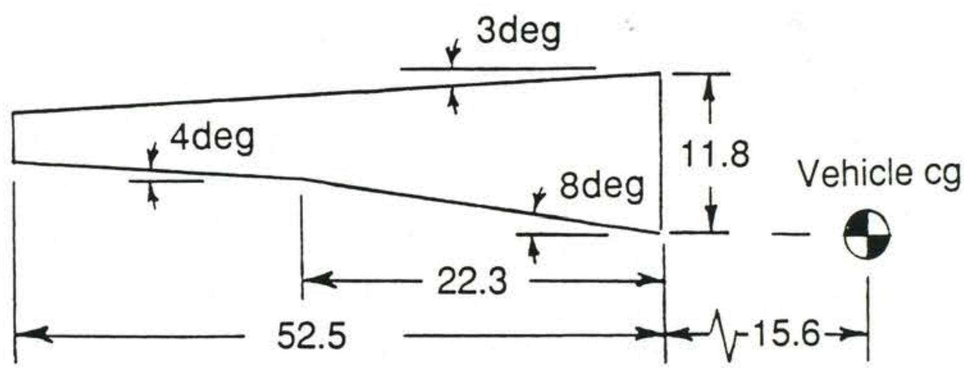

Figure 2. Hydrogen Tank Configuration

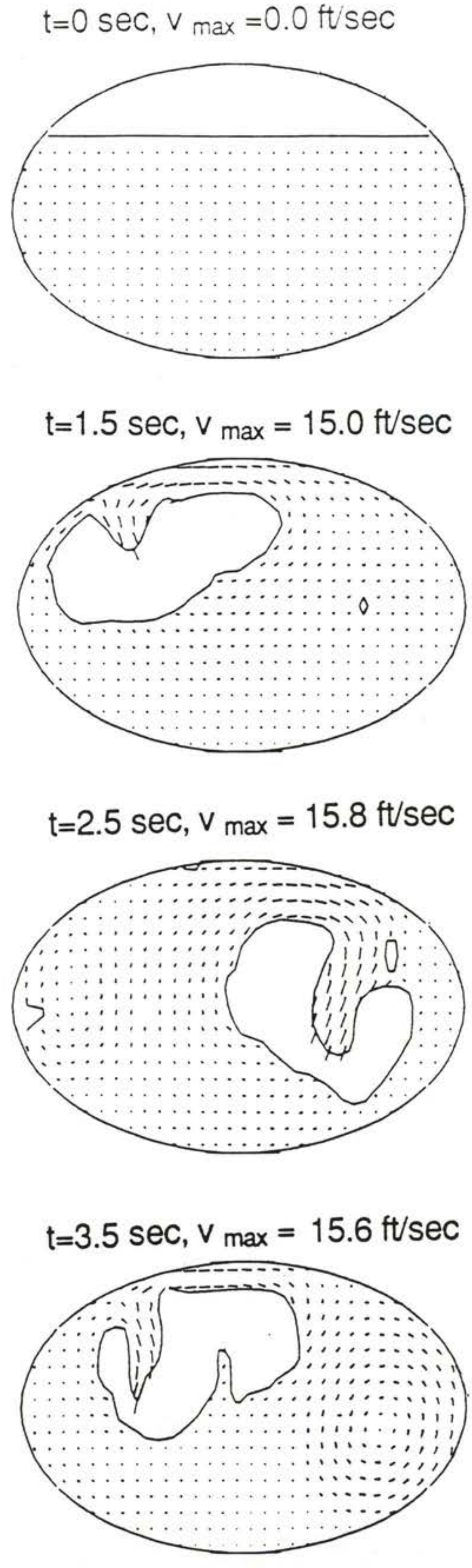

Figure 3. Velocity Vectors and Liquid Surface Configuration, Non-Cavitating Oxygen Tank

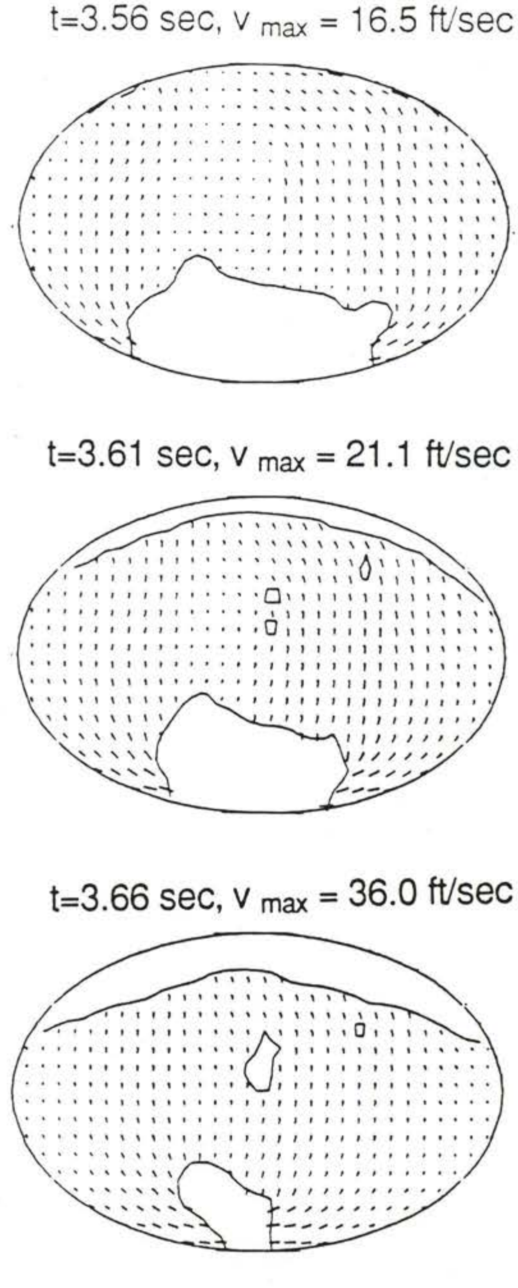

Figure 4. Velocity Vectors and Liquid Surface Configuration, Cavitating Oxygen Tank

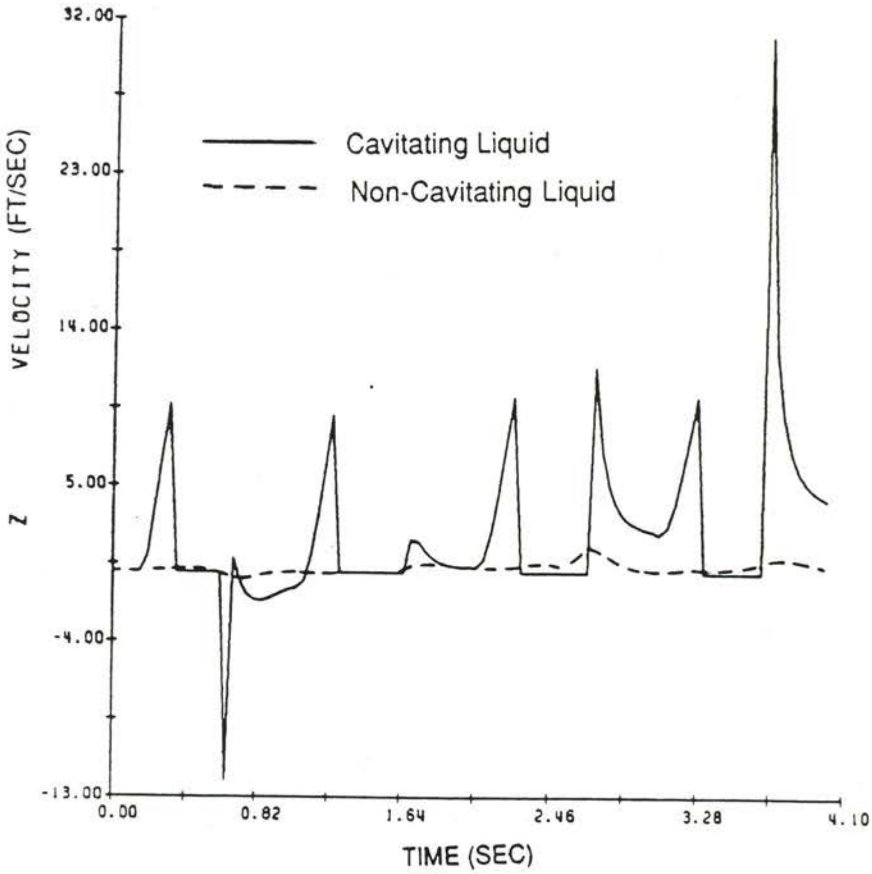

Figure 5. Oxygen Tank Liquid Impact Velocities at the Tank Bottom

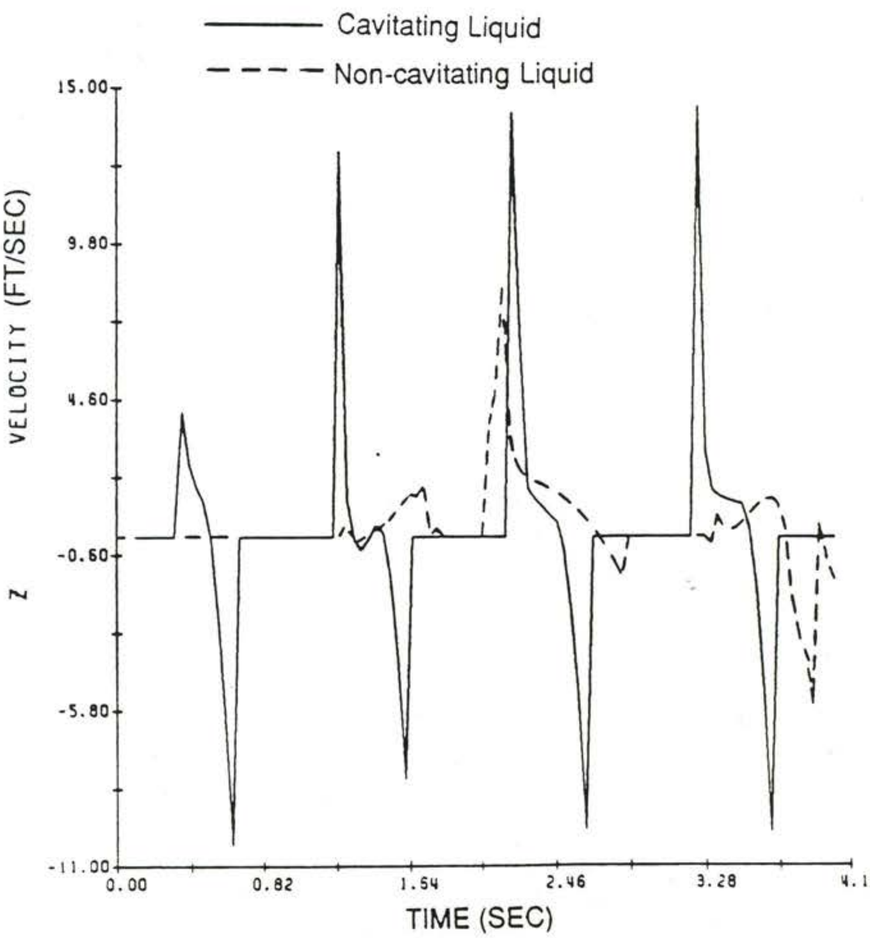

Figure 6. Oxygen Tank Liquid Impact Velocities at the Top of the Tank

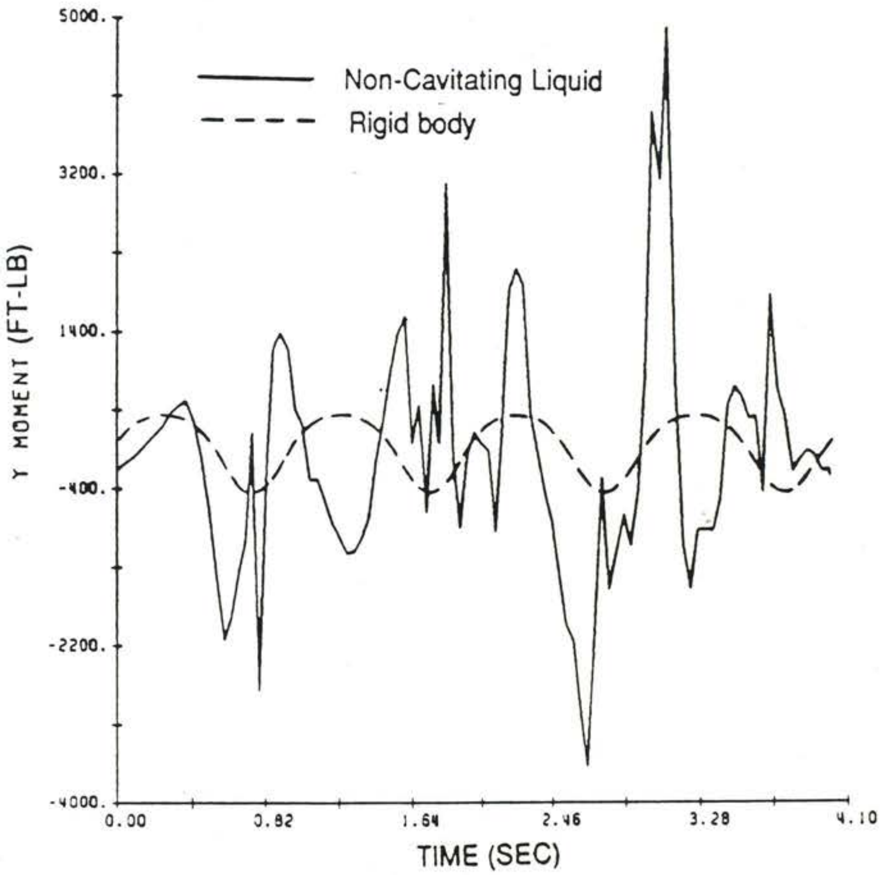

Figure 7. Oxygen Tank Disturbing Moments Caused by Propellant Sloshing

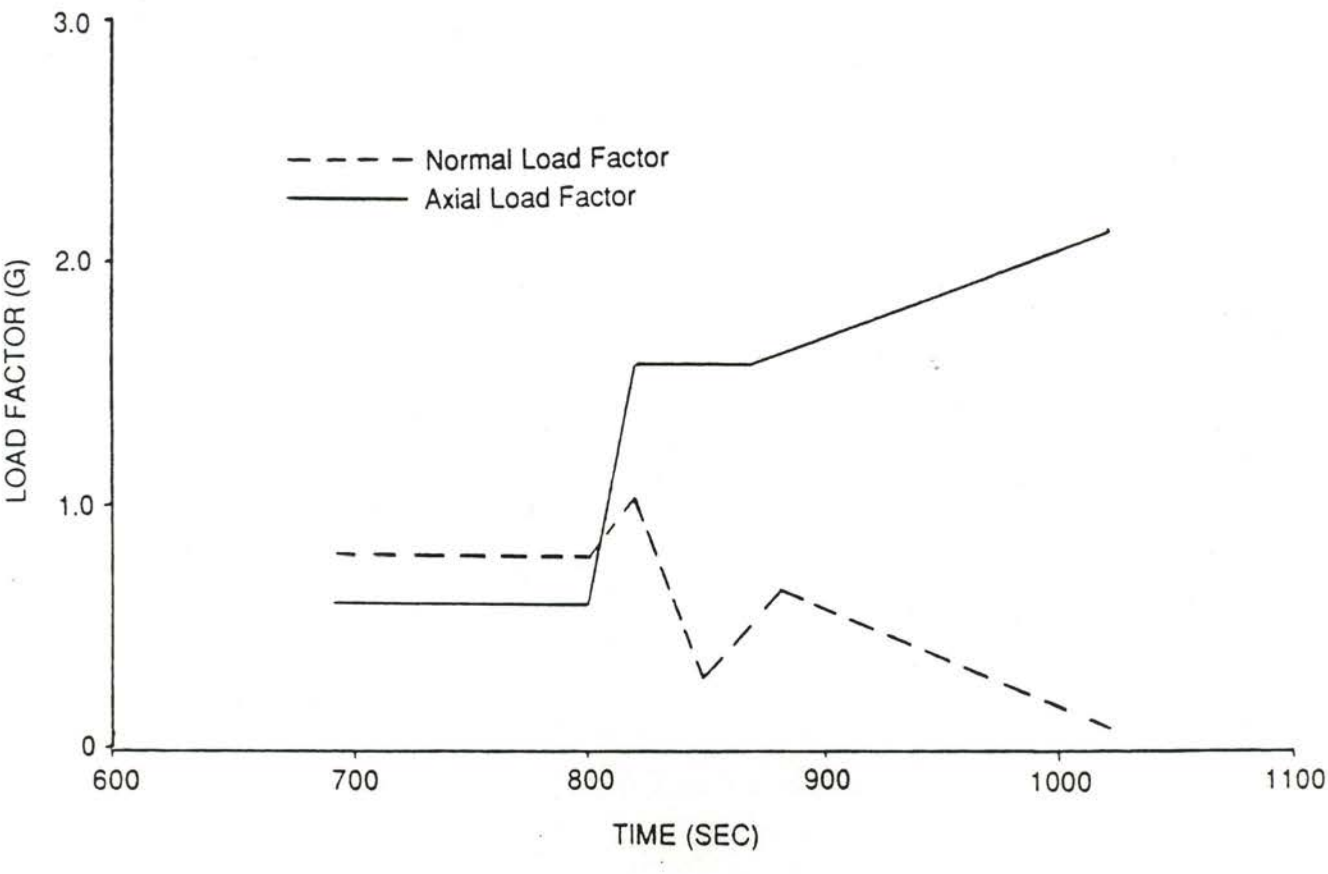

Figure 8. Load Factors used in Hydrogen Tank Analysis

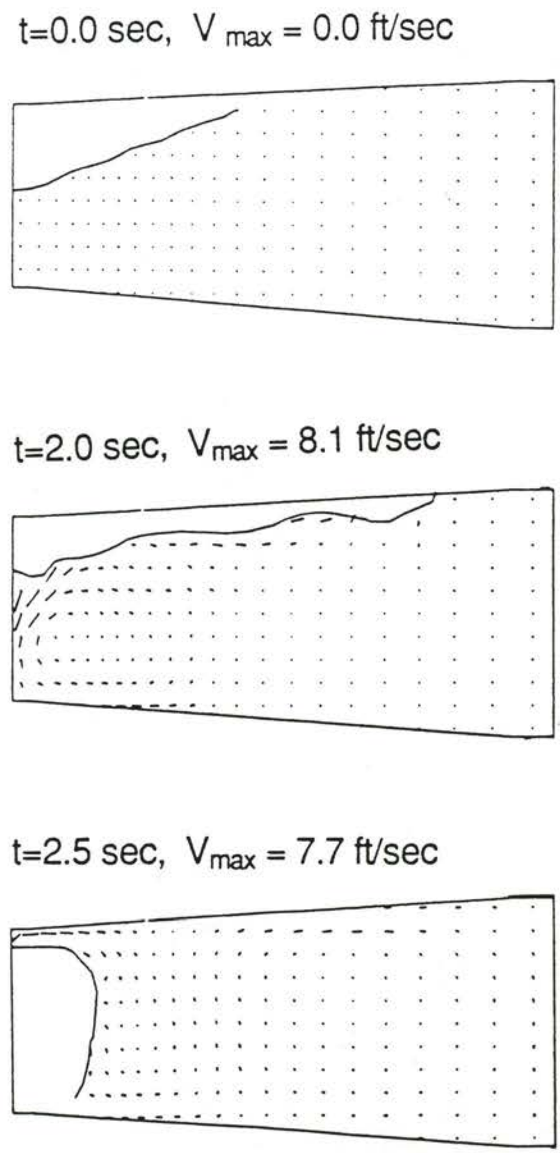

Figure 9. Hydrogen Tank Liquid Surface Deformation and Circulation Characteristics, ± 2° Rotation About the Vehicle Center of Gravity at 1.0 Hz Frequency

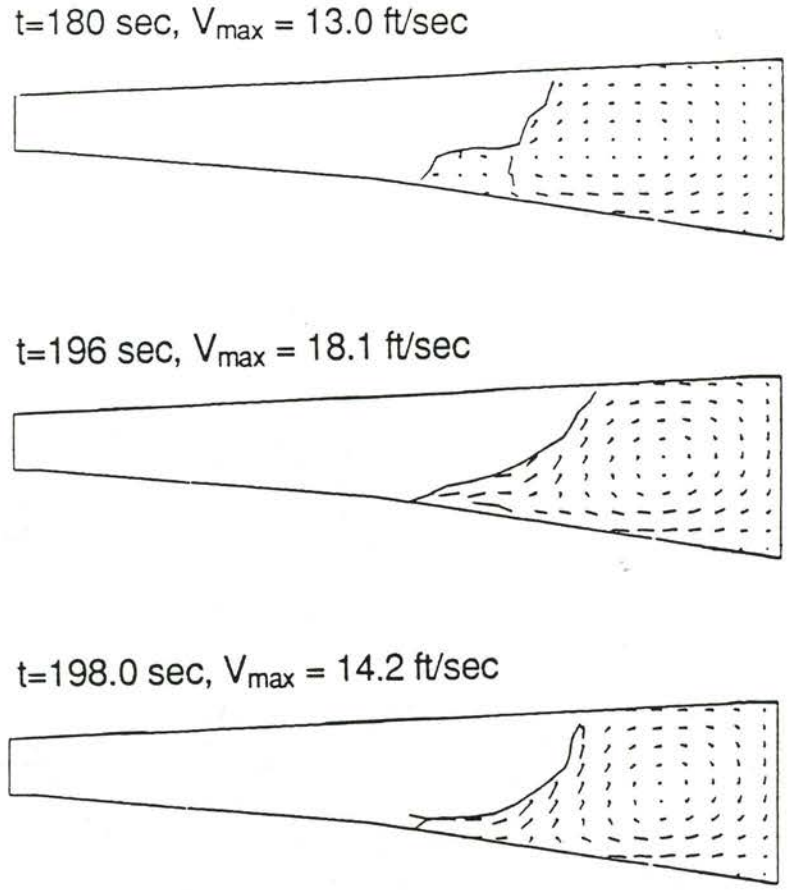

Figure 10. Hydrogen Tank Surface Deformation and Circulation Characteristics, ± 2° Rotation About the Vehicle Center of Gravity at 1.0 Hz Frequency