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Liquid Hydrogen Slosh Waves Excited by Constant Reverse Gravity Acceleration of Geyser Initiation

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A key objective of the cryogenic fluid management of the spacecraft propulsion system is to develop the technology necessary for acquisition or positioning of liquid and vapor within a tank in reduced gravity to enable liquid outflow or vapor venting. The requirement to settle or to position liquid fuel over the outlet end of the spacecraft propellant tank before main engine restart poses a microgravity fluid behavior problem. Resettlement or reorientation of liquid propellant can be accomplished by providing the optimal acceleration to the spacecraft such that the propellant is reoriented over the tank outlet. In this study slosh wave excitation induced by the resettling flowfield during the course of liquid reorientation with the initiation of geyser for liquid-filled levels of 30, 50, 65, 70, and 80% have been studied. Characteristics of slosh waves with various frequencies excited are discussed. Slosh wave excitations will affect the fluid stress distribution exerted on the container wall and shift the fluid mass distribution inside the container, which imposes the time-dependent variations in the moment of inertia of the container. This information is important for the spacecraft control during the course of liquid reorientation.

I. Introduction

FOR space-based spacecraft engine restart, it is necessary to have the liquid settle with no bubbles near the tank outlet so that the initial flow of propellant will not carry vapor to the pump or engine. The slosh wave amplitude should be relatively low to keep the center of mass shifts within an acceptable range and wave motion low enough to avoid pressure collapse caused by interface agitation. For venting, it is probably necessary that virtually all bubbles be displaced from the bulk liquid so that a two-phase mixture is not vented. Propellant transfer requires that the liquid be completely settled with virtually no bubbles. Outflow of a liquid near the tank outlet can result in the premature ingestion of gas while a significant amount of liquid is still in the tank under microgravity environment. This phenomenon is termed "suction dip." Slosh wave motion must be minimal because the combination of suction dip and sloshing could cause gas pull-through to occur more readily in microgravity than if the surface were essentially quiescent.

During the prepressurization of cryogenic propellant in microgravity, significant heat and mass transfer will occur if the liquid interface is disturbed. Interface disturbances may result from 1) impingement of the gas on the liquid surface at a mass flow rate sufficient to cause Kelvin-Helmholtz instability, 2) globule formation from breaking waves caused by wave motion over baffles or internal hardware, 3) globule and surface froth formation resulting from movement of bubbles through the liquid to the surface, and 4) surface froth formation because of gas impingement.

A key objective of the cryogenic fluid management of the spacecraft propulsion system, such as a space transfer vehicle (STV) or an orbital maneuvering vehicle (OMV),[1] is to develop the technology necessary for acquisition or positioning of liquid and vapor within a tank in reduced gravity to enable liquid outflow or vapor venting. Liquid acquisition techniques can be divided into two general categories: 1) active liquid acquisition by the creation of a positive acceleration environment resulting from the propulsive thrust of small auxiliary engines, and 2) passive liquid acquisition utilizing the liquid capillary forces provided by using solid baffles of liquid traps made of fine mesh screen material. In this study, active liquid acquisition is investigated by numerically simulating the resettlement of cryogenic liquid hydrogen.[2]

Recently, Leslie[3] was able to measure and numerically compute the bubble shapes at various ratios of centrifugal force to surface tension force in 2-, 4-, and 6.3-cm-deep cylinders in the microgravity environment. The results showed excellent agreement between model computation and measurements. Hung and Leslie[4] extended Leslie's work[3] to rotating free surfaces influenced by gravity with higher rotating speeds when the bubble shapes intersect with both the top and the bottom walls of the cylinder. Hung et al.[5,6] further extended the work to include rotating speeds that resulted in bubbles intersecting and/or not intersecting the top, bottom, and side walls of the cylinder.

An analysis of time-dependent dynamical behavior of surface tension on partially filled rotating fluids in both low gravity and microgravity environments was carried out by numerically solving the Navier-Stokes equations subjected to the initial and the boundary conditions.[5,7] At the interface between the liquid and the gaseous fluids, both the kinematic surface boundary condition and the interface stress conditions for components tangential and normal to the interface were applied. The initial condition for the bubble profiles was adopted from steady-state formulations developed by Hung and Leslie[4] and Hung et al.[7] for a rotating cylinder tank, and by Hung et al.[6,8] for the Dewar-shaped container to be used in the Gravity Probe-B Spacecraft.[9] Some of the steady-state formulations of bubble shapes, in particular for bubbles intersecting at the top wall of the cylinder, were compared with the experiment carried out by Leslie[3] in a free-falling aircraft (KC-135). Comparisons of time-dependent results between numerical computations and experiments were unavailable. This was because the calibration of the recordings of time-dependent gravity variations in a KC-135 aircraft during the short time periods of microgravity environment is very difficult. Also, accelerometer data on the actual levels of microgravity were not available.

Production of a geyser during the propellant reorientation[2] is not a desirable motion for the space fluid management because a geyser is always accompanied by the vapor entrain-

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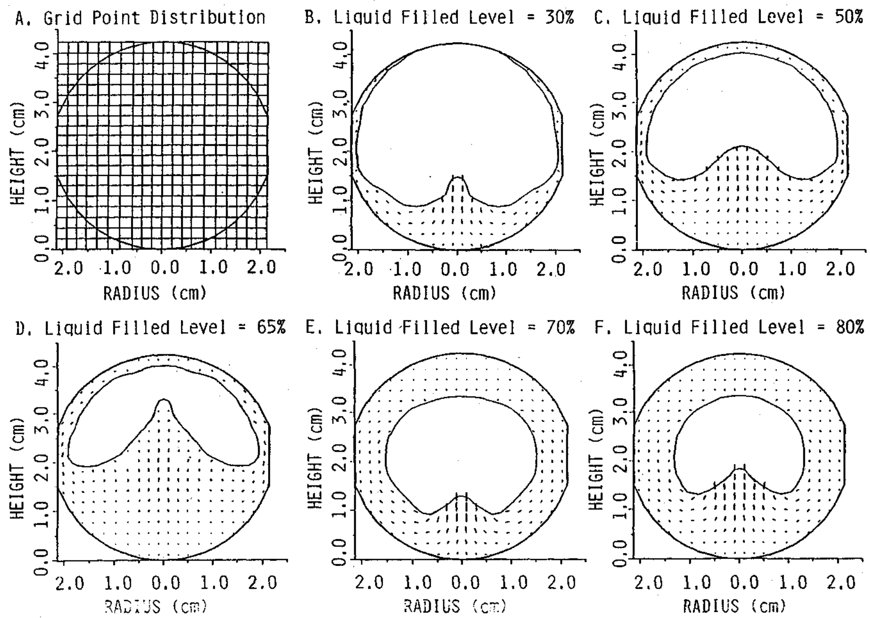

Fig. 1 Grid point distribution and selected flow profiles of fluid reorientation with geyser initiation; a) grid point distribution, b) flow profile with geyser initiation for liquid-filled level of 30%, c) flow profile for liquid-filled level of 50%, d) flow profile for liquid-filled level of 65%, e) flow profile for liquid-filled level of 70%, and f) flow profile for liquid-filled level of 80%.

ment and globule formation. A geyser is observed at reverse gravity thrust that is greater than certain critical values of acceleration during the course of liquid reorientation.[2] In other words, a geyser will not be observed at very low reverse gravity levels below a certain critical value. Numerical simulation of positive liquid acquisition was attempted by introducing reverse gravity acceleration, resulting from the propulsive thrust of small auxiliary engines, which exceeds the critical valuefor geyser initiation.[10–12] The reverse gravity acceleration was started with a small value and increased gradually until the initiation of geyser was detected in the computer simulation for the liquid reorientation of the propellant tank with various liquid-filled levels.[10–12]

In this study, time-dependent computations have been carried out to investigate the dynamical behavior of the characteristics of slosh waves excitation during fluid reorientation. This resettling of liquid propellant is required before main engine firing for spacecraft restart. Slosh wave excitations will affect the fluid stress distribution exerted on the container wall and shift the fluid mass distribution inside the container, which imposes the time-dependent variations in the moment of inertia of the container.[13] This information is particularly important for the spacecraft control during the course of liquid reorientation.[13]

II. Slosh Wave Excitation Due to Constant Reverse Gravity Acceleration During Reorientation with Geyser Initiation

A propellant tank with liquid-filled levels of 30, 50, 65, 70, and 80% is considered. Also, the time-dependent, axial-symmetry mathematical formulation is adopted for the purpose of this study. Detailed descriptions of the mathematical formulation and of initial and boundary conditions suitable for the analysis of cryogenic fluid management under microgravity environment are given in earlier studies.[2,5,7,13–16] The initial profiles of liquid-vapor interface are determined from the computations based on algorithms developed for the steady-state formulation of microgravity fluid management.[4–8]

A staggered grid for the velocity components is used in this computer program. The method was first developed by Harlow and Welch[17] for their marker and cell (MAC) method of studying fluid flows along a free surface. The finite difference method employed in this numerical study was the "hybrid scheme" developed by Spalding.[18] The formulation for this method is valid for any arbitrary interface location between the grid points and is not limited to middle point interfaces.[19] An algorithm for a semi-implicit method[20] was used as the procedure for modeling the flowfield. The time step is determined automatically based on the size of the grid points and the velocity of flowfields. A detailed description of the computational algorithm applicable to microgravity fluid management is illustrated in earlier studies.[2,5,7,13–16]

For the purpose of facilitating comparison between computational results and experimental measurements, a subscale model of 0.01-size prototype is adopted in the computer simulation. The dimensions of the prototype are height $L = 423.672$ cm (166.8 in.) and diameter $D = 426.72$ cm (168 in.). Model dimensions are $L = 4.24$ cm and $D = 4.27$ cm, as shown in Fig. 1a. If the spacecraft had been coasting for a long time, aligned with its direction of motion, the most significant force (drag) would be axial and with the acceleration of $10^{-5}g_0$ along an upward direction of Fig. 1a. The position of the fuel outlet is located at the bottom of the tank at $r = \pm 0.2$ cm. The hydrogen vapor is originally positioned at the bottom of the tank due to drag. In the recent study of computer simulation,[10] a small value of reverse gravity acceleration (downward direction in Fig. 1a) was provided by the propulsive thrust of a small auxiliary engine to initiate the reorientation of liquid propellant (originally positioned at the upper part of the tank, and to resettle toward the bottom of the tank, as shown in Fig. 1). This small value of reverse gravity acceleration of propulsive thrust increased gradually until reaching the critical value on which initiation of geyser was detected during the course of fluid resettlement.[10] We term this reverse gravity acceleration of propulsive thrust, which is able to initiate geyser, as "geyser initiation gravity level." This geyser initiation gravity level was investigated through the method of trial and error for the various liquid-filled levels of the propellant tank as a base to simulate cases of reduced gravity fluid behaviors during the course of reorientation. Cryogenic liquid hydrogen at a temperature of 20 K was considered. Hydrogen density of 0.071 g/cm^3, surface tension coefficient at the interface between liquid hydrogen and hydrogen vapor of 1.9 dyne/cm, hydrogen viscosity coefficient of 1.873×10^{-3} cm^2/s, and contact angle of 0.5 deg were used in the computer simulation.[10]

It was found that the geyser initiation gravity levels are 5.5×10^{-2}, 6.52×10^{-2}, 6.6×10^{-2}, 6.7×10^{-2}, and

Table 1 Characteristics of major slosh waves caused by resettlement of liquid reorientation, constant geyser initiation reverse acceleration = $5.5 \times 10^{-2} g_0$, liquid-filled level = 30%

Wave period, s	Wavelength, cm	Phase velocity, cm/s	Propagation direction (clockwise from positive axial direction), deg	Ratio of maximum wave amplitude to wavelength, 10^{-2}
0.12	1.62	13.54	± 173	0.195
0.21	0.11	0.53	± 170	0.273
0.50	2.71	5.42	± 177	5.078

8.2×10^{-2} g_0 for liquid-filled levels of 30, 50, 65, 70, and 80%, respectively.[10] Figures 1b-1f show the selected flow profiles with geysering motion during the course of fluid reorientation for cryogenic hydrogen with liquid-filled levels of 30, 50, 65, 70, and 80%, respectively.

The instability of a liquid surface can be induced by the presence of longitudinal and lateral accelerations, vehicle vibration, rotational fields of spacecraft, reorientation, and resettlement of liquid in a microgravity environment. Slosh waves are thus excited, which produces high and low frequency oscillations in the liquid propellant. The sources of the residual accelerations range from the effects of the Earth's gravity gradient, atmospheric drag on the spacecraft, and spacecraft attitude motion to the various frequency ranges of "g-jitters" arising from machinery vibrations, thruster firings, and crew motions.[13-16,21,22]

Various modes of slosh wave excitation for liquid-filled levels of 30, 50, 65, 70, and 80% have been investigated.

Slosh Waves Associated with Liquid-Filled Level of 30%

Slosh wave excitation during the course of liquid reorientation and resettlement was investigated. Figure 2 shows an example of the time series of wave amplitudes for liquid-vapor interface fluctuations during the time period for the initiation of geyser for 30% liquid-filled levels at $r_1 = 0.1$, $r_2 = 0.5$, and $r_3 = 0.974$ cm in the radial coordinate measured from the axial coordinate of the container. The wave period of various modes of slosh waves can be determined from the Fourier spectral analysis of the time series at r_1, r_2, and r_3, whereas wavelength, phase velocity, and propagation direction of slosh waves can be deduced from the cross-correlation analysis of the combinations of any two time series selected out of the three time series.[23-26] Figure 3 shows a sample Fourier power spectral analysis of time series at r_1. This figure clearly indicates that there are three major peaks of wave modes corresponding to wave periods of 0.12, 0.21, and 0.50 s. A filter shall be properly chosen to apply certain ranges of a window for separating these three wave modes from each other in three time series at r_1, r_2, and r_3, as shown in Fig. 2, for the determination of wavelength, phase velocity, and propagation direction of slosh waves.[23-26]

Table 1 shows the characteristics of major slosh waves induced by the resettling flowfield during the course of liquid fluid reorientation associated with a liquid-filled level of 30%. There are three major modes of slosh waves—high frequency (wave period of 0.12 s), medium frequency (wave period of 0.21 s), and low frequency (wave period of 0.50 s)—that resulted from this analysis. Propagation direction is measured clockwise from the positive axial direction. The ratio of maximum wave amplitude to wavelength [max(A/λ), where A stands for the wave amplitude, and λ is the wavelength of slosh wave] for each slosh wave is calculated based on the following procedures: 1) determine each wave mode based on the peaks of power intensity shown in the power spectral density analysis in the Fourier domain (see Fig. 3); 2) apply the proper window of filter to separate each wave mode shown on the peaks of power intensity; 3) calculate wavelength, phase velocity, and propagation direction of each wave mode from the cross-correlation analysis based on the separated wave modes through the filtering process of time series in the Fourier domain at locations r_1, r_2, and r_3; 4) apply reverse Fourier transform to the separated wave mode through the filtering process of time series in the Fourier domain to time domain and obtain the amplitude of each mode of slosh waves; and 5) compute the ratio of maximum wave amplitude

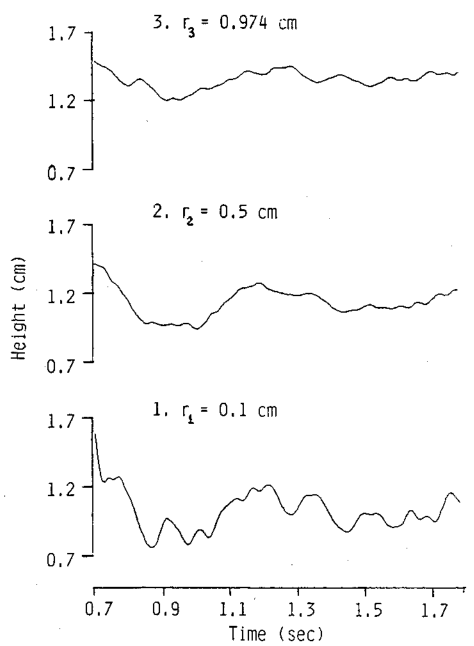

Fig. 2 Time series of wave amplitude fluctuations for the liquid-vapor interface with liquid-filled level of 30% during the course of liquid reorientation. Three time series shown in the figure are detected from interface at $r_1 = 0.1$, $r_2 = 0.5$, and $r_3 = 0.974$ cm in radial axis.

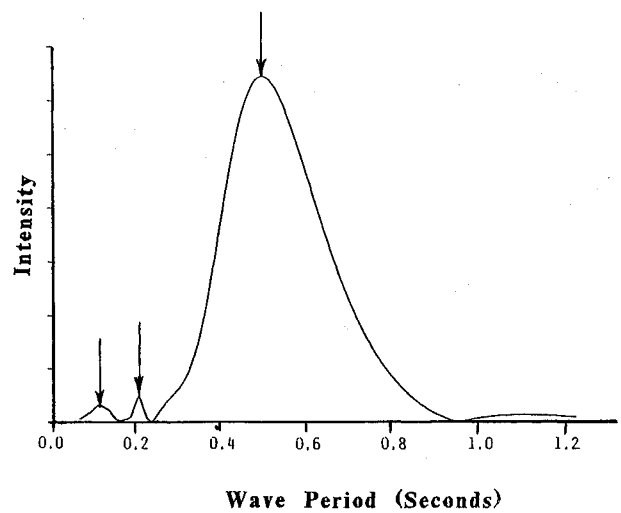

Fig. 3 Sample Fourier power spectral analysis of major peaks of wave modes for liquid-filled level of 30%.

Table 2 Characteristics of major slosh waves caused by resettlement of liquid reorientation, constant geyser initiation reverse acceleration = $6.52 \times 10^{-2} g_0$, liquid-filled level = 50%

Wave period, s	Wavelength, cm	Phase velocity, cm/s	Propagation direction (clockwise from positive axial direction), deg	Ratio of maximum wave amplitude to wavelength, 10^{-2}
0.15	0.66	4.42	± 177	0.195
0.20	0.24	1.20	± 6	0.391
0.50	1.73	3.46	± 169	2.852

Table 3 Characteristics of major slosh waves caused by resettlement of liquid reorientation, constant geyser initiation reverse acceleration = $6.6 \times 10^{-2} g_0$, liquid-filled level = 65%

Wave period, s	Wavelength, cm	Phase velocity, cm/s	Propagation direction (clockwise from positive axial direction), deg	Ratio of maximum wave amplitude to wavelength, 10^{-2}
0.17	0.53	3.14	± 8	0.195
0.22	0.35	1.57	± 2	0.391
0.50	16.61	33.21	± 161	5.66

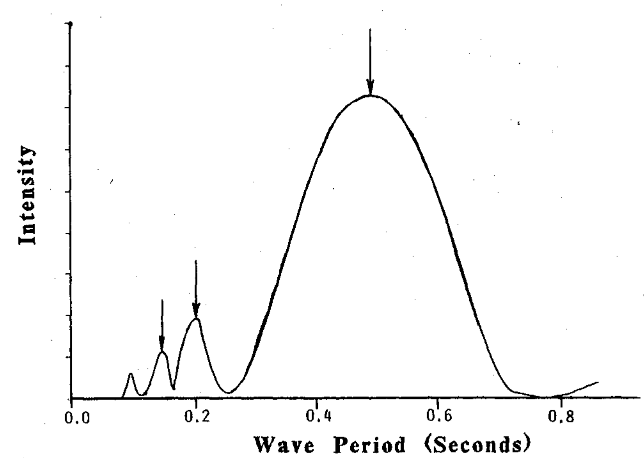

Fig. 4 Sample Fourier power spectral analysis of major peaks of wave modes for liquid-filled level of 50%.

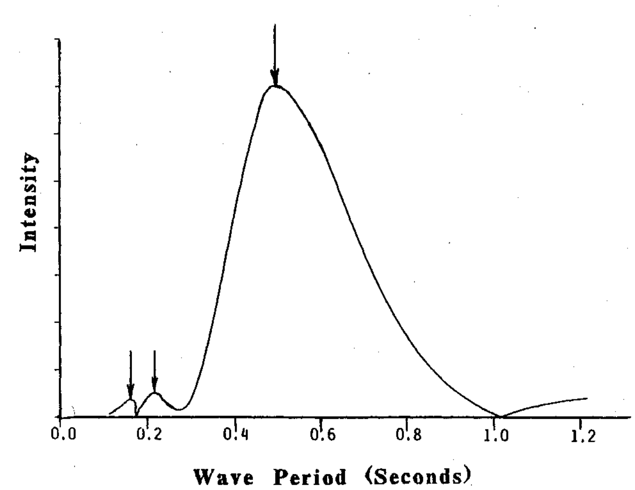

Fig. 5 Sample Fourier power spectral analysis of major peaks of wave modes for liquid-filled level of 65%.

to wavelength [max(A/λ)] for each mode of slosh waves from items 3 and 4. Three major slosh waves, shown in Fig. 3, provide the major contribution in liquid-vapor interface fluctuations that, in turn, shift fluid mass distribution of spacecraft.[16]

The study of slosh wave excitation induced by fluid reorientation associated with liquid-filled levels of 30% leads to the following conclusions: 1) a series of longitudinal wave trains of the slosh waves propagates more or less along the axial direction of the container, 2) slosh waves with the lowest frequency are associated with the highest value of max(A/λ) ratio wave modes, 3) slosh waves with the lowest frequency contain the highest wave intensity (see Fig. 3), which is also equivalent to the highest wave energy, and 4) reverse gravity acceleration along the axial direction is responsible for the excitation of slosh waves with various frequencies.

Slosh Waves Associated with Liquid-Filled Level of 50%

Computer simulation of the time series evolution of liquid-vapor interface fluctuations, Fourier spectral analysis of time series, cross-correlation analysis of wave spectrum, etc., for slosh wave excitation associated with a liquid-filled level of 50% are similar to those with a liquid-filled level of 30%. Figure 4 shows a sample Fourier power spectral analysis of time series associated with a liquid-filled level of 50%. This figure shows that there are three major peaks of wave modes corresponding to wave periods of 0.15, 0.20, and 0.50 s. Table 2 shows the characteristics of major slosh waves induced by the resettling flowfield during the course of liquid reorientation associated with liquid-filled level of 50%.

The conclusions drawn from the study of slosh wave excitations associated with a liquid-filled level of 50% are as follows: 1) The characteristics of slosh waves associated with 30 and 50% liquid-filled levels show basically no prominent differences. 2) The reverse gravity acceleration needed to activate the liquid reorientation with an initiation of geyser requires $6.52 \times 10^{-2} g_0$ for 50% liquid-filled level, which takes $5.5 \times 10^{-2} g_0$ for 30% liquid-filled level.[10-12]

Slosh Waves Associated with Liquid-Filled Levels of 65, 70, and 80%

Figures 5, 6, and 7 show the sample Fourier power spectral analysis of time series associated with liquid-filled levels of 65, 70, and 80%, respectively. These figures show that there are three major peaks corresponding to 1) wave periods of 0.17, 0.22, and 0.50 s for liquid-filled levels of 65%; 2) wave periods

Table 4 Characteristics of major slosh waves caused by resettlement of liquid reorientation, constant geyser initiation reverse acceleration = $6.7 \times 10^{-2} g_0$, liquid-filled level = 70%

Wave period, s	Wavelength, cm	Phase velocity, cm/s	Propagation direction (clockwise from positive axial direction), deg	Ratio of maximum wave amplitude to wavelength, 10^{-2}
0.13	0.89	6.83	± 9	0.313
0.23	0.28	1.21	± 7	0.43
0.57	0.58	1.01	± 14	2.54

Table 5 Characteristics of major slosh waves caused by resettlement of liquid reorientation, constant geyser initiation reverse acceleration = $8.2 \times 10^{-2} g_0$ liquid-filled level = 80%

Wave period, s	Wavelength, cm	Phase velocity, cm/s	Propagation direction (clockwise from positive axial direction), deg	Ratio of maximum wave amplitude to wavelength, 10^{-2}
0.11	4.41	40.08	± 174	1.95
0.21	0.99	4.70	± 13	2.73
0.43	0.49	1.14	± 10	7.03

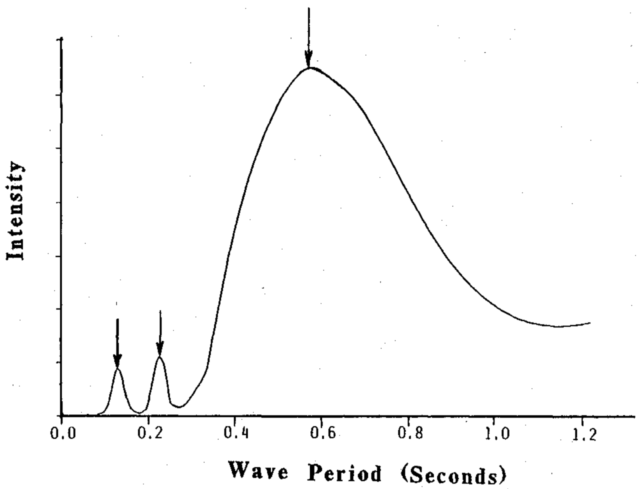

Fig. 6 **Sample Fourier power spectral analysis of major peaks of wave modes for liquid-filled level of 70%.**

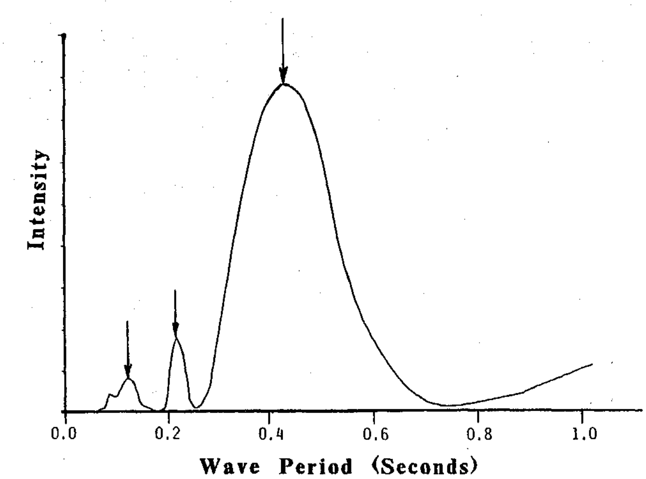

Fig. 7 **Sample Fourier power spectral analysis of major peaks of wave modes for liquid-filled level of 80%.**

of 0.13, 0.23, and 0.57 s for liquid-filled level of 70%; and 3) wave periods of 0.11, 0.21, and 0.43 s for liquid-filled level of 80%. Tables 3, 4, and 5 show the characteristics of major slosh waves induced by the resettling flowfield during the reorientation associated with liquid-filled levels of 65, 70, and 80%, respectively.

In addition to the conclusions drawn earlier, it is further confirmed that the reverse gravity acceleration required to activate reorientation with the initiation of geyser shall increase from $6.6 \times 10^{-2} g_0$ for a liquid-filled level of 65% to $6.7 \times 10^{-2} g_0$ for a liquid-filled level of 70%, and then to $8.2 \times 10^{-2} g_0$ for a liquid-filled level of 80%.[10-12] There is no geysering flow initiated for the reverse gravity acceleration below the corresponding values of liquid-filled levels mentioned earlier. Also, there are no prominent differences in the characteristics of slosh wave excitations for the variations of liquid-filled levels among 30, 50, 65, 70, and 80%. It is shown that slosh waves with the lowest wave frequency excited by the fluid reorientation for each liquid-filled level contain the highest wave intensity longitudinal modes that propagate along the axial direction of the propellant tank.

III. Discussion and Conclusions

The requirement to settle or to position liquid fluid over the outlet end of the spacecraft propellant tank before main engine restart poses a microgravity fluid behavior problem. Retromaneuvers of spacecraft require settling or reorientation of propellant prior to main engine firing. Cryogenic liquid propellant is positioned over the tank outlet by using auxiliary thrusters (or idle-mode thrusters from the main engine) that provide a thrust parallel to the tank's major axis in the direction of flight.

Our results show that there is a group of wave trains with various frequencies and wavelengths of slosh waves generated by the resettling flowfield activated by the reverse gravity acceleration. The following conclusions have been drawn from the present study.

1) A series of longitudinal wave trains of slosh waves, which propagate along the direction of the thrust force, are excited during the course of liquid reorientation.

2) Slosh waves with the lowest frequency are always associated with the highest values of $\max(A/\lambda)$ ratio wave modes.

3) Slosh waves with the lowest frequency contain the highest wave intensity (see Figs. 3–7), which are equivalent to the highest wave energy.

4) Reverse gravity acceleration along the axial direction is responsible for the excitation of slosh waves with various frequencies.

5) Reverse gravity acceleration required to activate the liquid reorientation must increase the thrust forces accordingly to maintain the momentum for the initiation of geyser as the liquid-filled levels increase.

6) There are no distinctive differences in wave characteristics for the slosh waves excited with the various liquid-filled levels of the propellant tank.

Lack of distinctive difference among the wave characteristics can be explained by the fact of similarity in the flow patterns at the moment of geyser initiation for the different liquid-filled levels. It is noted that the amount of reverse gravity acceleration required for the activation of liquid reorientation increases with increasing liquid-filled levels for adjusting the flow patterns of geyser initiation.[10-12,27]

Any fluid capable of motion relative to the spacecraft will be subject to an acceleration relative to the mass center of the spacecraft that arises from the gravity gradient of the Earth.[28-30] In addition to the Earth's gravitational force, the interaction between the particle mass of fluids and the spacecraft mass due to gravity gradient accelerations[28] are capable of the excitation of slosh waves in the fluid systems. These subjects are all considered in this study.

Slosh wave excitation during the course of liquid reorientation will change and disturb both the fluid stress distribution exerted on the container wall and also the moment of inertia of the propellant container.[13] In other words, fluctuations in fluid stress distribution will cause the disturbance in torque applied to the container, and the change of moment of inertia through the shifting of liquid distribution due to the slosh wave excitation will perturb the angular momentum of the container during the liquid reorientation.[13] The study presented can be used to simulate the fluid behavior during the course of liquid resettling and reorientation, in particular, the excitation of slosh waves due to resettling flowfield activated by the reverse gravity acceleration. Results may provide information of interest to handling and managing of cryogenic liquid propellant to be used in the space-based spacecraft propulsion system (in particular, the guidance and control of the spacecraft).

Acknowledgments

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