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EXPERIMENTAL INVESTIGATION OF STABILITY BOUNDARIES FOR PLANAR AND NONPLANAR SLOSHING IN SPHERICAL TANKS

by Irving E. Sumner

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Cleveland, Ohio

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EXPERIMENTAL INVESTIGATION OF STABILITY BOUNDARIES FOR PLANAR AND NONPLANAR SLOSHING IN SPHERICAL TANKS

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SUMMARY

An experimental investigation was conducted to determine the stability boundaries for both planar and nonplanar motion of the liquid surface in partly filled spherical tanks undergoing lateral sinusoidal oscillations near the fundamental frequency of the liquid oscillations. Tests were conducted over a range of excitation amplitudes for liquid depths from nearly full to nearly empty in tanks with diameters of 0.813, 0.523, and 0.241 meter. The contained slosh liquid was water in all cases.

Three distinct types of motion of the liquid surface were observed: stable planar, stable nonplanar, and unstable. The tank excitation frequencies and amplitudes, which define the stability boundaries separating stable and unstable motion, are presented in terms of nondimensional parameters that generalize the effect of tank size for the range investigated.

INTRODUCTION

When a partly filled liquid container is subjected to lateral, sinusoidal oscillations with excitation frequencies equal to or near the fundamental frequency of the contained liquid, the relatively flat free surface may not necessarily continue to undergo a steady-state harmonic motion in which the liquid surface appears to pivot about one stationary nodal diameter that remains normal to the direction of excitation of the container. Instead, a rotating wave may be set up in which both the direction and rate of rotation of the nodal diameter may or may not vary with time. In addition, the peak wave height (maximum wave height of free surface above the quiescent liquid level and adjacent to the tank wall during a given slosh cycle) may or may not vary with time. This behavior of the liquid surface under sloshing conditions may occur in the propellant tanks of boost, upper atmosphere, and space vehicles, thereby adversely affecting the stability of the vehicle. In one instance, a rotary or swirling motion of the liquid surface in a propellant tank apparently was the cause for the failure of such a vehicle.

Three distinct types of liquid motion or sloshing can be noted over a range of excitation frequencies encompassing the fundamental frequency of the contained liquid. These types of motion are defined as (1) stable planar, (2) stable nonplanar, and (3) unstable; each type of motion may be described as follows:

(1) Stable planar motion of the liquid surface is a steady-state harmonic motion with (a) a peak wave height that does not vary with time and (b) a single stationary nodal diameter that remains normal to the direction of tank excitation. The oscillation frequency of the liquid surface is equal to the excitation frequency of the tank. This type of motion is most generally associated with the fundamental mode of liquid sloshing.

(2) Stable nonplanar motion is a steady-state rotary motion of the liquid surface with (a) a constant peak wave height and (b) a single nodal diameter that rotates in one direction at a constant angular velocity. The frequency of the angular rotation of the nodal diameter is equal to the excitation frequency of the tank.

(3) Unstable motion is a rotary motion of the liquid surface that never attains a steady-state harmonic response; that is, the (a) peak wave height and (b) nodal diameter rate and direction of rotation continually change with time. The wave height of the liquid surface may build up and decay; the nodal diameter may rotate first in one direction, stop, and then rotate in the other direction. At times the liquid surface may oscillate for several cycles with the nodal diameter parallel to the direction of tank excitation; the nodal diameter may then rotate and stop in a position normal to the direction of tank excitation at which time the liquid surface may again oscillate for several cycles. The nodal diameter may, however, stop in any angular position in the horizontal plane with respect to the direction of tank excitation. The frequency of the angular rotation of the nodal diameter is less than the excitation frequency of the tank.

Generally, the free surface of the liquid remains essentially plane, and it is the rotation of this inclined plane about the vertical axis of symmetry (fig. 1) that creates the apparent rotary motion of the liquid surface in stable nonplanar and unstable sloshing.

The unstable motion of the liquid surface in partly filled tanks has been observed by numerous investigators. The first known analytical description (ref. 1) relates this phenomenon to a pendulum analogy that led to the establishment of stability boundaries between regions of stable planar and unstable motion for cylindrical tanks. The analysis predicts the existence of threshold excitation frequencies beyond which unstable motion of the liquid surface due to lateral oscillations of the tank will occur. The pendulum analogy was extended to include appropriate third-order terms (ref. 2), which led to a comprehensive nonlinear theory of the motion of the free surface for cylindrical tanks (ref. 3). This theory demonstrates that the rotary liquid motion arises as a consequence of a nonlinear coupling between liquid motions parallel and perpendicular to the plane of excitation, and that this coupling takes place through the free surface waves (ref. 4). The small amount of experimental data obtained for cylindrical tanks (refs. 1, 3, and 5) show good agreement with the theory. In addition, a theoretical and experimental investigation was conducted to determine the liquid particle motion in the direction of the free surface wave for a partly filled cylindrical tank (ref. 6).

The existence of unstable sloshing characteristics in partly filled spherical tanks has been noted previously in several experimental investigations (e.g., ref. 7). However, no known analytical or experimental investigations of the stability boundaries for planar and nonplanar motion of the liquid surface have been initiated for the spherical tank configuration.

Therefore, an experimental investigation was conducted at the NASA Lewis Research Center to determine the stability boundaries for both planar and nonplanar motion of the liquid free surface in partly filled spherical tanks. The primary purpose of this investigation was to provide information of liquid sloshing characteristics in support of a program dealing with the pressurization and expulsion of cryogenic propellants from large-scale spherical tanks. In the investigation reported herein, small-scale spherical tanks with diameters of 0.813, 0.523, and 0.241 meter were utilized. Stability boundaries were determined for a range of liquid depths from a nearly full to a nearly empty tank; data were obtained over a range of excitation amplitudes at each liquid depth. The contained liquid was water in all cases. The results are presented in a dimensionless form to generalize the effect of tank diameter.

SYMBOLS

D tank diameter, m

f angular rate of rotation of nodal diameter, cps

f_n fundamental frequency of liquid oscillations, cps

f_o excitation frequency of tank, cps

f_o/f_n excitation frequency ratio

h liquid depth, m

h/D liquid depth ratio

k_1,k_2 constants determined for eq. (1)

X_o excitation amplitude, m

X_o/D excitation amplitude parameter

APPARATUS

Spherical tanks with diameters of 0.813, 0.523, and 0.241 meter were fabricated from clear plastic. The diameter of each tank was carefully measured at several places in the horizontal plane of the equator. The eccentricity ($\Delta D/D$) of the equatorial diameter varied between values of 0.0021 to 0.0029 for the three tanks. Each tank was mounted on the test facility so that the major axis of the slightly elliptical great circle of the equator was parallel to the direction of excitation of the tank.

The test facility is shown in figure 2. Each tank was mounted on a test bed that was suspended and pinned to a frame. The frame was suspended from overhead crossbeams and was free to oscillate in one direction in the horizontal plane. The driving force was provided by a hydraulic piston and cylinder actuated by an electrically controlled servovalve. The excitation amplitude of the test facility could be varied from 0 to 0.0254 meter, and the excitation frequency could be varied from 0 to 20 cycles per second.

PROCEDURE

Each tank was filled with water to an arbitrary liquid depth; liquid-depth ratios h/D of 0.1, 0.3, 0.5, 0.7, and 0.9 were chosen for this investigation. The fundamental frequency f_n was obtained by timing several cycles of the planar oscillations of the liquid surface with a stop watch and then averaging the results of at least six such experimentally determined frequencies. The experimentally determined averages are compared in table I with analytically predicted values (ref. 7) for each tank size and with previously determined experimental values (ref. 8) for the 0.813-meter-diameter tank.

An arbitrary excitation amplitude within the range $0.00088 \leq X_o/D \leq 0.01484$ was selected, and the excitation frequency was initially set well below or above the fundamental frequency of the contained liquid so that stable planar motion of the liquid surface was established. The excitation frequency was then varied in small discrete increments to approach the fundamental frequency (resonance). At each excitation frequency setting, the planar motion was allowed to oscillate for a minimum of 10 cycles to ensure that the peak wave height of the liquid surface had reached steady state. The motion of the liquid surface was observed visually, and the excitation frequency at which unstable motion initially appeared was determined. Data were generally obtained over a range of excitation amplitudes for each liquid-depth ratio. The stability boundaries for stable nonplanar motion were determined in the same manner as for stable planar motion.

The excitation amplitude and frequency ($f_o < 1.2$ cps) of the tank could be set with accuracies better than ±2 and ±0.5 percent, respectively. To obtain higher excitation frequencies ($f_o > 1.2$ cps), it was necessary to switch to the next higher decade of frequency settings on the signal function generator. Since it was desirable to keep the incremental changes in the excitation frequency as small as possible, which in turn, necessitated an almost imperceptible change in the dial setting of the function generator, the excitation frequencies of the tank were determined from oscillograph traces of a feedback signal from the servovalve for each data point. Although the incremental changes in excitation frequency were irregular and greater above 1.2 cycles per second than below, the excitation frequency could still be determined with an accuracy better than ±0.5 percent.

RESULTS AND DISCUSSION

General

The response of the free surface in a spherical tank undergoing a lateral oscillatory motion of an arbitrary but constant excitation amplitude is shown in figure 3 for a range of excitation frequencies encompassing the fundamental frequency of the contained liquid. When the tank was oscillated at a frequency appreciably below the fundamental frequency ($f_o/f_n \ll 1$), a steady-state harmonic (stable planar) motion was established in which the peak wave height was constant and the nodal diameter remained normal to the direction of excitation. The frequency of oscillation of the liquid surface was equal to the excitation frequency of the tank. As the excitation frequency was increased to approach resonance, the peak wave height also increased until point 1, which represents the maximum peak wave height that could be obtained for stable planar motion, was reached. If a further increase of the excitation frequency toward resonance occurred, the nodal diameter began to rotate at an unsteady rate ($f < f_o$) and with a varying peak wave height characteristic of unstable motion. The unstable motion persisted as the excitation frequency was increased up to or slightly above resonance.

When the tank was oscillated at an excitation frequency somewhat above the fundamental frequency (but well below the second natural frequency) of the contained liquid, stable planar motion of the liquid free surface could again be established. As the excitation frequency was decreased toward resonance, the peak wave height again increased until point 2 was reached. A further decrease of the excitation frequency resulted in unstable motion. The range of excitation frequency ratios between points 1 and 2 represents the unstable region for planar motion.

It should be observed, however, that if the tank was oscillated at an excitation frequency somewhat above the fundamental frequency (but well below the second natural frequency) of the contained liquid, it was also possible to establish stable nonplanar motion in which the peak wave height remained constant with time and the nodal diameter rotated at a constant angular rate ($f = f_o$). As the excitation frequency was decreased toward resonance, the peak wave height decreased, and the angular rotational rate of the nodal diameter also decreased (so that f remained equal to f_o) until point 3 was reached. A further decrease of the excitation frequency resulted in unstable motion.

For the assumption that the excitation frequency ratio (f_o/f_n) was initially nearly equal to 1.0 so that unstable motion of the liquid free surface was established, an increase of the excitation frequency somewhat above resonance could result in either stable planar or stable nonplanar motion depending upon the liquid sloshing conditions during the time that the excitation frequency was increased. When the peak wave height was small and/or the rotational rate of the nodal diameter was relatively low during the time that the excitation frequency was increased to a value somewhat greater than that at point 2, stable planar motion of the liquid free surface was established. If, however, the peak wave height was large and the rotational rate of the nodal diameter was relatively high ($f \approx f_o$) during the time that the excitation frequency was increased to some value greater than that at point 3, stable nonplanar motion of the liquid surface could be established. Under actual test conditions, however, it was difficult to establish stable nonplanar motion (1) without a very slow and careful increase of the excitation frequency and (2) unless the excitation frequency was increased above the unstable region for planar motion (greater than that associated with point 2). It should be noted here that stable nonplanar motion, if already established, would persist over the excitation frequency range between points 2 and 3. However, stable nonplanar motion could not be established over the excitation frequency range between points 2 and 3 if the liquid free surface was initially in the unstable mode of sloshing.

The purpose of this experimental investigation was to determine the particular stability boundaries or excitation frequency ratios corresponding to points 1, 2, and 3 for stable planar and nonplanar motion at which any further variation of the excitation frequency ratio toward resonance would produce unstable motion. Experimental data were obtained over a range of excitation amplitudes for each liquid-depth ratio investigated. The experimental results are presented in terms of the parameters $(X_o/D)^{2/3}$ and $(f_o/f_n)^2$ to obtain a straight-line relation between the excitation amplitude parameter X_o/D and the excitation frequency ratio f_o/f_n as well as to generalize the effect of tank size (ref. 3).

Planar Motion

The stability boundaries for planar motion of the liquid surface are shown in figure 4 for the liquid-depth ratios (h/D = 0.1, 0.3, 0.5, 0.7, and 0.9) investigated in the 0.813-, 0.523-, and 0.241-meter-diameter tanks. Generally, the stable regions of planar motion are located both above and below the resonant condition, and the unstable region, located near resonance, separates the stable regions. It was observed, however, that for small values of the excitation amplitude parameter, the planar motion remained stable, even when the tank was oscillated at the resonant frequency. This was apparently a result of a small but finite amount of liquid damping present, which tended to limit the peak wave height of the liquid surface.

It was observed that, for liquid-depth ratios h/D greater than or equal to 0.5 (figs. 4(c) to (e)), there were regions where drops of liquid splashed from the tank wall and showered through the ullage (fig. 2(b)). The severity of the splashing increased as the resonant frequency was approached. Although no rotation of the nodal diameter was observed in this splash region, the motion of the liquid surface was arbitrarily defined to be unstable. The curvature of the tank wall undoubtedly caused the liquid splashing to occur and also limited the peak wave height of the free surface; it is believed that a rotary unstable motion of the nodal diameter probably would have occurred in this region if the peak wave height had not been limited by the tank wall. The existence of this region is noted here since it may have important implications in the pressurization and expulsion studies for cryogenic liquids (e.g., liquid splashing through the ullage volume may cool the relatively hot pressurant gas thereby causing a reduction in the tank pressure or an increased pressurant gas demand to maintain a constant tank pressure).

Generally, the planer motion of the liquid free surface became unstable over a wider range of excitation frequency ratios encompassing the resonant condition as (1) the excitation amplitude parameter was increased for each liquid-depth ratio and (2) the liquid-depth ratio was increased for a given value of the excitation amplitude parameter. The experimental results in the generalized form, $(X_o/D)^{2/3}$ as a function of $(f_o/f_n)^2$, were coincident for the three tank diameters investigated indicating that the stability boundaries presented herein should be applicable for spherical tanks of any size containing lightly damped liquids.

The transition from stable planar to unstable motion was generally quite definite when the excitation frequency was shifted across the stability boundary. The surface of the liquid, however, did not necessarily remain completely flat, but generally had many ripples imposed upon it as the stability boundary was reached. In addition, there was a narrow region lying roughly parallel to but displaced slightly from the lower stability boundary in the stable planar region where a vertical (axisymmetric) oscillation of the liquid surface at the vertical axis of symmetry of the tank appeared and was superimposed on the normal planar (asymmetric) motion of the liquid surface. The frequency of this vertical oscillation was equal to twice the excitation frequency, and the peak amplitude of the vertical motion occurred when the wave height of the liquid surface at the tank wall was approximately equal to the quiescent liquid level. The existence of the vertical oscillations was more predominant at the lower liquid-depth ratios and higher excitation amplitudes. No attempt was made, however, to map out the exact regions where these vertical oscillations occurred.

Nonplanar Motion

The stability boundaries for nonplanar motion of the liquid surface are shown in figure 5. Generally, as the excitation amplitude parameter was increased, the nonplanar motion became unstable at greater values of the excitation frequency ratio above resonance. This differs from the results presented in reference 3 for cylindrical tanks where the nonplanar motion became unstable at lower values of the excitation frequency parameter below resonance as the excitation amplitude parameter was increased. The reason for this discrepancy is not clear at the present time. Little effect of the liquid-depth ratio on the location of the stability boundaries was noted. The experimental results in the generalized form, $(X_o/D)^{2/3}$ as a function of $(f_o/f_n)^2$, were coincident for the three tank diameters investigated indicating that the stability boundaries presented herein should be applicable for spherical tanks of any size containing lightly damped liquids.

There was a finite transition region between the stable nonplanar and unstable regions where the liquid surface appeared to rotate at a constant speed $(f = f_o)$; however, the peak wave height of the liquid surface did not remain constant but appeared to vary sinusoidally at a frequency equal to twice the excitation frequency (fig. 6). Generally, the peak wave height (1) increased when the nodal diameter was parallel to the direction of tank motion and (2) decreased when the nodal diameter was normal to the direction of tank motion while traversing the transition region from the stable toward the unstable regions. The stability boundary was assumed to have been reached at the excitation frequency where the peak wave height, for which the nodal diameter was normal to the direction of excitation, approached zero, and there was no apparent rotary motion of the nodal diameter for short periods of time. The width of this transition region was generally small for all liquid depths investigated with the exception of $h/D = 0.7$ (fig. 5(d)), where the width of the transition region appeared to be quite large and considerable difficulty was experienced in determining the stability boundary. In addition, the stable nonplanar motion of the liquid surface became more difficult to establish as the excitation amplitude parameter decreased, particularly at the lower liquid-depth ratios.

The faired curves of the stability boundaries presented in figures 4 and 5 were in general, hand drawn on the basis of experimental data obtained for the 0.813-meter-diameter tank because the incremental changes of the excitation frequency could be varied more accurately than for the two smaller tank sizes investigated. Experimental data for the 0.523- and 0.241-meter-diameter tanks were then plotted to check the scaling parameters $(X_o/D)^{2/3}$ and $(f_o/f_n)^2$.

Stability Boundary Equation

The experimental stability boundaries of both the planar and nonplanar motion of the liquid surface can be expressed in terms of the following equation:

$$\left(\frac{f_o}{f_n}\right)^2 = k_1 + k_2\left(\frac{X_o}{D}\right)^{2/3} \tag{1}$$

The values of the constants k_1 and k_2 determined in this investigation are presented in figure 7 for the range of liquid-depth ratios investigated.

SUMMARY OF RESULTS

An experimental investigation was conducted to determine the stability boundaries for both planar and nonplanar motion of the liquid surface in partly filled spherical tanks undergoing lateral sinusoidal oscillations. Tests were conducted over a range of excitation amplitudes at liquid depths from nearly full to nearly empty for tanks with diameters of 0.813, 0.523, and 0.241 meter.

It was observed that planar motion of the liquid surface became unstable over a wider range of excitation frequencies encompassing the resonant condition as the excitation amplitude parameter and liquid-depth ratio were increased. The nonplanar motion generally became unstable at greater values of the excitation frequency ratio above resonance as the excitation amplitude parameter was increased, but little effect with a variation of liquid-depth ratio was noted. The experimental results in the generalized form, excitation amplitude parameter $(X_o/D)^{2/3}$ as a function of excitation frequency ratio $(f_o/f_n)^2$, were coincident for the three tank diameters investigated indicating that the stability boundaries presented should be applicable for spherical tanks of any size containing lightly damped liquids. The transition region between stable and unstable motion was generally observed to be small except in the case of nonplanar motion at a liquid-depth ratio of 0.7 where a wide transition region was found.

It was also observed that regions of severe splashing of liquid through the ullage existed for planar motion without any rotary motion of the nodal diameter for liquid-depth ratios equal to or greater than 0.5. The motion of the liquid surface in this region was arbitrarily defined to be unstable.

In addition, there was a narrow region lying roughly parallel to but displaced slightly from the lower stability boundary in the stable planar region where a vertical oscillation of the liquid surface at the vertical axis of symmetry of the tank appeared and was superimposed on the normal planar motion of the liquid surface. No attempt was made, however, to map out the exact regions where these vertical oscillations occurred.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 10, 1965.

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TABLE I. - COMPARISON OF EXPERIMENTAL AND ANALYTICAL FUNDAMENTAL FREQUENCIES OF PLANAR SLOSHING IN SPHERICAL TANKS

Liquid depth ratio, h/D	Analytical (ref. 7)			Experimental (a)			Experimental (ref. 8)
	Tank diameter, D, m						
	0.241	0.523	0.813	0.241	0.523	0.813	0.813
	Fundamental frequency, cps						
0.1	1.517	1.028	0.826	1.480	0.988	0.797	0.791
.3	1.632	1.105	.888	1.612	1.087	.876	.870
.5	1.799	1.219	.980	1.792	1.208	.972	.969
.7	2.085	1.412	1.135	2.091	1.410	1.134	1.134
.9	2.837	1.922	1.545	2.800	1.930	1.550	1.552

[a]Average value, maximum deviation, ±3 percent.

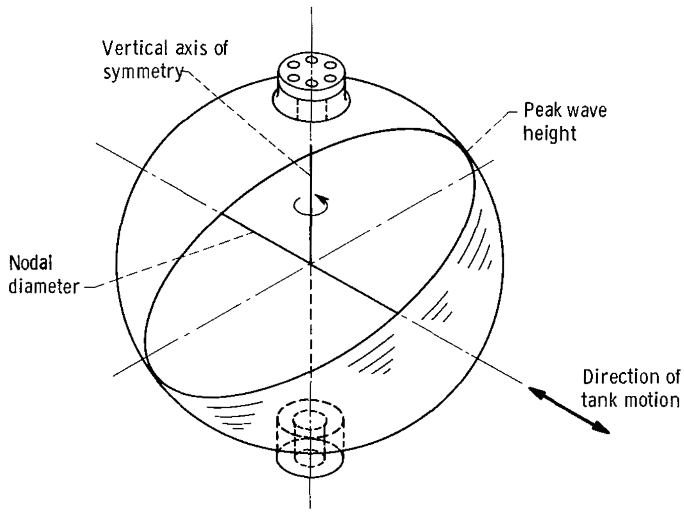
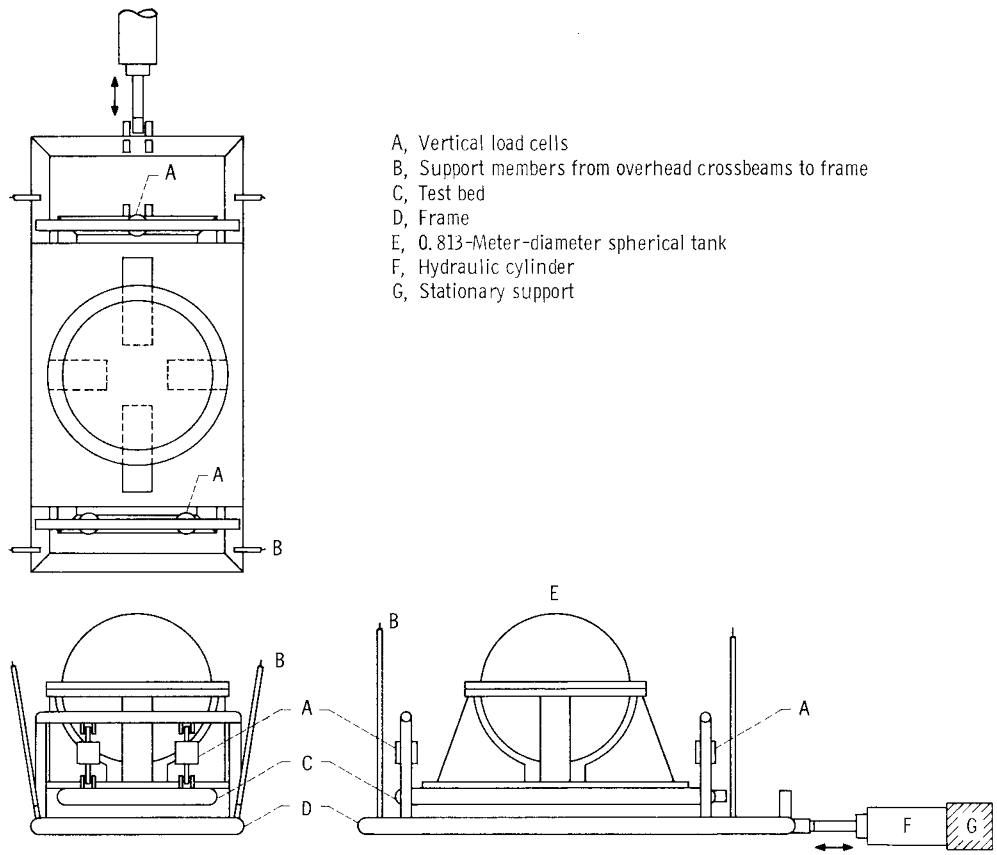
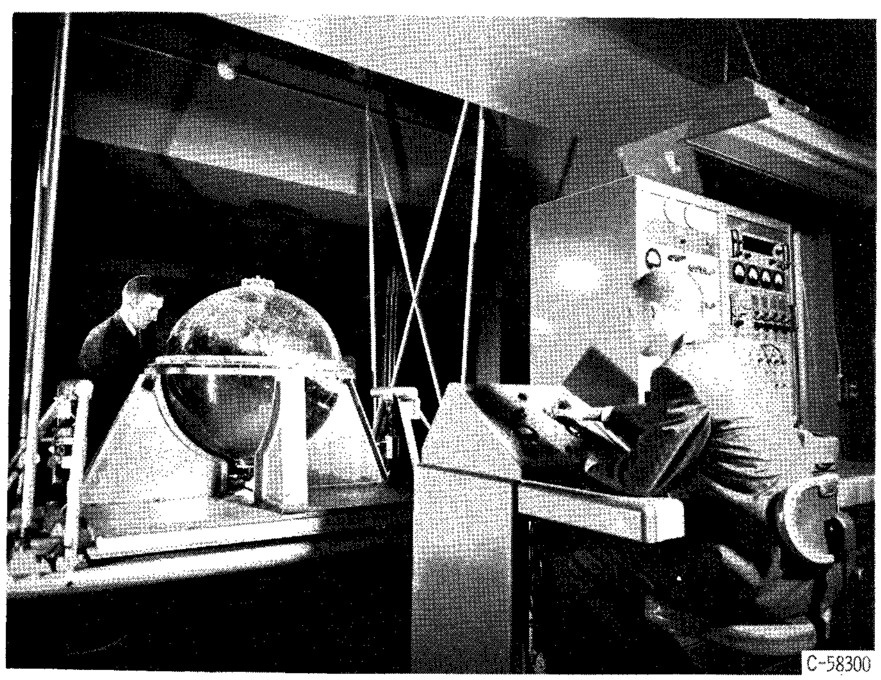


Figure 1. - Typical rotary motion of liquid surface.



(a) Schematic view.



(b) Pictorial view.

Figure 2. - Experimental test facility.

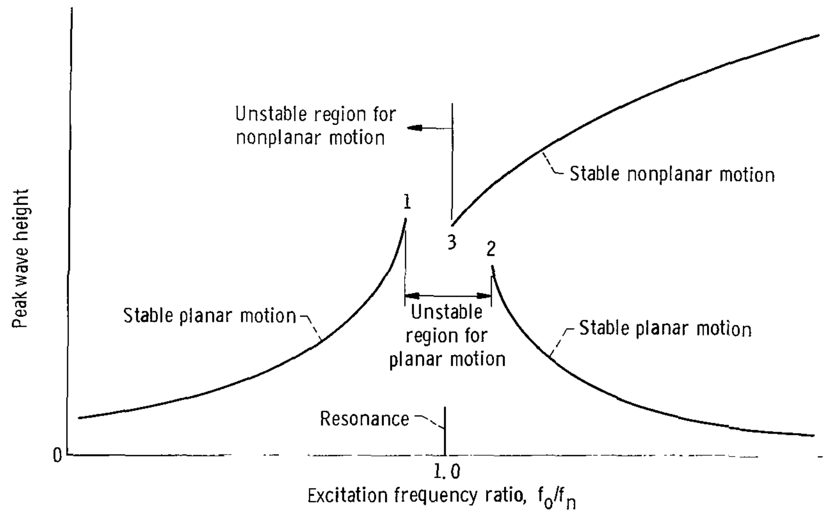
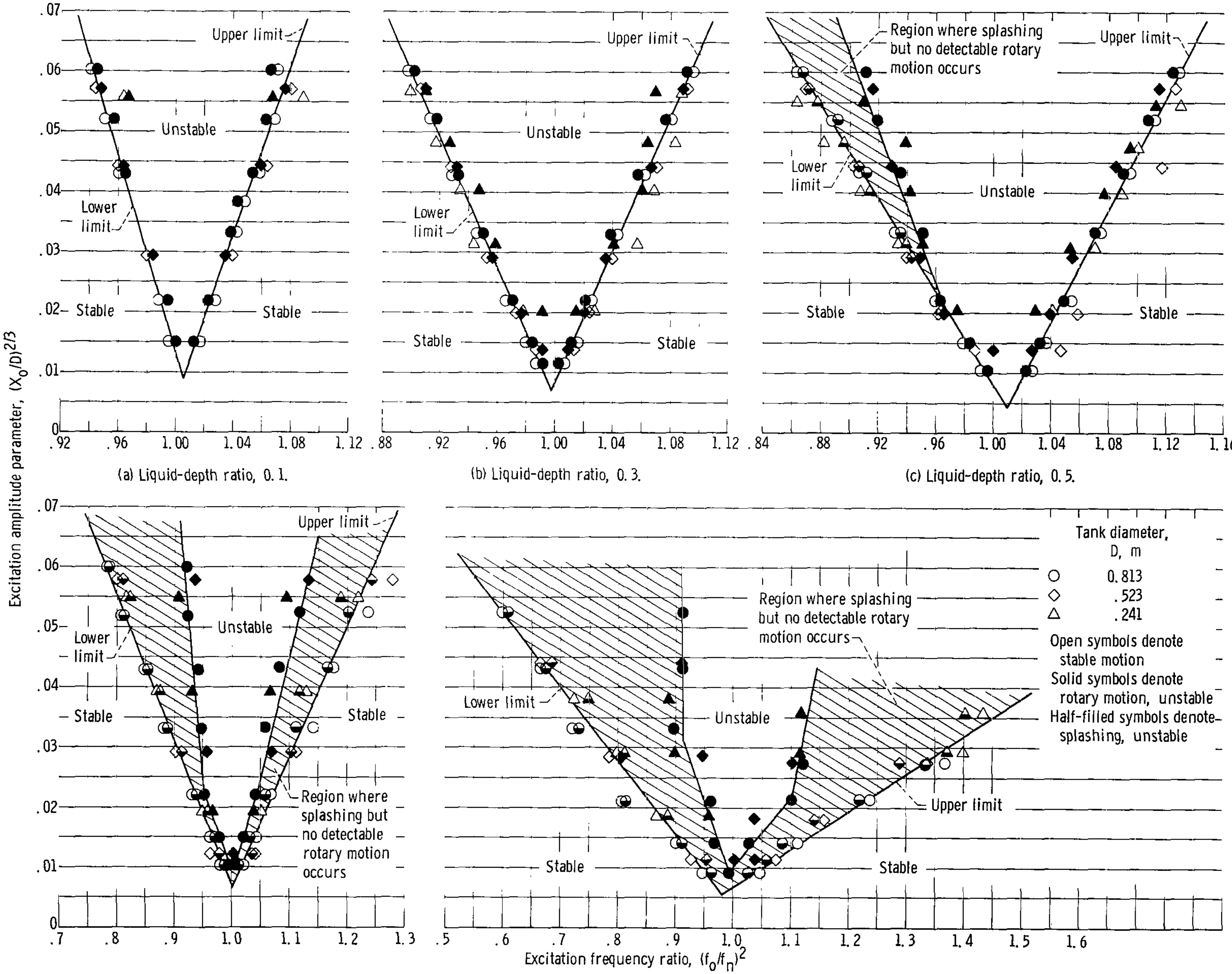


Figure 3. - Stable branches of liquid motion for forced oscillations of a partly filled spherical tank. Excitation amplitude parameter, constant.



(a) Liquid-depth ratio, 0.1.

(b) Liquid-depth ratio, 0.3.

(c) Liquid-depth ratio, 0.5.

(d) Liquid-depth ratio, 0.7.

(e) Liquid-depth ratio, 0.9.

Figure 4. - Planar motion stability boundaries.

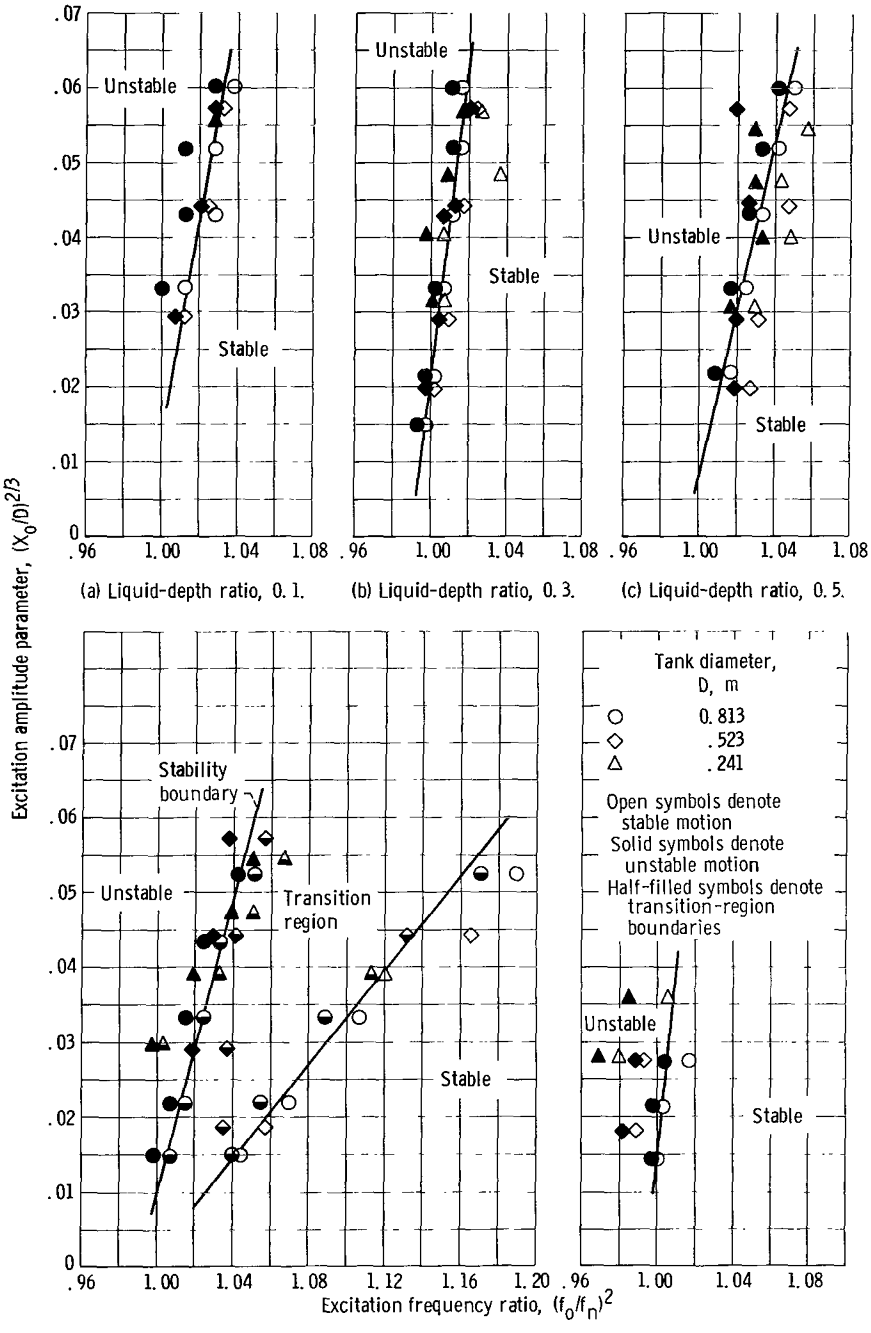
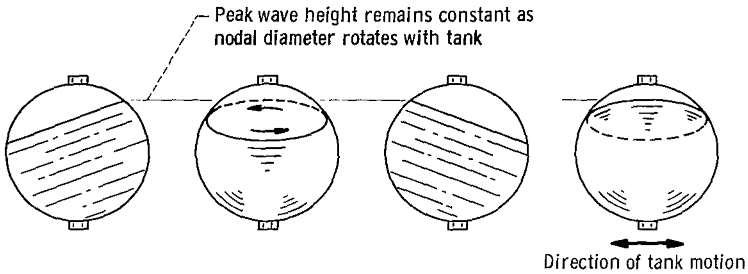
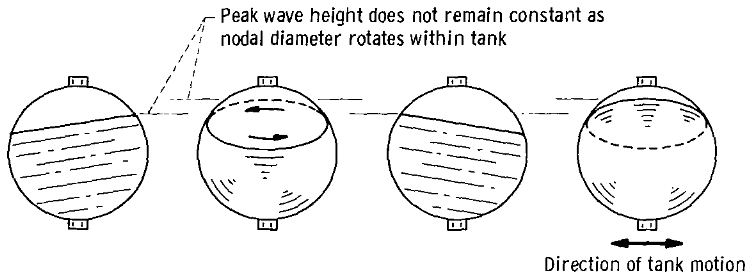


Figure 5. - Nonplanar motion stability boundaries.

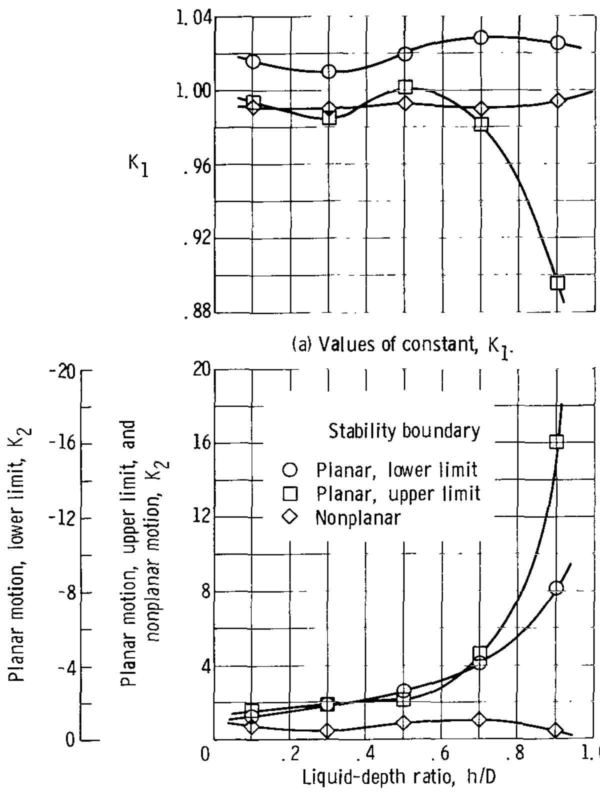


(a) Stable region.



(b) Transition region.

Figure 6. - Nonplanar motion of liquid surface for stable and transition regions. Side view of tank showing position of liquid surface at 90° intervals of rotation (counter-clockwise when viewed from top of tank) of nodal diameter.



(b) Values of constant, K_2.

Figure 7. - Values of constants for equation (1).

NASA-Langley, 1966 E-3146

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