NASA TECHNICAL NOTE

NASA TN D-4458

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NASA TN D-4458

EFFECTS OF LIQUID DEPTH ON LATERAL SLOSHING UNDER WEIGHTLESS CONDITIONS

by Jack A. Salzman, Thom A. Coney, and William J. Masica

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1968

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SUMMARY

As a part of the general study of liquid behavior in weightlessness, an experimental drop-tower investigation was conducted to determine the effects of shallow liquid depths on lateral (asymmetric) sloshing in a zero Bond number environment. Contact angles were restricted to very near 0°, so that the sloshing equilibrium interface was hemispherical. Cylindrical tanks, 0.635 and 0.952 centimeter in radius, were tested with both hemispherical and flat bottoms. Natural frequency data were correlated as a function of normalized liquid depth for both tank bottom shapes, and damping data were compared with predictions from high Bond number theory.

INTRODUCTION

Design criteria for space-vehicle stability and control include the ability to predict the behavior and characteristics of liquid-propellant systems when they are experiencing lateral sloshing motion. The frequencies and damping of the sloshing liquid mass must be understood under all gravity conditions and for a wide range of fillings (including very shallow liquid depths) in order to permit an analysis of possible interactions with vehicle stability and other systems of the vehicle. A comprehensive summary of most of the high Bond number slosh investigations and some of the original work by Reynolds and Satterlee in low Bond number sloshing is contained in reference 1. (Bond number is the ratio of acceleration to capillary forces.) For high Bond numbers (greater than approximately 50), where the equilibrium liquid surface is reasonably flat, analytical and experimental correlations exist for a wide range of sloshing phenomena pertinent to space-vehicle applications. For low Bond numbers, and especially with low contact angles where the equilibrium interface is highly curved, only limited information is available.

Current information on low Bond number sloshing may be found in references 2 to 5. In general, these studies have considered certain basic characteristics of both free and forced lateral sloshing motion in low Bond number environments. With the exception of the analytical study in reference 3 and limited experimental work, no other investigations of the effect of shallow liquid depths on low Bond number sloshing have been published.

The purpose of this report is to present the results of an experimental investigation conducted at the NASA Lewis Research Center of the effects of shallow liquid depths on lateral sloshing under effectively zero (i.e., less than 0.001) Bond number conditions. Cylindrical tanks were used with both hemispherical and flat bottoms. Contact angles were restricted to very near 0^{o}, so that the sloshing equilibrium liquid surface was nearly hemispherical. Further restrictions were that the slosh oscillations were of small amplitude and that the contact angle did not vary during sloshing. The data obtained on natural frequency are correlated as a function of normalized liquid depth by using the analytical results of reference 3. Damping data are compared with high Bond number correlations.

SYMBOLS

a	system acceleration, cm/sec^2
B_o	Bond number ($B_o = aR^2/\beta$)
g	acceleration due to gravity, cm/sec^2
h	centerline interface height from tank bottom, cm
K_d, K_1, K_2	nondimensional constants
R	cylinder radius, cm
t	time, sec
t_f	formation time, sec
V_L	liquid volume, cm^3
β	specific surface tension ($\beta = \sigma/\rho$), cm^3/sec^2
δ	logarithmic decrement
θ	contact angle, deg
μ	viscosity, cP
ρ	density, g/cm^3

σ surface tension, dynes/cm

Ω^2 natural frequency parameter or fundamental mode eigenvalue ($\Omega^2 = \omega_1^2 R^3/\beta$)

ω_1 natural frequency, rad/sec

BACKGROUND INFORMATION

Natural Frequency

Flat-bottom cylinders. - If the liquid depth in a lateral (asymmetric) sloshing system is made shallow enough, the natural frequency of free oscillation will decrease. For the case of a flat-bottomed cylinder and a flat equilibrium liquid surface (i.e., 90° contact-angle boundary condition), the free natural frequency ω_1 may be expressed nondimensionally in the following form (ref. 1, p. 415):

$$\Omega^2 = (6.255 + 1.841\ B_o) \tanh\left(1.841\ \frac{h}{R}\right) \tag{1}$$

where Ω^2 is defined as

$$\Omega^2 = \frac{\omega_1^2 R^3}{\beta} \tag{2}$$

and h is the centerline depth between the liquid surface and the tank bottom. For large Bond numbers, these equations reduce to the normal-gravity equation

$$\omega_1^2 = 1.841\ \frac{g}{R} \tanh\left(1.841\ \frac{h}{R}\right) \tag{3}$$

No simple relation exists for other contact angles at arbitrary Bond numbers, particularly for those combinations of contact angles and Bond numbers resulting in a highly curved equilibrium liquid surface. At deep liquid depths ($h/R > 2$), the value of Ω^2 was experimentally determined to be 2.6 for a zero Bond number, 0° contact-angle system (ref. 4). Limited experimental data for low-contact-angle, low Bond number systems (ref. 6) indicate that the frequency dependence on liquid depth departs considerably from the form of equation (1).

Hemispherical-bottom cylinders. - A recent analytical study of low Bond number (including zero) lateral sloshing in cylinders with hemispherical bottoms is contained in

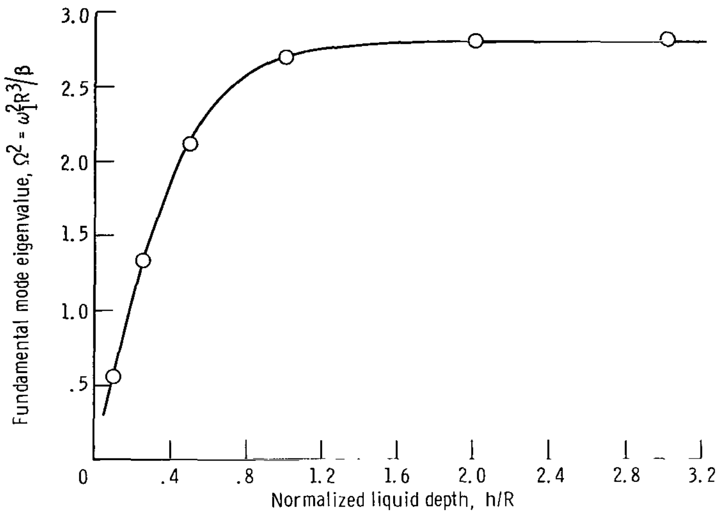


Figure 1. - Computed, zero Bond number eigenvalues as function of liquid depth for cylindrical tank with hemispherical bottom. Contact angle, 5°; computed values from reference 3.

reference 3. By using finite-difference techniques, normal modes were computed over a range of liquid depths at a contact angle of 5°. The computed, fundamental-mode, zero Bond number eigenvalues (ref. 3, p. 94) are plotted in figure 1 as a function of normalized liquid depth. As before, h is the centerline depth between the liquid surface and the tank bottom. A hyperbolic tangent approximation can be used to fit a functional relation to these calculated points. This relation, represented by the curve in figure 1, is

$$\Omega^2 = 2.8 \tanh\left(2 \frac{h}{R}\right) \tag{4}$$

or, in terms of the natural frequency,

$$\omega_1^2 = 2.8 \frac{\beta}{R^3} \tanh\left(2 \frac{h}{R}\right) \tag{5}$$

The empirical value of 2 in the argument of the hyperbolic tangent function is, of course, an approximation accurate to the indicated number of significant figures. It is interesting to note the similarity between the depth-dependent terms in equations (1) and (4).

For depth ratios larger than about 2, bottom effects are negligible. The calculated zero Bond number eigenvalue of 2.8 (5° contact angle) at these deep depths agrees favorably with the experimental value of 2.6 (0° contact angle) reported in reference 4.

In this investigation the zero Bond number natural frequency dependence on liquid depth for both hemispherical-bottom and flat-bottom cylinders was obtained experimentally. The study was restricted to near 0° static contact angles that did not vary during the sloshing motion. Under these conditions, the equilibrium liquid-vapor interface was hemispherical in all cases. The results in hemispherical-bottom cylinders were obtained first and compared with the analytical study of reference 3 (i.e., eq. (5)). An analogous equation describing the results for flat-bottom cylinders was then obtained empirically.

Damping

Deep liquid depth ($h/R > 2$) lateral slosh damping can be described in terms of the logarithmic decrement by

$$\delta = K_d \left(\frac{\mu}{\rho R^2 \omega_1} \right)^{1/2} \tag{6}$$

The value of K_d is 6.1 for high Bond numbers (ref. 7) and 28.1 for zero Bond numbers (ref. 4).

If the liquid depth is made sufficiently shallow, the damping is expected to increase. For high Bond numbers and flat-bottom cylinders, the increase in damping is predicted analytically in reference 8 and verified experimentally in reference 6. From these studies, the logarithmic decrement can be predicted by the following relation (ref. 1, p. 110):

$$\delta = 5.23\,\mu^{1/2}\rho^{-1/2}R^{-3/4}g^{-1/4}\left[\tanh^{-1/4}\left(1.84\,\frac{h}{R}\right)\right]\left[1 + 2\left(1 - \frac{h}{R}\right)\operatorname{csch}\left(3.68\,\frac{h}{R}\right)\right] \tag{7}$$

Substituting the high Bond number natural frequency (eq. (3)) into equation (7) yields

$$\delta = \left[6.1\left(\frac{\mu}{\rho R^2 \omega_1}\right)^{1/2}\right]\left[1 + 2\left(1 - \frac{h}{R}\right)\operatorname{csch}\left(3.68\,\frac{h}{R}\right)\right] \tag{8}$$

This equation shows that the total increase in high Bond number damping at shallow depths is due to two factors: (1) the decrease in natural frequency ω_1 contained in the first bracket of equation (8); and (2) the increased viscous effects caused by the proximity of the tank bottom. The functional increase in damping due to the increased viscous effects is expressed by the second bracketed term in equation (8).

High Bond number, shallow-depth damping relations for other tank geometries are presented in reference 1. In general, the same separation in factors as given in equation (8) may be obtained, although the forms become more complex because of their empirical nature. Analytical or experimental investigations of the damping depth dependence in low Bond number environments appear nonexistent.

If the logarithmic decrement is normalized in the form

$$\frac{\delta}{K_d\left(\dfrac{\mu}{\rho R^2 \omega_1}\right)^{1/2}} = f\left(\frac{h}{R}\right) \tag{9}$$

then the right side of the equation represents the increase in damping caused by viscous bottom effects alone. Thus, a direct comparison can be made between high Bond number and zero Bond number damping forms by appropriate substitution of the respective values for K_d. While this approach is not rigorously valid (in one case the interface is flat and in the other it is hemispherical), it is, nevertheless, useful in establishing comparative damping magnitudes.

APPARATUS AND PROCEDURE

The experimental apparatus used in this study is shown in figure 2. A near zero Bond number environment was obtained by permitting the experiment package to free fall a distance of 26 meters (a free fall time of approximately 2.2 sec). Precautions taken to reduce the air drag on the package resulted in an effective acceleration level of less than 10^{-5} g. This low level of acceleration together with the range of specific surface tensions (11.8 to 28.5 cm^3/sec^2) and small cylinder radii (0.635 and 0.952 cm) used in the experiments resulted in Bond numbers of less than 0.001. This was regarded as a zero Bond number environment.

Flat-bottom cylinders were assembled from precision-bore, borosilicate glass tubing and plate glass. Bottom edge distortions resulting from assembly were insignificant. Hemispherical-bottom cylinders were machined from acrylic plastic. The analytic-reagent-grade test liquids exhibited near 0° static contact angles on the cylinder surfaces. Care was taken to avoid a dynamic contact angle variation during free slosh-

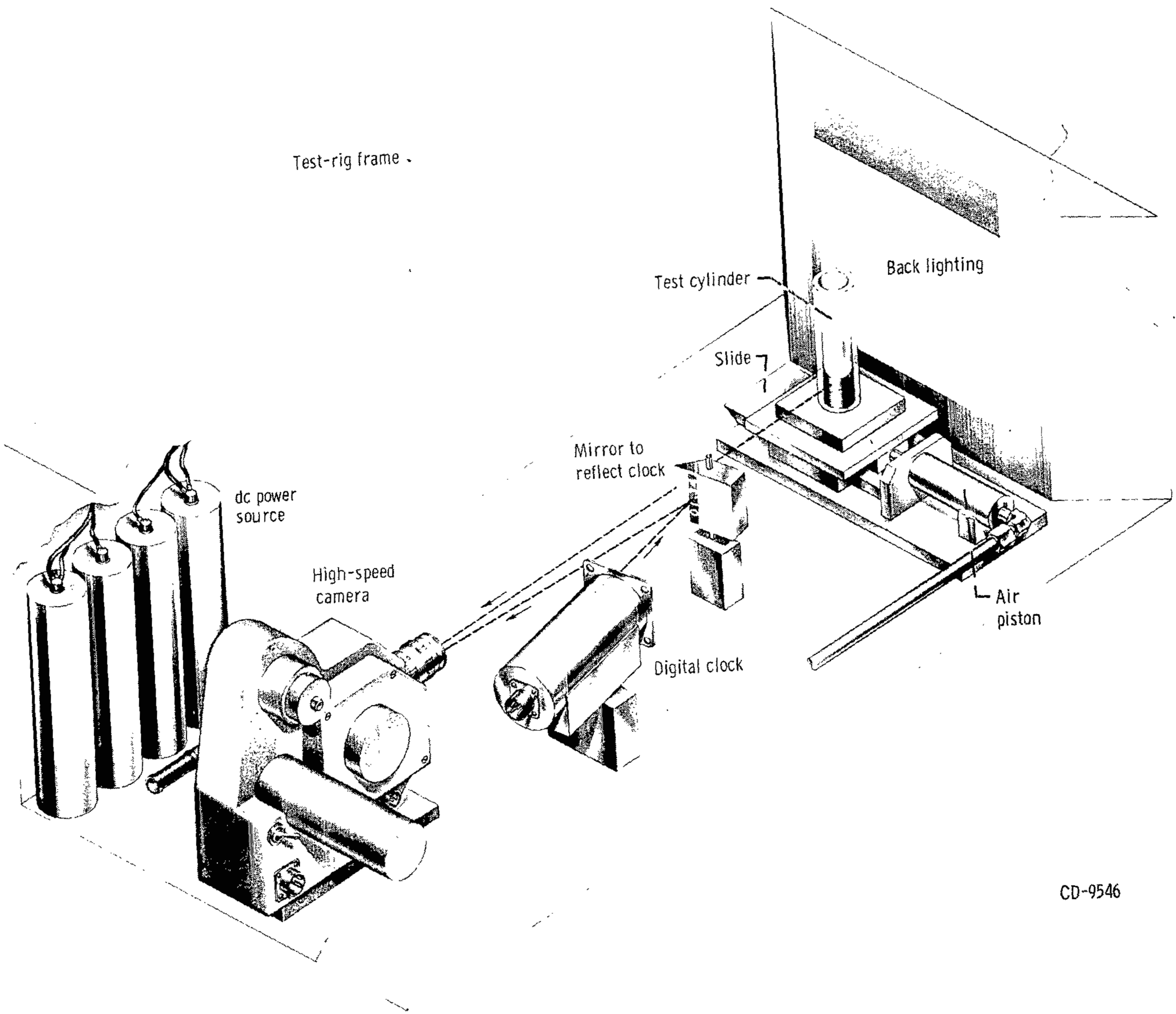


Figure 2. - Experimental apparatus.

TABLE I. - SUMMARY OF PARAMETERS

Liquid	Surface tension,[a] σ, dynes/cm	Density,[a] ρ, g/cm^3	Viscosity,[a] μ, cP	Cylinder radius, R, cm	Normalized liquid depth, h/R	Measured natural frequency, ω_1, rad/sec	Logarithmic decrement, δ
Hemispherical-bottom cylinders							
Trichloro-trifluoro-ethane	18.6	1.58	0.70	0.635	2.00	10.6	0.99
					1.75	11.0	----
					1.50	10.6	----
					1.25	10.3	----
					1.10	10.8	.75
					1.00	10.4	1.11
					.90	10.8	.87
					.75	10.2	.98
					.60	9.23	.84
					.50	9.34	.96
					.40	7.66	1.18
					.30	7.48	1.45
					.20	6.96	1.47
Carbon tetra-chloride	26.9	1.59	0.97	0.635	2.00	13.2	0.85
					.85	12.4	1.07
					.65	11.9	.86
					.40	10.5	.96
					.20	8.26	1.20
Methanol	22.6	0.79	0.60	0.952	2.00	9.40	0.78
					.75	8.84	.77
					.50	7.95	1.00
					.35	7.22	1.06
					.25	6.94	1.47
Flat-bottom cylinders							
Trichloro-trifluoro-ethane	18.6	1.58	0.70	0.635	2.00	10.6	0.99
					1.75	11.0	----
					1.25	10.2	.94
					.75	10.8	.89
					.50	10.3	1.11
					.35	9.66	.91
					.25	10.2	.76
					.20	9.47	.83
					.15	8.26	1.44
					.10	7.67	1.24
					.05	7.63	1.47
					≈0	7.54	----
Carbon tetra-chloride	26.9	1.59	0.97	0.635	2.00	13.2	0.85
					.6	12.8	.91
					.4	12.2	1.22
					.25	11.5	1.22
					.15	11.0	.98
Methanol	22.6	0.79	0.60	0.952	2.00	9.40	0.78
					1.35	9.51	----
					1.00	9.22	.80
					.55	8.93	.77
					.30	8.64	1.12
					.05	6.93	----
					≈0	5.26	----

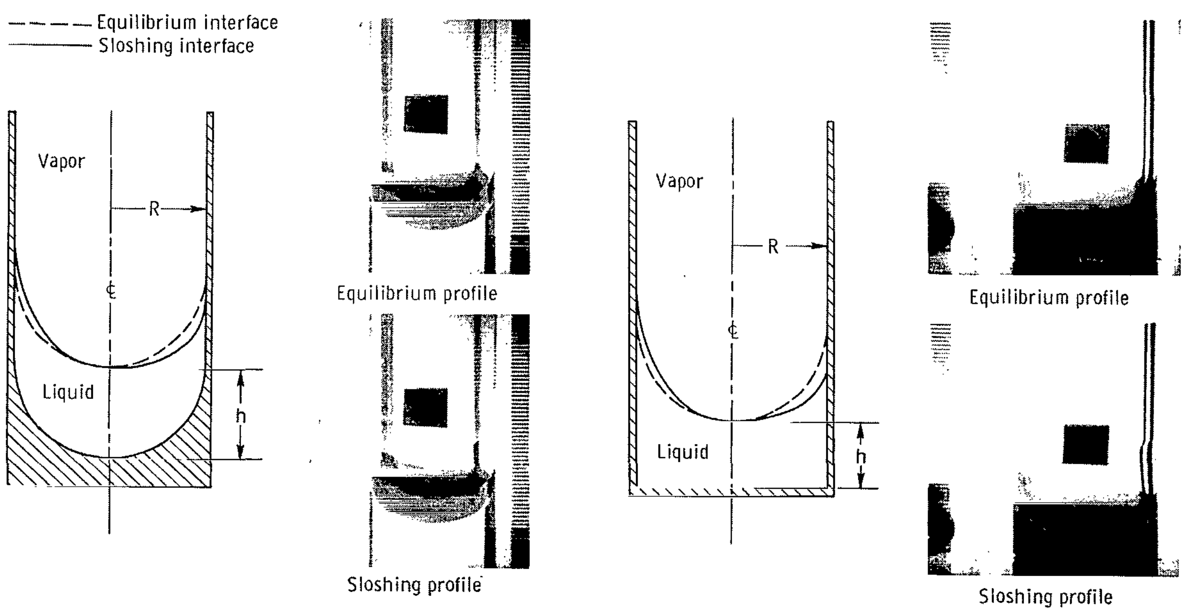
[a]At 20° C.

ing, and for the data presented, no variation was observed. The tank radii and test liquids were chosen so as to maximize the number of sloshing oscillations while retaining a large enough cylinder size to ensure that the interface motion could be measured easily. Liquid depths were calculated before each test by means of a volumetric relation, and these volumes were placed in the cylinders with a hypodermic syringe. Liquid depths were also measured directly during the data analysis. Properties of the test liquids, the cylinder sizes, and the liquid depths used are presented in table I.

Small-amplitude, lateral sloshing motion was induced by initially displacing the liquid-vapor interface from its equilibrium position and then allowing its free motion. The lateral impulse which initially displaced the interface was supplied by an air piston (fig. 2) and was activated after a predetermined time increment which allowed the interface to form its zero Bond number configuration. The minimum time required for the interface to reach a sufficiently quiescent configuration was empirically determined to be (ref. 4)

$$t_f = 1.8\left(\frac{R^3}{\beta}\right)^{1/2} \tag{10}$$

While this allowed formation time was not sufficient to ensure a completely quiescent



(a) Hemispherical-bottom cylinder.

(b) Flat-bottom cylinder.

Figure 3. - Liquid-vapor interface configurations.

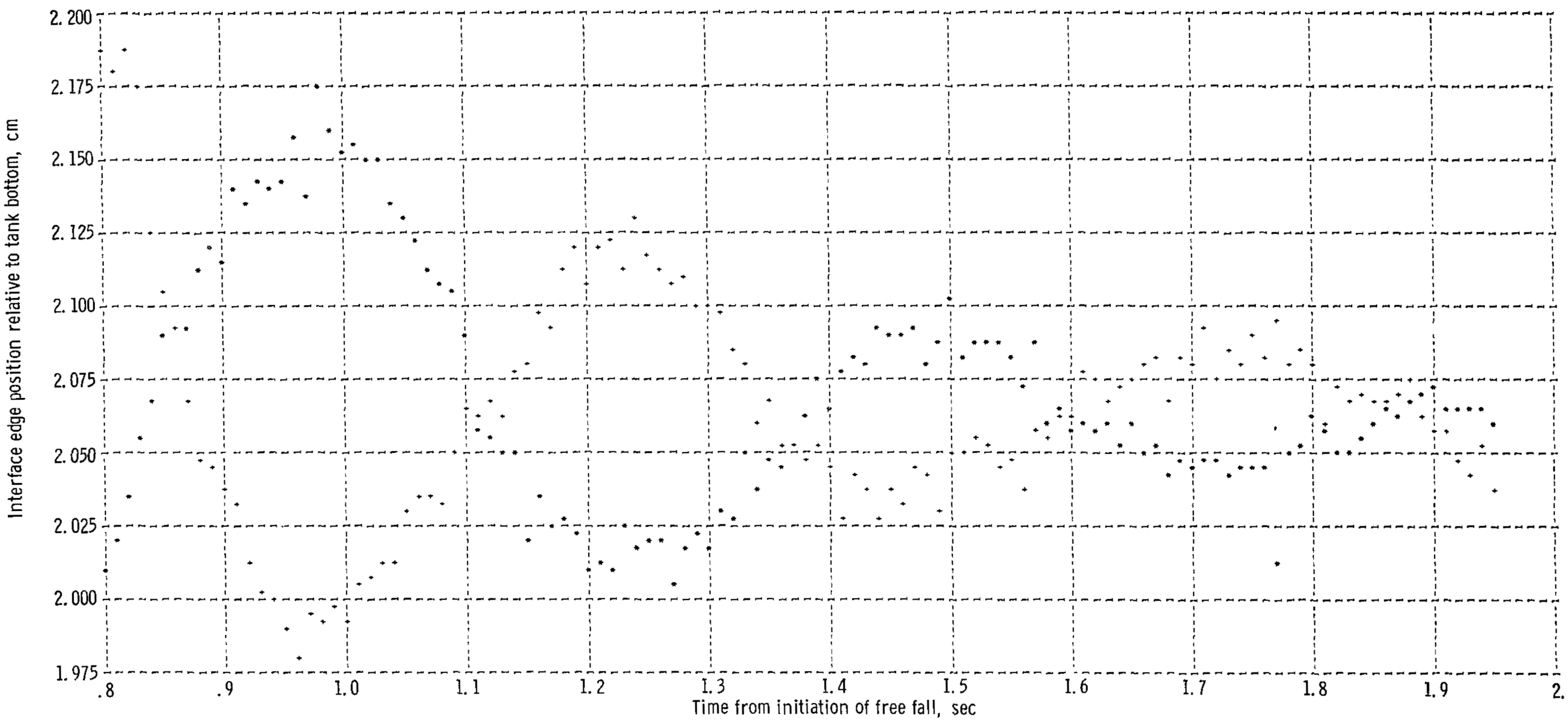


Figure 4. - Sample data plot of interface edge motion.

hemispherical interface, the motion was sufficiently damped so that it had no effect on the ensuing slosh wave.

Interface motion was recorded by means of high-speed photography. Time measurements were obtained by viewing a precision digital clock with a calibrated accuracy of 0.01 second. Figure 3 shows both the equilibrium configuration and the lateral-sloshing (displaced) profile for both tank geometries tested. The initial process in obtaining the natural frequency and damping data involved the use of a motion-picture analyzer to reduce the sloshing motion from pictorial to numerical form. Motion of the interface leading edge at the tank wall was recorded as a function of time. The result, from which the data were obtained, is a graph (fig. 4) showing a damped sinusoidal wave for each edge.

PRESENTATION OF DATA AND DISCUSSION OF RESULTS

Natural Frequency

Hemispherical-bottom cylinders. - The first part of this investigation was directed toward experimental measurements of the zero Bond number natural frequency at shallow liquid depths in hemispherical-bottom cylinders. Two different sized cylinders and three different liquids were tested, with liquid depth as the primary experimental parameter. Data were obtained at liquid depths down to a minimum of 0.2 radius. At depths below this minimum, the liquid-vapor interface was merely a thin film along the tank bottom, and measurements of the sloshing motion were not possible. The particular systems which were tested and their respective frequency data are presented in table I. The natural frequency for each system (i.e., for each set of values for R, β, and h/R) was calculated by averaging the half periods for that test run. The recorded frequencies for this bottom shape had an average mean deviation of 6 percent.

The natural frequency data are presented in figure 5 in normalized form so as to utilize the empirically determined, deep-liquid depth constant of 2.6 (ref. 4). The curve in figure 5 is the approximated analytical depth dependence, $\tanh^{1/2}[2(h/R)]$, from equation (5); the data agree favorably with this curve. Therefore, the zero Bond number natural frequency in hemispherical-bottom cylinders can be described by the relation

$$\omega_1 = \left(2.6 \frac{\beta}{R^3}\right)^{1/2} \tanh^{1/2}\left(2 \frac{h}{R}\right) \tag{11}$$

A significant decrease in the natural frequency does not occur until the liquid depth is lowered below 1 radius. Note the similarity between the frequency-depth dependence of

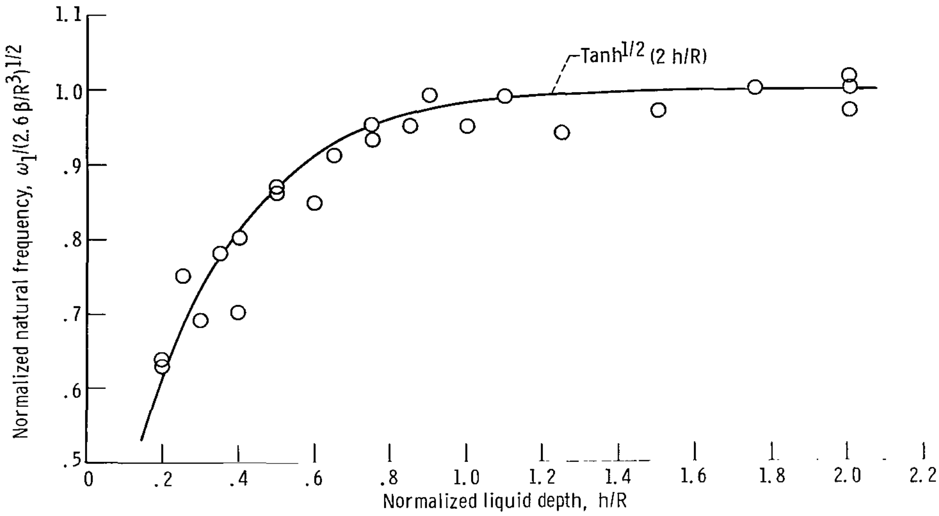


Figure 5. - Effect of liquid depth on natural frequency in hemispherical-bottom cylinders.

equation (11) and of the flat-interface, flat-bottom case previously predicted in equation (3).

Although the frequency measured was not truly the natural frequency but was, instead, a damped-system frequency, the measured damping was sufficiently low so that the variation from the natural frequency was in all cases less than 5 percent.

Flat-bottom cylinders. - For the investigation of the effects of shallow liquid depths on the zero Bond number natural frequency in flat-bottomed cylinders, the same tank radii and test liquids were used as those for the hemispherical-bottom investigation. With this flat-bottom shape, data for liquid depths down to essentially zero were obtained. Measured frequencies for this bottom shape are recorded in table I. The recorded frequencies had an average mean deviation of 5 percent.

The frequency data are presented in normalized form in figure 6. The solid curve in this figure represents equation (11). The data in this figure indicate that the natural frequency for a flat-bottom cylinder starts to decrease at a lower liquid depth than does the natural frequency for a hemispherical-bottom cylinder and that the correlation for hemispherical-bottom cylinders (eq. (11)) cannot be used to represent the natural frequency for a flat-bottom cylinder. The functional trend shown by these data does indicate that a hyperbolic tangent relation can be used to represent the data if an additional constant is used. The resulting relation is of the form

$$\omega_1 \propto \tanh^{1/2}\left[K_1\left(\frac{h}{R} + K_2\right)\right] \tag{12}$$

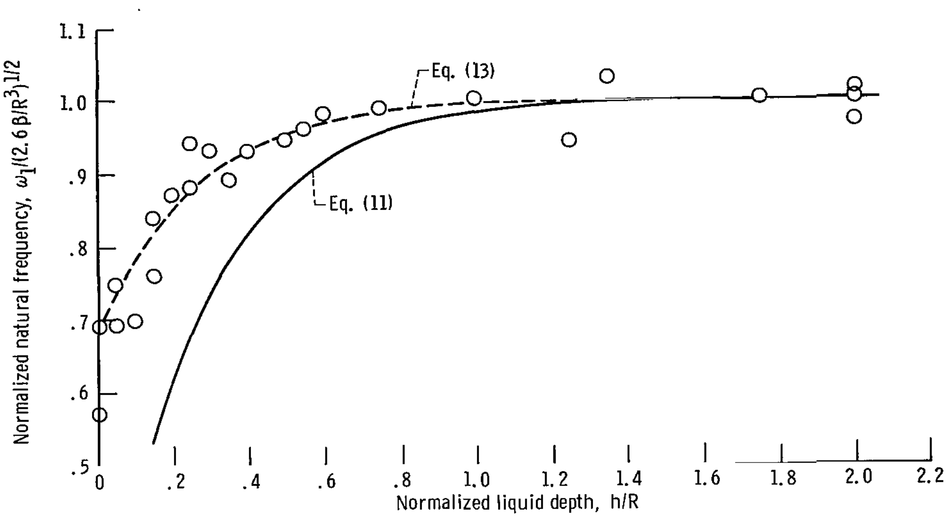


Figure 6. - Effect of liquid depth on natural frequency in flat-bottom cylinders.

If the value of K_1 is taken to be 2 in order to facilitate comparison with the previous correlation, the value of K_2 best representing the data is 0.25. The dashed curve shown in figure 6 is the relation

$$\omega_1 = \left(2.6\,\frac{\beta}{R^3}\right)^{1/2} \tanh^{1/2}\left[2\left(\frac{h}{R} + 0.25\right)\right] \qquad (13)$$

Examination of the figure shows that the zero Bond number natural frequency in flat-bottom cylinders can be satisfactorily predicted by equation (13). Equation (13) and figure 6 show that the natural frequency in flat-bottom cylinders does not decrease significantly until the liquid depth is lowered below 0.75 radius.

Equivalent bottom shapes. - High Bond number sloshing investigations (refs. 1 and 9) have shown that tanks with different bottom shapes may be represented by a single equivalent bottom shape through normalization or equating of liquid volumes. The form of equation (12) and the relative magnitude of K_2 (i.e., 0.25) suggest that the same approach can be used for a normalization of the zero Bond number frequency data. Data obtained in the flat-bottom cylinders can be represented in equivalent hemispherical-bottom form by applying a value of 0.33 to K_2. This equalizes the volumes for both bottom shapes at any value of h/R. Equation (12) is then in the form

$$\omega_1 \propto \tanh^{1/2}\left[K_1\left(\frac{h}{R} + 0.33\right)\right] \qquad (14)$$

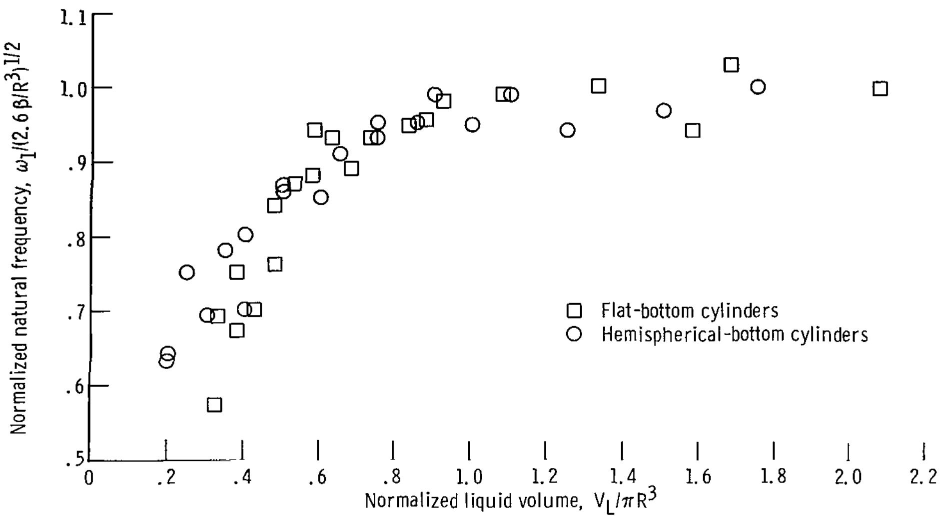


Figure 7. - Comparison of bottom shape effect on natural frequency by use of equivalent volumes.

or in terms of normalized liquid volume

$$\omega_1 \propto \tanh^{1/2}\left[K_1\left(\frac{V_L}{\pi R^3}\right)\right] \tag{15}$$

Normalized frequency data from both bottom shapes are presented as a function of normalized liquid volume in figure 7. Although some parametric spread is evident, the correlation is sufficient for engineering purposes if a value of 2 is employed for K_1. Equations (14) and (15) should not, however, be used to predict a sloshing frequency in flat-bottom cylinders at a liquid volume V_L less than $0.33/\pi R^3$ (or $h/R < 0$) because this volume condition would obviously require a distortion of the hemispherical interface and of the sloshing mode.

Damping Data

Data on the effects of shallow liquid depths on zero Bond number slosh damping were obtained in both hemispherical- and flat-bottom cylinders. The damping was exponential for all tests and was measured in terms of the logarithmic decrement. Values were determined graphically from measurements of the decaying amplitudes. An example of this method may be found in reference 4. The logarithmic decrement for each set of parameters is given in table I. Because of the limited number of measured amplitudes

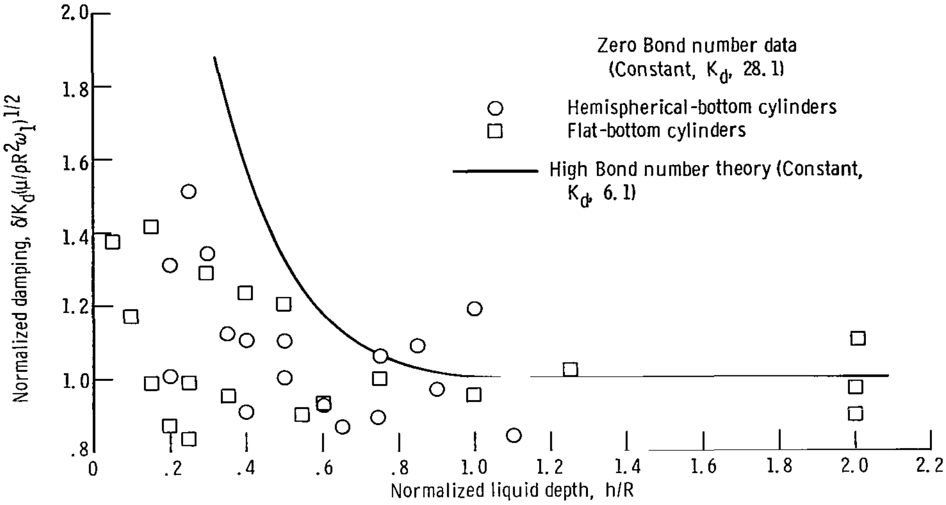


Figure 8. - Effect of liquid depth on damping.

in each test run, there was considerable scatter in the damping data which prohibited any specific correlation.

The damping data are shown in figure 8. These data have been normalized as in equation (9) by using the zero Bond number value of 28.1 for K_d and the actual measured frequencies given in table I. As has been discussed in the section titled Damping, this was done so that the observed increase in damping can be attributed solely to viscous bottom effects and not to a decrease in the natural frequency. The curve plotted in figure 8 represents the correlated, high Bond number (flat bottom), viscous-damping depth dependence. This depth dependence has been normalized as in equation (9) by using 6.1 for the value of K_d and represents the second bracketed term in equation (8).

Even though the data contain considerable scatter, it is evident from figure 8 that the depth dependence of zero Bond number damping cannot be correlated by the verified high Bond number theory. Although the damping does increase with decreasing liquid depth, a significant increase does not occur until a lower depth than that indicated by the high Bond number theory (i.e., at an h/R of approximately 0.5 rather than 1.0).

No damping data were obtained at a liquid depth of zero because of a very high reduction in the slosh amplitude in only one cycle of oscillation at this depth.

SUMMARY OF RESULTS

An experimental investigation was conducted to determine the effect of shallow liquid depths (i.e., less than 2 tank radii) on the natural frequency and damping characteristics of lateral (asymmetric) sloshing in a zero Bond number environment. The study employed right circular cylinders, 0.635 and 0.952 centimeter in radius R, with both hemispherical and flat bottoms. Test liquids were restricted to those which possess near 0° static contact angles on the cylinder walls; the contact angle did not vary during the sloshing motion. Specific surface tensions β of the test liquids ranged from 11.8 to 28.5 cubic centimeters per second squared. The study was restricted to small amplitude oscillations and yielded the following results:

1. The natural frequency ω_1 in hemispherical-bottom cylinders was correlated as a function of normalized liquid depth. Experimental results can be described by the relation

$$\omega_1^2 = \left(2.6 \frac{\beta}{R^3}\right) \tanh\left(2 \frac{h}{R}\right)$$

where h is the centerline height from the liquid-vapor interface to the tank bottom.

2. The natural frequency in flat-bottom cylinders follows a relation similar to that in hemispherical-bottom cylinders. Experimental results for this bottom shape can be described by the relation

$$\omega_1^2 = \left(2.6 \frac{\beta}{R^3}\right) \tanh\left[2\left(\frac{h}{R} + 0.25\right)\right]$$

3. The damping in terms of the logarithmic decrement increases with decreasing liquid depth for both bottom shapes. The depth at which damping starts to increase in a zero Bond number environment is lower than that at which a similar increase occurs at large Bond numbers.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 22, 1967,
124-09-03-01-22.

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