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EXPERIMENTAL INVESTIGATION OF THE SLOSH-DAMPING EFFECTIVENESS OF POSITIVE-EXPULSION BAGS AND DIAPHRAGMS IN SPHERICAL TANKS

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EXPERIMENTAL INVESTIGATION OF THE SLOSH-DAMPING EFFECTIVENESS OF POSITIVE-EXPULSION BAGS AND DIAPHRAGMS IN SPHERICAL TANKS

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SUMMARY

An experimental investigation was conducted to evaluate the slosh-damping effectiveness of positive-expulsion bags and diaphragms in spherical tanks ranging in size from 9.5 to 32 inches in diameter. The scaling effects for sloshing forces and damping ratios were determined for the butyl rubber positive-expulsion devices tested. The maximum slosh forces that occur at the first natural mode frequency increased with an increase in excitation amplitude and decreased as the diaphragm material thickness increased. The damping ratio (or logarithmic decrement) was found to be essentially independent of the excitation amplitude and increased with an increase in diaphragm material thickness. The second natural mode force peak and the fluid swirl at the natural mode frequencies, which were observed for the unrestricted liquid sloshing, were completely suppressed.

INTRODUCTION

For space vehicles containing large masses of liquid propellants, sloshing is a potential source of disturbance that can be critical to the stability of the vehicle. Severe sloshing results when the frequency of the missile system is the same as the fundamental mode of the contained propellants. The forces that result from the coupling of the attitude control system with the propellant sloshing can produce moments on the vehicle and cause instability.

It is of interest, therefore, to provide a means of damping or eliminating sloshing in propellant tanks. Investigations have been conducted to study liquid sloshing characteristics and to evaluate methods of damping liquid oscillations by the use of baffles in various tank configurations (e.g., refs. 1 to 7).

Spherical tanks have been investigated both analytically and experimentally to determine the sloshing frequencies and forces for unrestricted liquid oscillations (refs. 8 and 9).

In some applications, elastomer positive-expulsion diaphragms or bags may be used for propellant transfer under weightless conditions. A preliminary experimental program conducted to study the potential slosh-damping effectiveness of such positive-expulsion devices in a 9.5-inch-diameter spherical tank is reported in reference 10. Results of this investigation indicate that the maximum slosh forces were reduced from 40 to 60 percent. Damping ratios as high as 0.28 were measured in these small-scale tests. It is of interest, therefore, to define the damping effectiveness and scale factors for positive-expulsion diaphragms and bags in various size spherical tanks.

An experimental investigation was conducted at the NASA Lewis Research Center to determine the slosh-damping effectiveness and scale factors for positive-expulsion diaphragms and bags in spherical tanks ranging in size from 9.5 to 32 inches in diameter. Diaphragms and bags of butyl rubber, ranging in thickness from 0.010 to 0.040 inch were tested over a range of excitation amplitudes from 0.100 to 0.600 inch. Slosh forces and damping ratios (logarithmic decrements) were measured over a range of excitation frequencies extending through the first two natural modes of the contained liquid. The results of this investigation are reported herein.

SYMBOLS

d	spherical diameter, in.
F_s	slosh force, lb
$F_s/\rho g d^3$	slosh force parameter
g	gravitational force, in./sec^2
R	spherical radius, in.
X_o	excitation amplitude, in.
X_o/d	excitation amplitude parameter
Y_o	material thickness, in.
Y_o/d	material thickness parameter
α	circular frequency, radians/sec
$\alpha\sqrt{R/g}$	oscillatory frequency parameter
δ	damping ratio or logarithmic decrement, $\ln(F_{s,n}/F_{s,n+1})$
ρ	liquid density, slugs/cu in.

Subscript:

n	1, 2, 3, 4, . . ., n

EXPERIMENTAL APPARATUS AND PROCEDURE

Large-Scale Test Facility

The large-scale experimental test facility is shown in figure 1. Spherical tanks 20.5 and 32 inches in diameter were mounted on the test bed, which was suspended from a frame through three vertically oriented load cells and one horizontally oriented load cell (fig. 1(b)). 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 cylinder and piston. The excitation amplitude and oscillatory frequency could be varied continuously from 0 to 1 inch and from 0 to 20 cycles per second, respectively. A sinusoidal excitation wave form was used for this investigation. The electric and hydraulic control circuits for the driving mechanism were designed so that the oscillatory motion could be "quick-stopped" at the point of maximum acceleration and zero velocity. The horizontal forces were sensed by the horizontal load cell and the signal was recorded on a continuously recording oscillograph. The three vertical load cells were not used for this investigation.

Acetylene tetrabromide (TBE), which has a specific gravity of 2.96, was used as the contained liquid to increase the accuracy potential of the data, that is, the more dense the contained liquid, the higher the slosh force for a given excitation amplitude (ref. 8).

The butyl rubber expulsion diaphragm and bag and their installation in the spherical tank are shown in figure 2. The ullage, which was open to the atmosphere for this investigation, was above the diaphragm and the liquid was below. In an actual operation, the diaphragm strokes through the spherical tank and thus positively expels the propellant. The diaphragm is constructed to fit exactly inside the sphere so that during expulsion or sloshing the diaphragm material will not be stretched.

For each bag and diaphragm, the tank was oscillated at a preselected frequency and amplitude and was quick-stopped, and the residual horizontal slosh forces were recorded. The amplitude was varied from 0 to 0.60 inch and the frequency was varied from 0 through the first two natural modes of the contained liquid for unrestricted sloshing.

Slosh forces and the effectiveness of slosh-suppression methods are most important to missile design at conditions where the forces are at a maximum. From investigation of unrestricted liquid sloshing characteristics in a spherical tank (ref. 8), it was observed that the maximum slosh forces occurred at a liquid-depth ratio (liquid depth/tank diameter) of 0.50 and at the first natural mode frequency. Therefore, all the tests reported herein were conducted at a liquid-depth ratio of 0.50. The configurations tested are shown in the following table:

Tank diameter, d, in.	Diaphragm thickness, Y_o, in.
20.5	0.010
	.020
	.030
32	.010
	.020
	.040

Butyl rubber positive-expulsion bags, ranging in thickness from 0.010 to 0.040 inch, were also tested in the 20.5-inch-diameter tank. A bag and its installation in the tank are shown in figure 2(b). The bag was installed with the ullage inside the bag and the liquid outside. The bag was constructed to fit exactly the inside of the sphere so that during expulsion or sloshing the bag material will not stretch. The test procedure for the bag was exactly the same as that for the diaphragm.

Small-Scale Test Facility

The small-scale test facility, which is discussed in detail in references 8 and 10, is shown in figure 3. A 9.5-inch-diameter spherical tank was formed in a lucite block. The block was mounted on ball bearings and was free to oscillate in a horizontal plane. The oscillatory motion of the block, which was provided by an electric motor and driving mechanism, could be quick-stopped so that only horizontal forces resulting from liquid motion could be measured. The driving amplitude was 0.10 inch and the frequency could be varied from 0 to 5 cycles per second. The forces were sensed by a strain gage, and the signal was recorded by means of a continuously recording oscillograph. Three diaphragms (0.010-, 0.015-, and 0.020-in. thick) were tested in the tank with TBE as the contained liquid at a liquid-depth ratio of 0.50. A diaphragm and its installation in the tank is shown in figure 4. The test procedure was the same as that previously described for the 20.5- and 32-inch-diameter tanks.

DATA REDUCTION

The experimental values of slosh force and frequency were reduced to dimensionless parameters $F_s/\rho g d^3$ and $\alpha\sqrt{R/g}$, as described in reference 1. The g term in these parameters is equal to the vertical acceleration on the tank; for the present investigation, g equals 386 inches per second squared. The force parameters were calculated by using the magnitude of the first force peak after the quick-stop. The frequency parameter was varied from 0 through 2.5, which included the natural frequencies of the first two modes for all configurations tested. The damping ratios were determined by averaging several successive values of $\ln(F_{s,n}/F_{s,n+1})$ for each run, where $F_{s,n}$ is the peak force on one slosh cycle and $F_{s,n+1}$ is the peak force on the succeeding cycle.

PRESENTATION AND DISCUSSION OF RESULTS

The slosh force parameter is shown as a function of the oscillatory frequency parameter in figure 5 for 0.010-inch-thick diaphragms installed in the 20.5- and 32-inch-diameter tanks.

The excitation amplitude was varied from 0.10 to 0.60 inch and the oscillatory frequency was varied from 0 through the first two natural modes of the contained liquid. The force parameter increased as the oscillatory frequency parameter (or frequency) increased to a peak value near the first mode for the unrestricted sloshing and then decreased as the oscillatory frequency increased. Figure 5 also shows that the larger the excitation amplitude X_o, the higher the slosh force parameter. At larger values of the excitation amplitude, there is little difference in peak values of the force parameter between the 20.5- and 32-inch-diameter tanks.

The damping ratio (or logarithmic decrement) is shown in figure 6 as a function of the oscillatory frequency parameter for 0.010-inch-thick diaphragms installed in the 20.5- and 32-inch-diameter tanks. Because of the limitations of the test facility, it was extremely difficult to obtain precise data to define the damping ratios, which resulted in the data scatter in figure 6. For the 20.5-inch-diameter tank (fig. 6(a)), the damping ratio increased slightly as the excitation amplitude increased. The damping ratio was essentially independent of the excitation amplitude for the 32-inch-diameter tank (fig. 6(b)). The damping ratio decreased as the tank diameter increased.

Figure 7 shows the slosh force parameter as a function of the oscillatory frequency parameter for diaphragms of different thicknesses tested in the 20.5- and 32-inch-diameter tanks. As the diaphragm thickness increased, the slosh force parameter decreased and the peak forces occurred at a higher value of the oscillatory frequency parameter. There is very little difference in the magnitude of the slosh force parameter between the 20.5- and 32-inch-diameter tanks.

The damping ratio is shown in figure 8 as a function of the oscillatory frequency parameter for the diaphragms of different thicknesses tested in the 20.5- and 32-inch-diameter tanks. As the diaphragm thickness increased, the damping ratio increased. The oscillatory frequency parameter had essentially no effect on the damping ratio for the 20.5-inch-diameter tank (fig. 8(a)). There was some effect of oscillatory frequency parameter on the damping ratio for the 32-inch-diameter tank (fig. 8(b)).

The effect of the excitation amplitude parameter X_o/d on the maximum force parameter for the 0.010-inch-thick diaphragms and bags is shown in figure 9. The figure includes data from tanks ranging in size from 9.5 to 32 inches in diameter with TBE as the contained liquid, as well as data from reference 10 and some unpublished NASA data for unrestricted slosh. The results compare well and can be represented by a single curve except for the data point from the 9.5-inch-diameter tank with TBE as the contained liquid. The specific reason for the low value of this one point is not known at present. There is no apparent difference in the force parameter level between the bags and diaphragms tested, which further substantiates the results of reference 10. It should also be noted that the slosh force parameter is only slightly dependent on the amplitude parameter for values greater than 0.01 for both restricted and unrestricted sloshing.

The effect of the material thickness parameter Y_0/d on the maximum slosh force parameter and the maximum damping ratio is shown in figures 10 and 11 for values of the amplitude parameter greater than 0.01. Data are shown for tanks ranging in size from 9.5 to 32 inches in diameter with TBE as the contained liquid plus data from references 8 and 10 and some unpublished NASA data. As the material thickness parameter increased, the slosh force parameter decreased linearly (fig. 10). A thickness parameter of zero represents unrestricted liquid sloshing, as reported in reference 8. For a specific liquid, the data can be generalized into a single curve. The difference between the two sets of curves is most likely due to the large difference in kinematic viscosity between TBE ($\nu = 3.5\times10^{-5}$ ft^2/sec) and mercury ($\nu = 0.122\times10^{-5}$ ft^2/sec). There is no appreciable difference between the bag and diaphragm configurations, as indicated in the figures. The damping increased as the material thickness parameter increased (fig. 11). Damping ratios for unrestricted sloshing were obtained from reference 8 and some unpublished NASA data. Again, for a given liquid, the data can be generalized by a single curve and the bags and diaphragms exhibit similar damping ratios.

The slosh-damping effectiveness of butyl rubber positive-expulsion diaphragms and bags can be generalized for various size spherical tanks and a given contained liquid by use of nondimensional parameters. The effect of amplitude parameter on slosh force parameter can be represented by a single curve for a given diaphragm or bag. The effect of material thickness parameter on slosh force parameter or damping ratio can be generalized for a given contained liquid. The second natural mode force peak and the liquid swirl, or liquid rotation, at the fundamental frequency, which was observed for unrestricted sloshing, were completely suppressed.

CONCLUDING REMARKS

An experimental investigation was conducted to evaluate the slosh-damping effectiveness of positive-expulsion bags and diaphragms in spherical tanks ranging in size from 9.5 to 32 inches in diameter. The scale effects for slosh forces and damping ratios were determined for the devices tested. The slosh force parameter increased with an increase in excitation amplitude and decreased with an increase in diaphragm or bag material thickness. The damping ratio is essentially independent of the excitation amplitude and increased as the diaphragm material thickness increased. Both the slosh force parameter and the damping ratios for the various size tanks can be presented in a generalized form by use of dimensionless parameters. A few selected positive-expulsion bags were tested and found to be very similar to diaphragms of comparable thickness. The second natural mode force peak and the fluid swirl at the natural frequencies, which was observed for the unrestricted liquid sloshing, were completely suppressed.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, January 31, 1963

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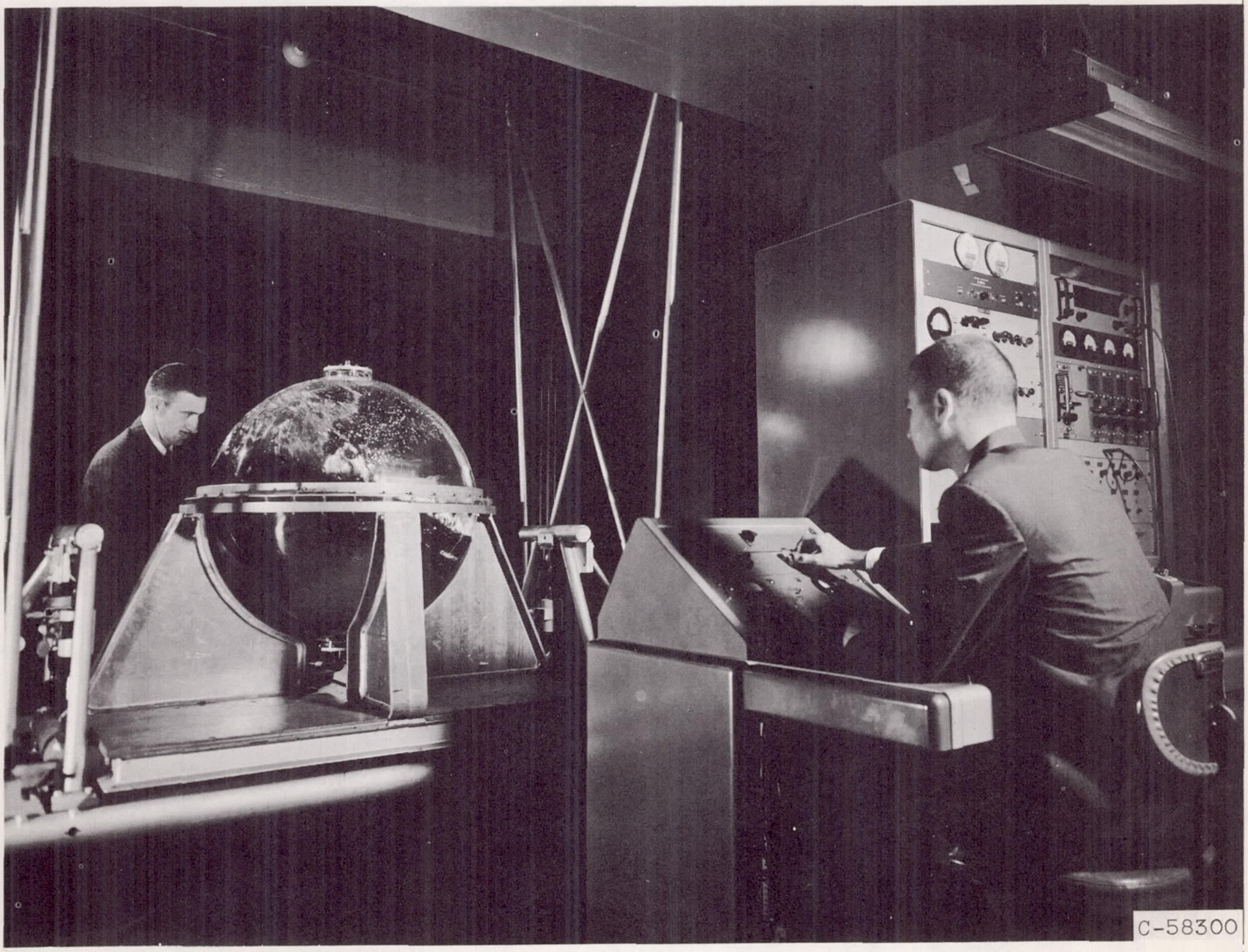
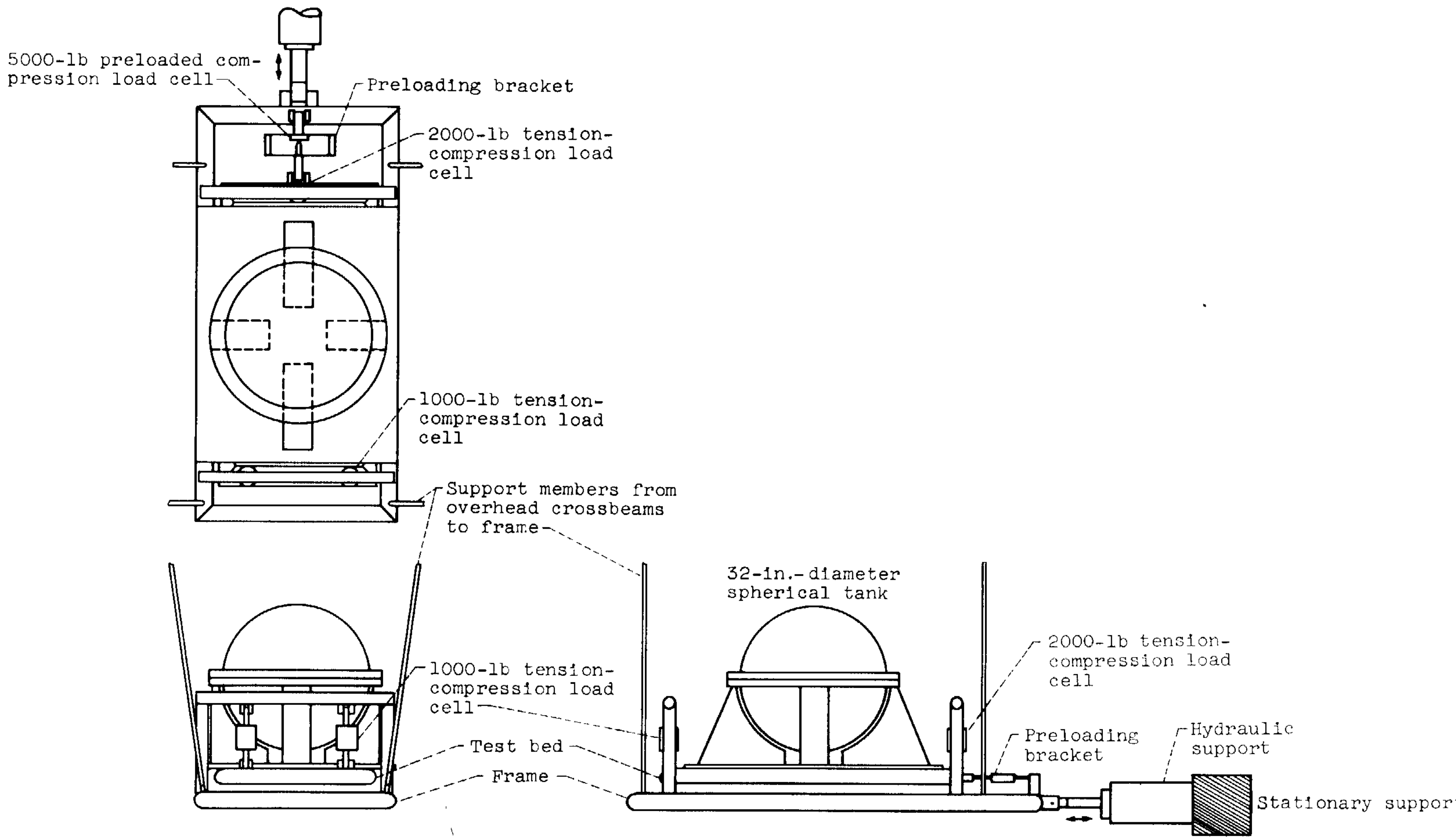


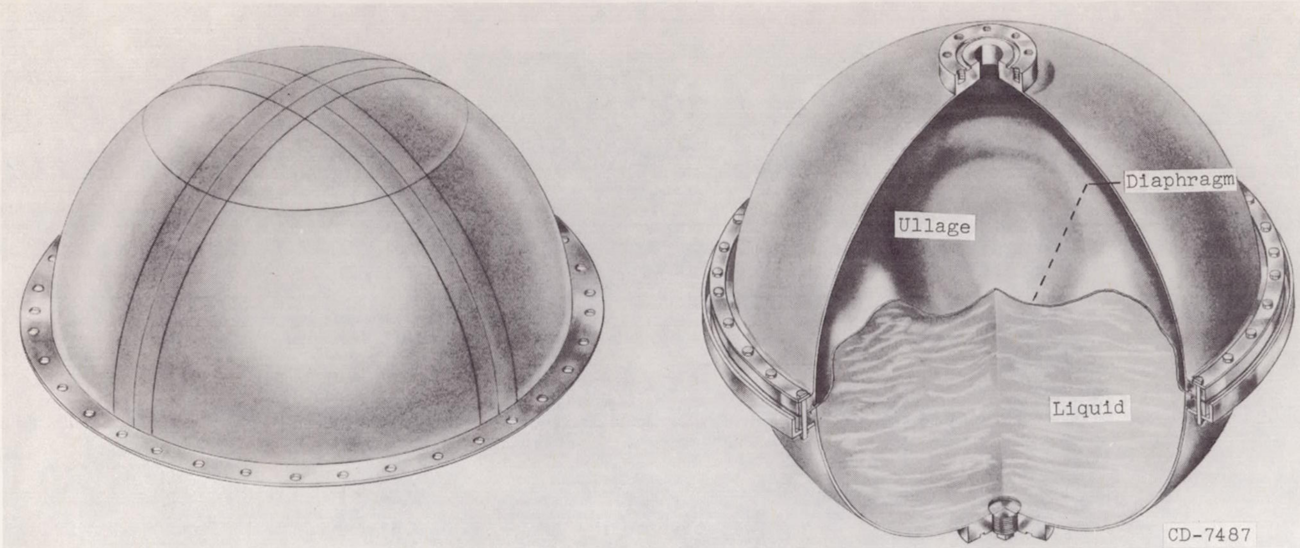
(a) Overall view.

Figure 1. - Large-scale experimental slosh force test facility.

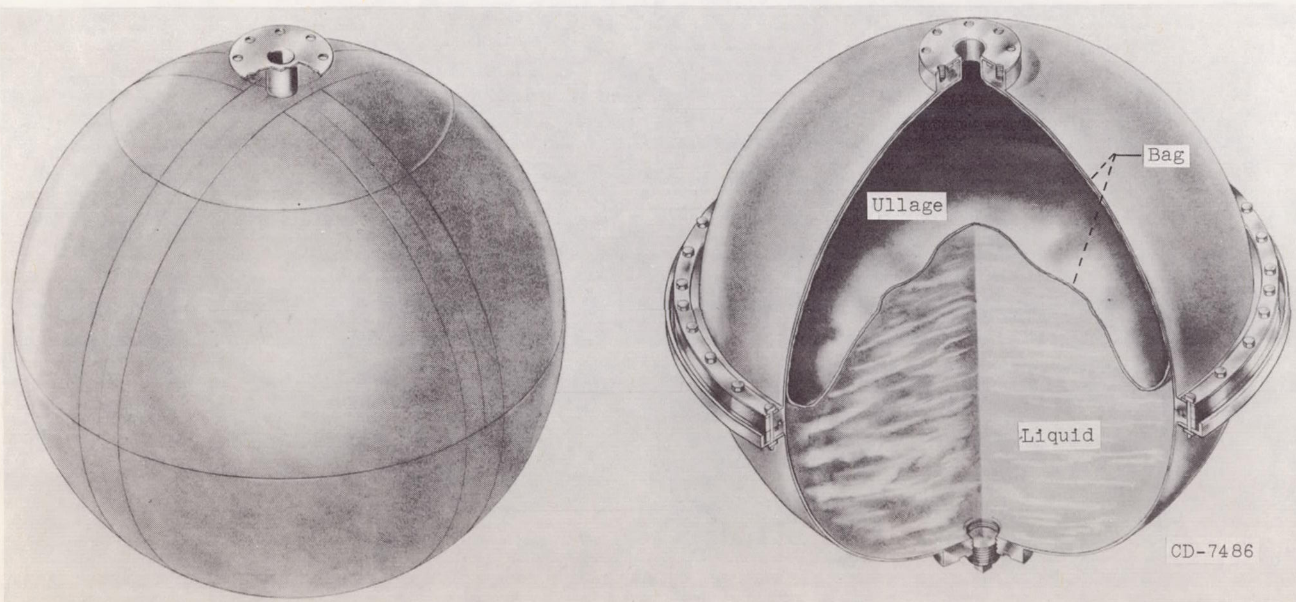


(b) Schematic drawing.

Figure 1. - Concluded. Large-scale experimental slosh force test facility.



(a) Diaphragm.



(b) Bag.

Figure 2. - Diaphragm and bag installation in spherical tank.

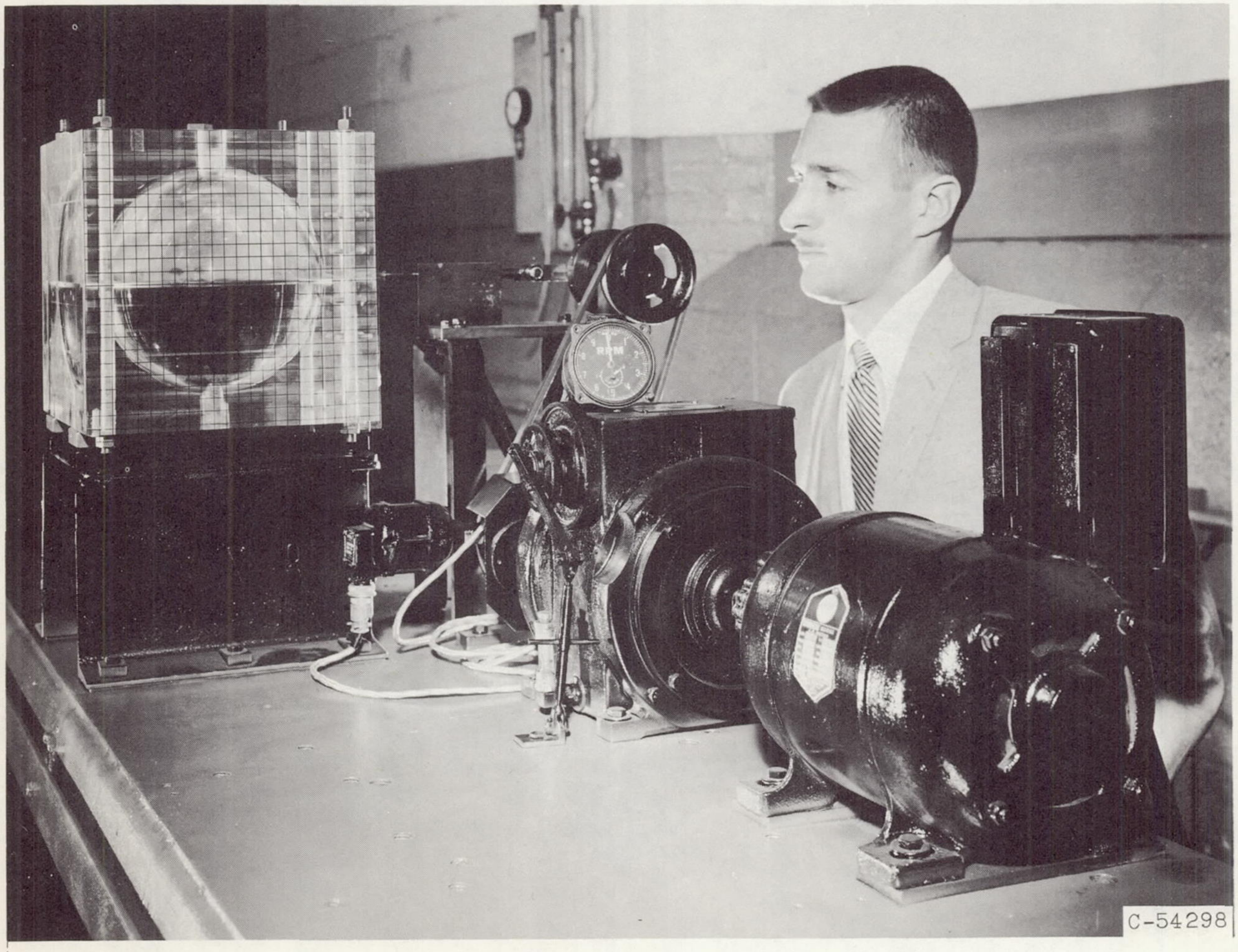


Figure 3. - Small-scale slosh force test facility.

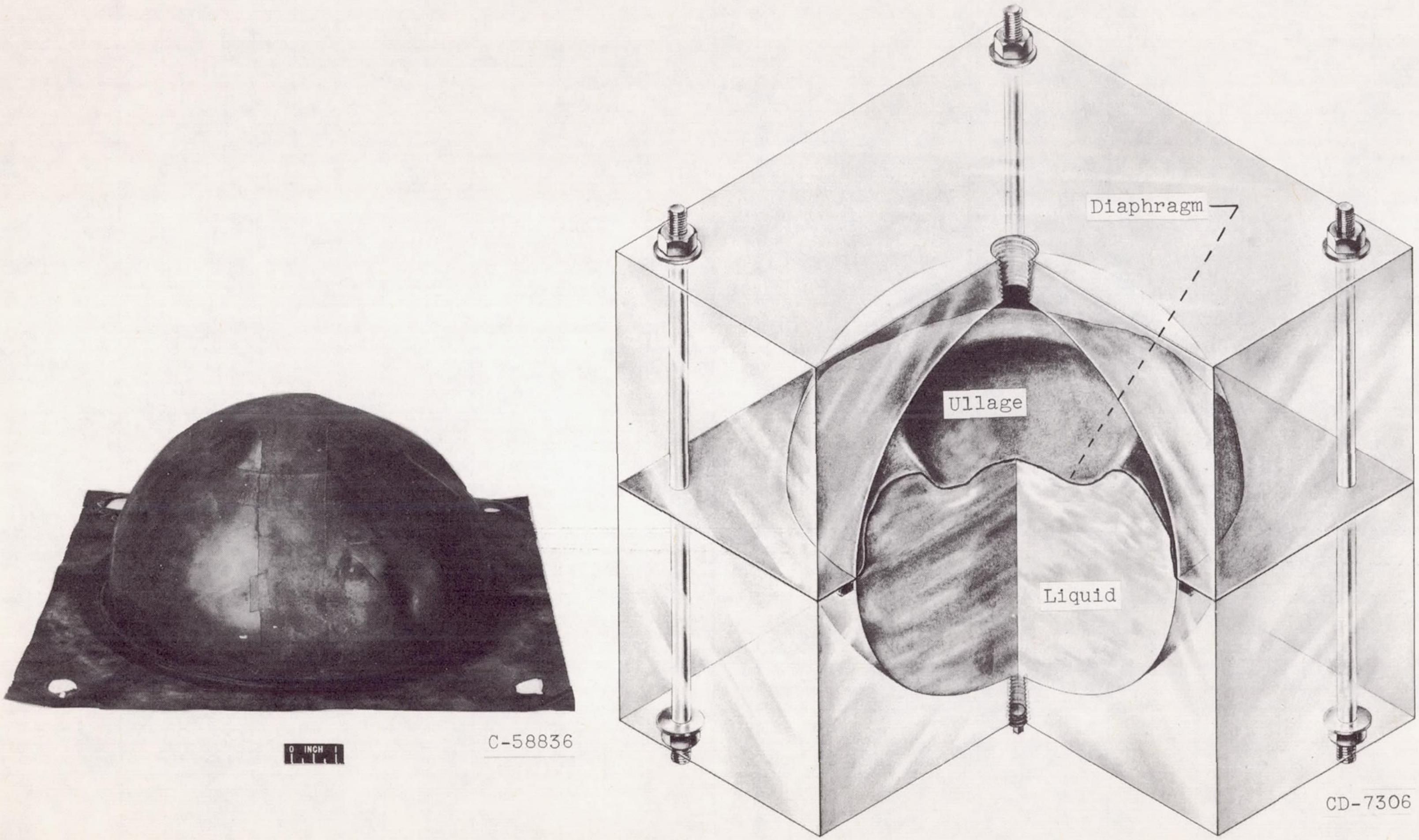
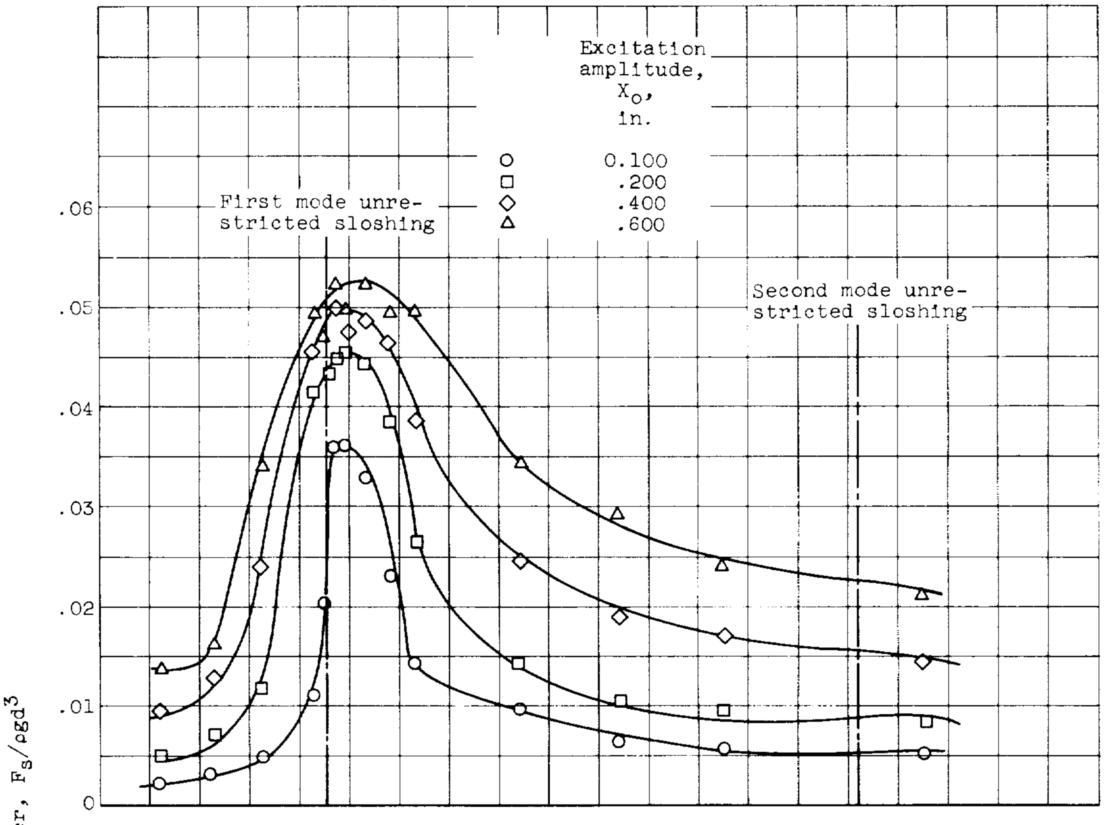
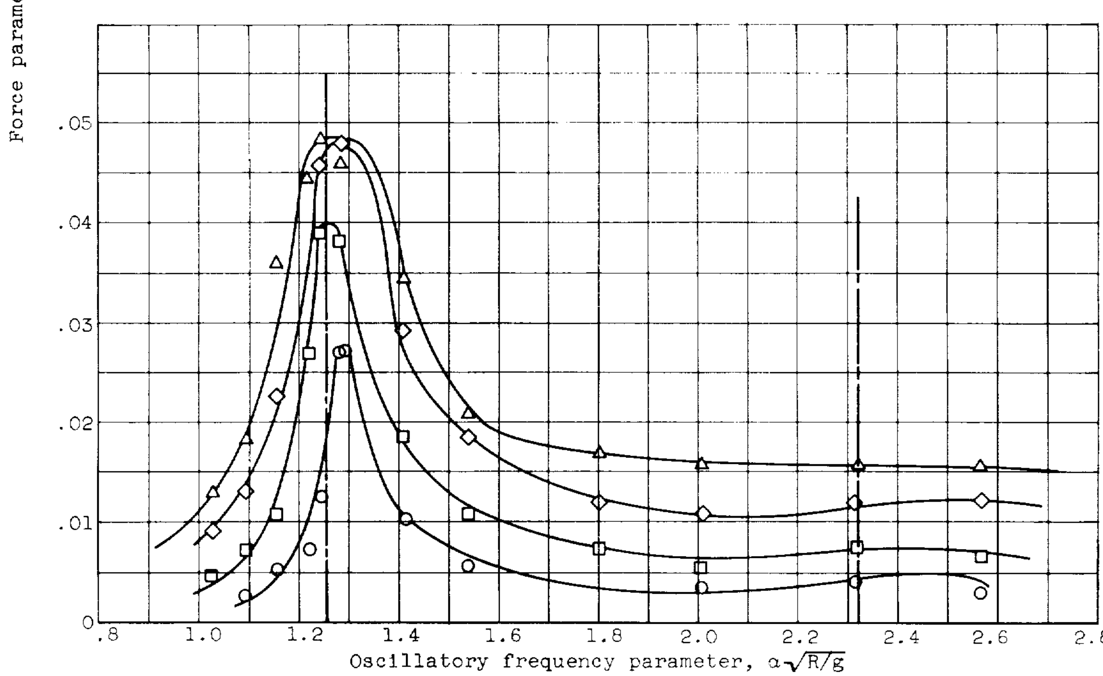


Figure 4. - Diaphragm and installation in tank.

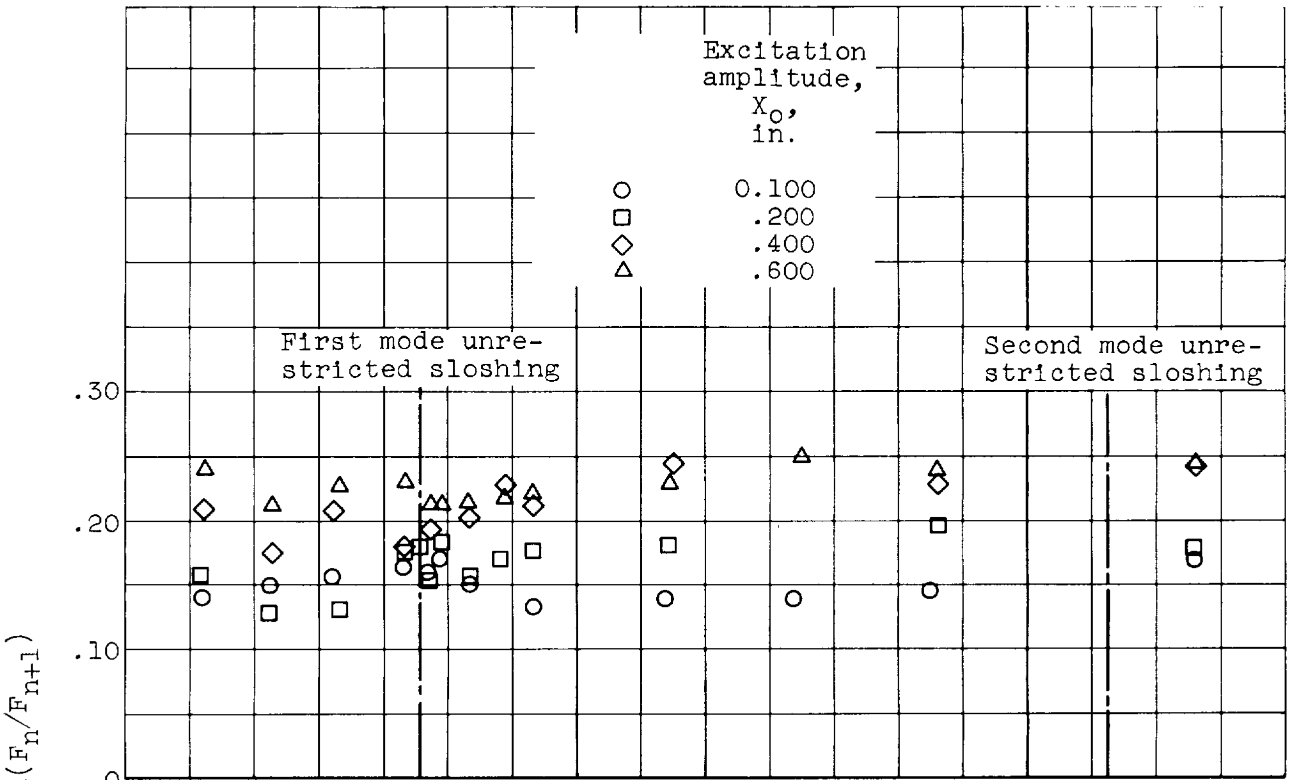


(a) Tank diameter, 20.5 inches.

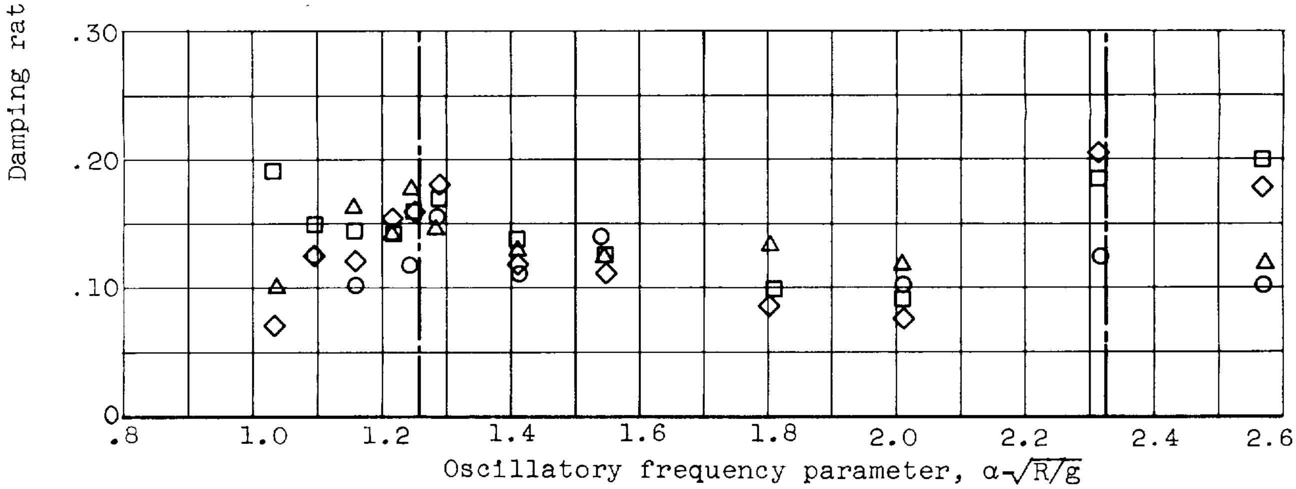


(b) Tank diameter, 32 inches.

Figure 5. - Effect of excitation amplitude on slosh force parameter for 0.010-inch-thick diaphragm.

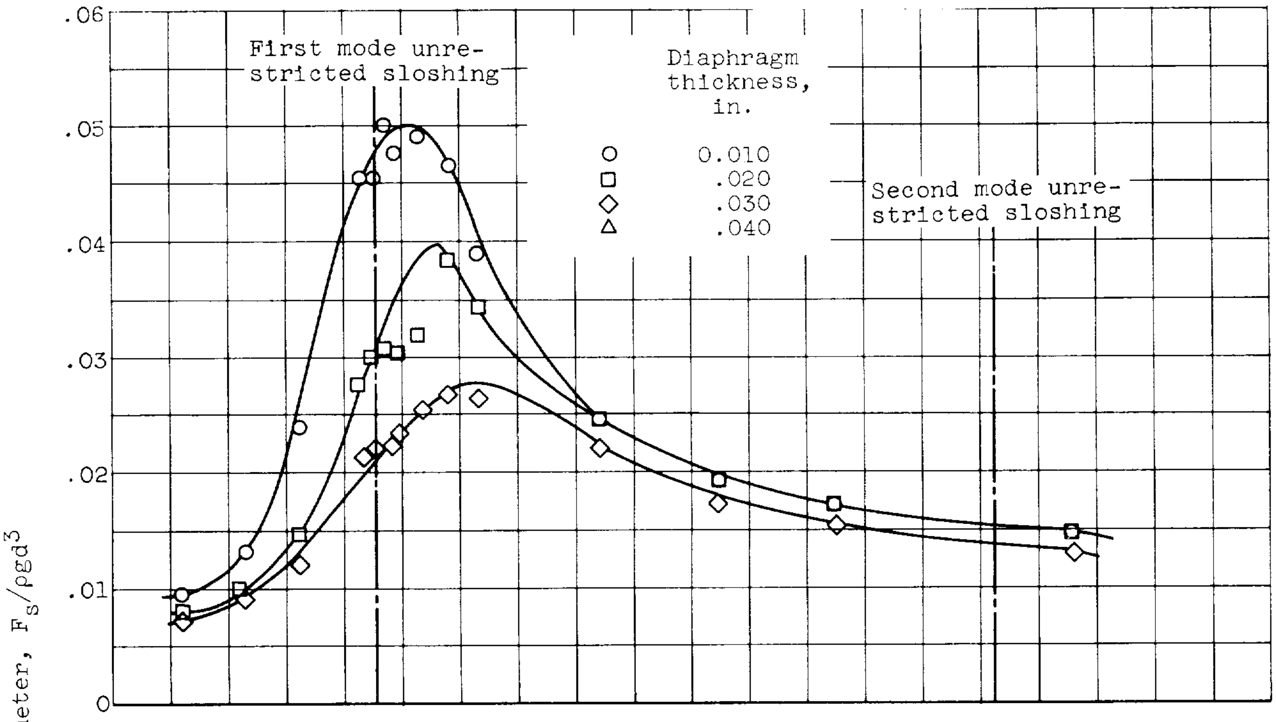


(a) Tank diameter, 20.5 inches.

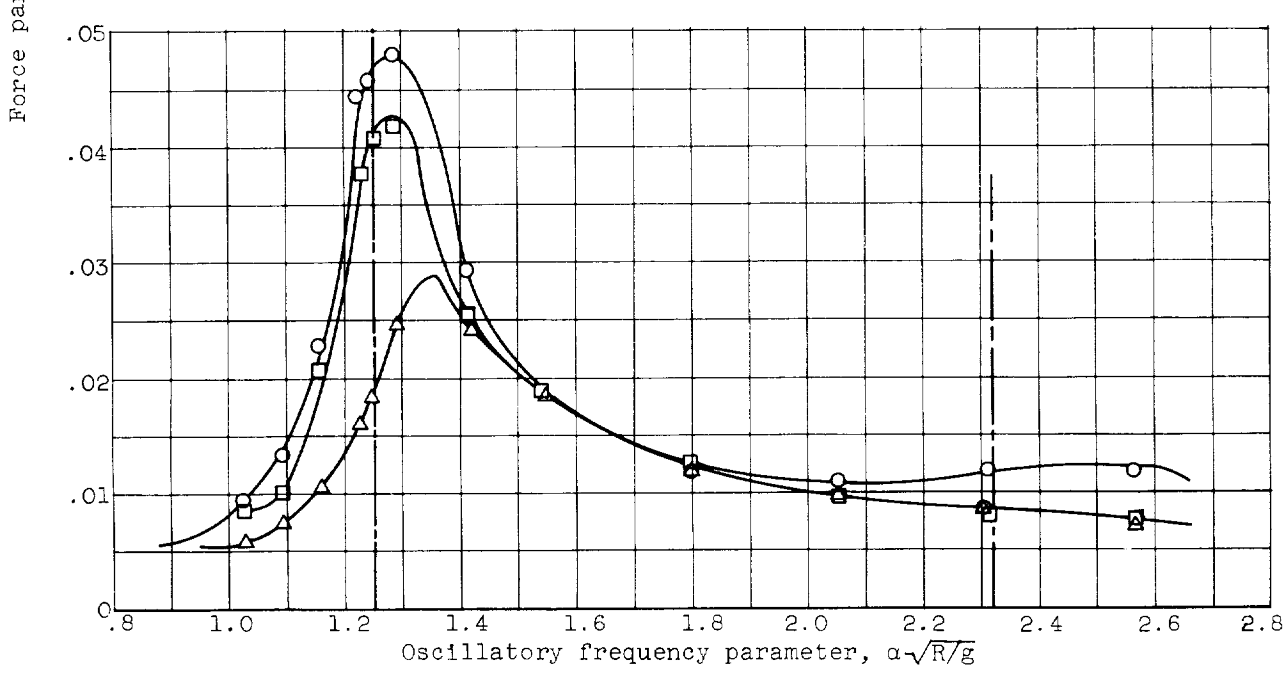


(b) Tank diameter, 32 inches.

Figure 6. - Effect of excitation amplitude on damping ratio for 0.010-inch-thick diaphragm.

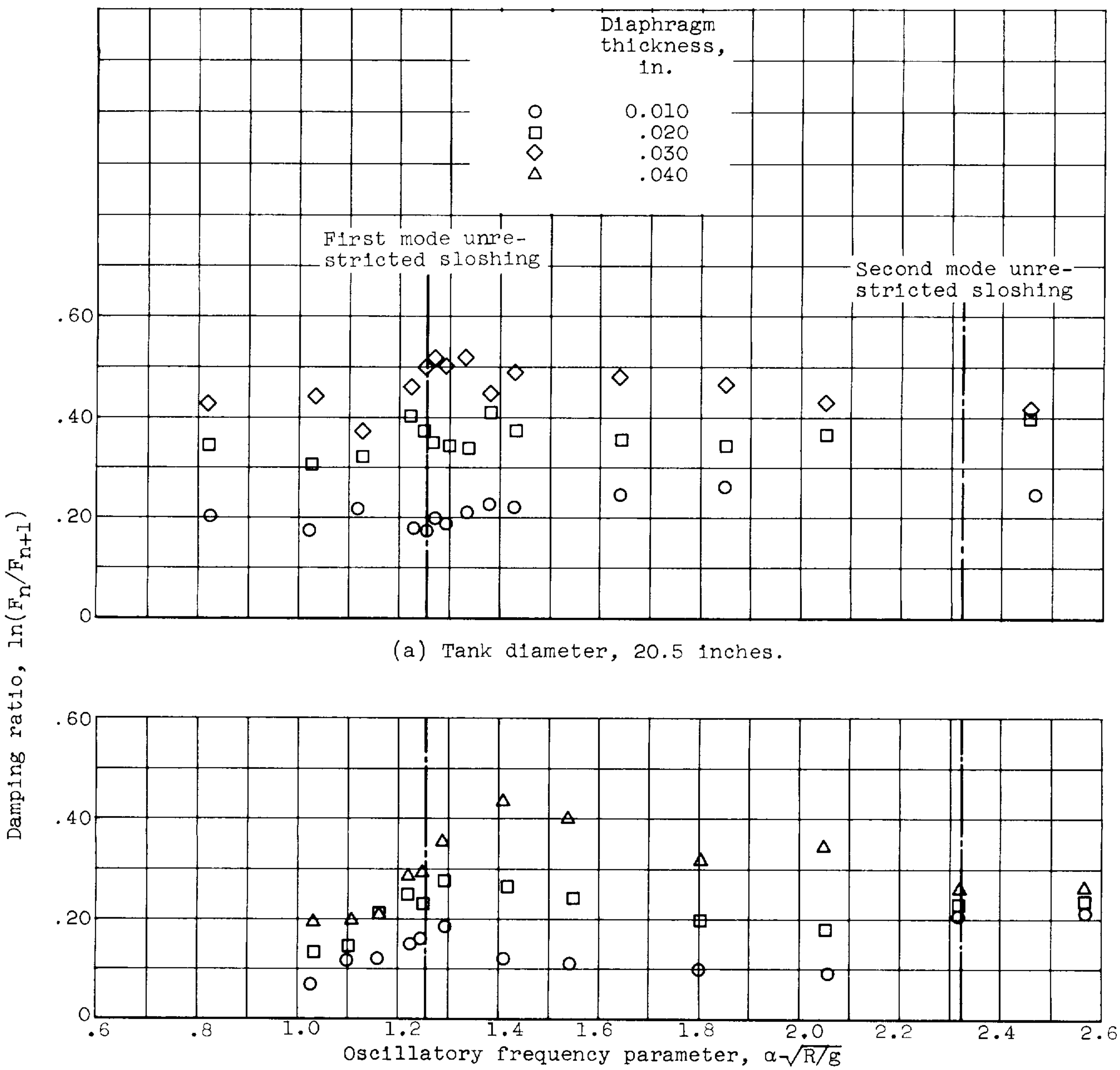


(a) Tank diameter, 20.5 inches.



(b) Tank diameter, 32 inches.

Figure 7. - Effect of diaphragm thickness on slosh force parameter for an excitation amplitude of 0.400 inch.



(a) Tank diameter, 20.5 inches.

(b) Tank diameter, 32 inches.

Figure 8. - Effect of diaphragm thickness on damping ratio for an excitation amplitude of 0.400 inch.

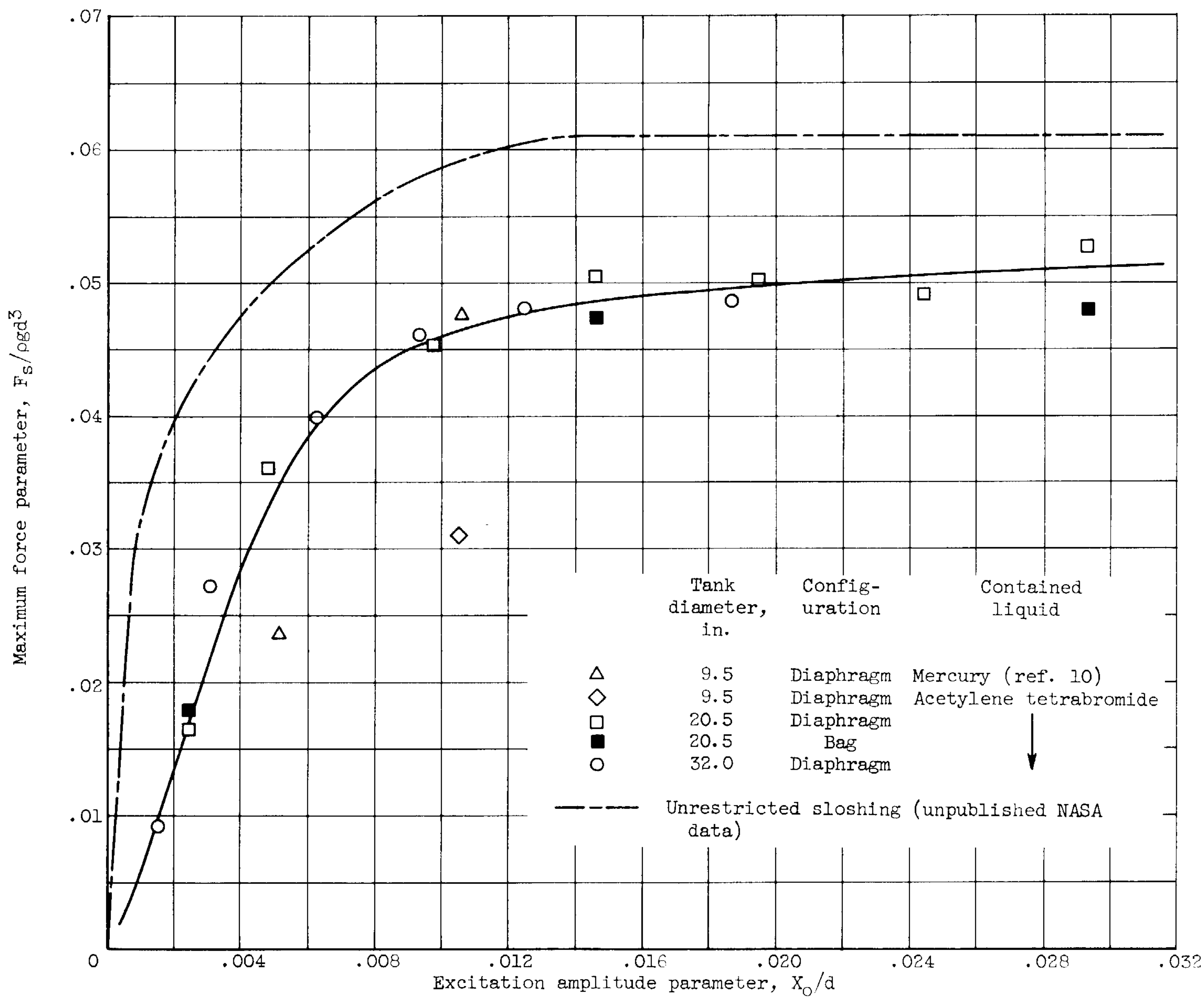


Figure 9. - Effect of excitation amplitude parameter on maximum force parameter for 0.010-inch-thick diaphragm and bag.

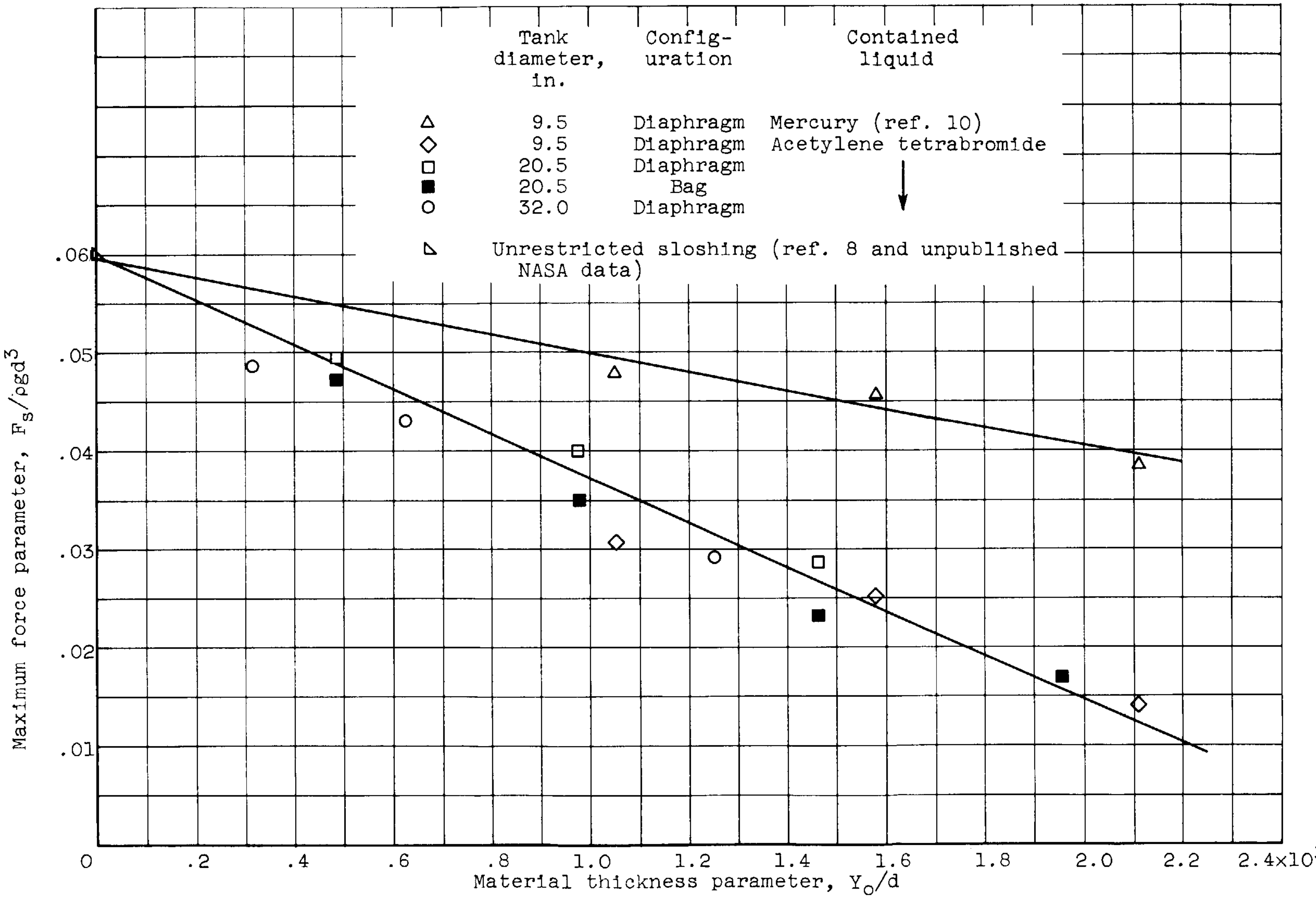


Figure 10. - Effect of material thickness parameter on the maximum force parameter for bags and diaphragms. Excitation amplitude parameter greater than 0.010.

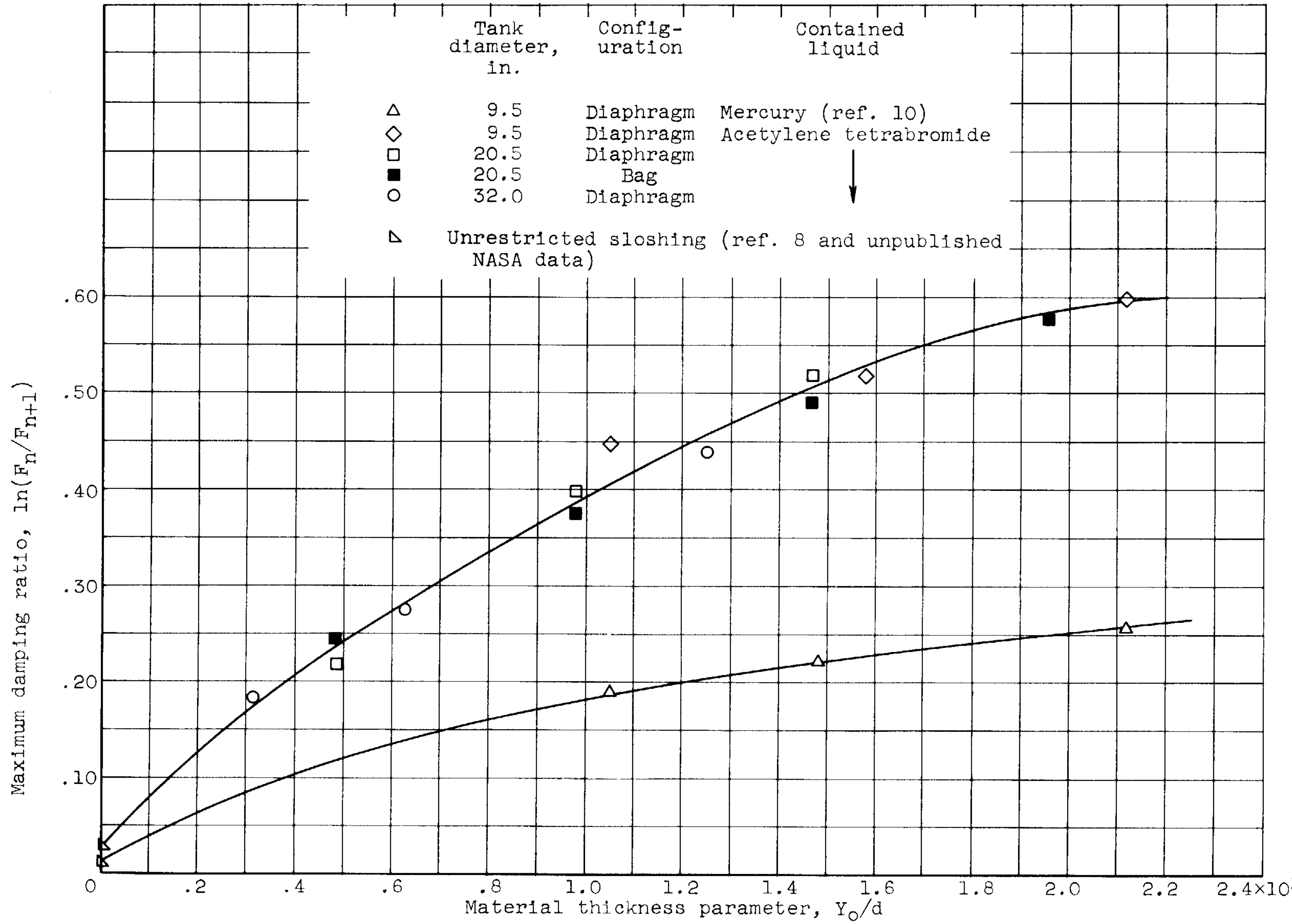


Figure 11. - Effects of material thickness parameter on maximum damping ratio for diaphragms and bags. Excitation amplitude parameter greater than 0.010.

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