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SUMMARY

An experimental investigation was conducted to determine the slosh-suppression effectiveness of rigid and flexible flat-plate annular-ring baffles in suppressing the fundamental antisymmetric mode of liquid oscillations in rigid spherical tanks having diameters of 32.0 and 9.5 inches. The baffles caused a variation in the fundamental frequency of liquid oscillations by effectively changing the tank geometry. The baffles were most effective in reducing the slosh forces and increasing the damping when the quiescent liquid surface was slightly above the baffle so that it remained submerged during the liquid oscillatory cycle. The optimum baffle width to tank radius ratio of those values investigated was 0.125. The experimental data are presented in terms of dimensionless parameters that generalized the results for a variation in tank diameter for specific values of baffle width ratio, liquid-depth ratio, and excitation amplitude parameter.

INTRODUCTION

Propellant sloshing is a potential source of disturbance critical to the stability and structural integrity of space vehicles containing relatively large masses of liquid propellants. Large side forces may be produced by the propellant oscillating at its fundamental (first natural mode) frequency in a partly filled tank. Since the liquid oscillatory frequency may nearly coincide with either the fundamental body bending frequency or the dynamic control frequency of the vehicle at some time during the powered phase of the flight, the slosh forces could interact with the vehicle structure or control system and cause a failure of structural components within the vehicle or excessive deviation from its planned flight path.

Several methods of limiting the magnitude of the propellant oscillations by increasing the damping applied to the contained liquid in tanks of varying configurations have been investigated. These investigations include the use of a floating lid device (ref. 1), positive-expulsion bags and diaphragms (refs. 2 and 3), high-viscosity liquids (ref. 4), and cans or annular-ring baffles (refs. 5 to 12). From the preceding information, it appears that one of the simplest and most promising slosh-suppression devices is the flat-plate annular-ring baffle.

The spherical tank, since it provides a minimum tank weight for a given volume, may provide definite advantages for some space vehicle applications. Previous investigations, however, have not included a comprehensive experimental study of the slosh-suppression characteristics and scaling factors for annular-ring baffles in spherical tanks.

Therefore, an experimental investigation was conducted at the NASA Lewis Research Center to (1) study the potential slosh-suppression effectiveness of flat-plate annular-ring baffles in spherical tanks, (2) determine an optimum baffle width from considerations of slosh-suppression characteristics and baffle weight, and (3) evaluate the suitability of previously utilized dimensionless parameters (refs. 2 to 4 and 13) as scaling factors for baffled spherical tanks of varying diameter. The fundamental frequencies of liquid oscillation, horizontal slosh forces, and damping ratios (logarithmic decrements) were obtained for baffled and unbaffled tanks over a range of (1) excitation frequencies and amplitudes for a one-half full tank and (2) liquid-depth ratios (liquid depth/tank diameter) where the excitation frequencies were equal to the fundamental frequencies of liquid oscillation. Spherical tanks having diameters of 32.0 and 9.5 inches were used in this investigation. The contained liquid was water in all cases.

Rigid single-ring baffles having baffle width ratios (baffle width/tank radius) of 0.0625, 0.125, 0.250, and 0.375 and a rigid three-ring baffle configuration having a baffle width ratio of 0.125 were investigated in the 32.0-inch-diameter tank. Rigid single-ring baffles having baffle width ratios of 0.125 and 0.250 were also investigated in the 9.5-inch-diameter tank for comparison with comparable configurations in the larger tank. A flexible single-ring baffle having a baffle width ratio of 0.375 was also investigated in the 32.0-inch-diameter tank for comparison with the comparable rigid baffle configuration. In all cases, the single-ring baffles were located at a depth ratio of 0.50, which corresponds to the liquid-depth ratio where maximum slosh forces have been shown to occur (ref. 13). The baffles of the three-ring configuration were located at depth ratios of 0.35, 0.50, and 0.65. The results of this investigation are presented herein.

SYMBOLS

D	diameter of spherical tank, ft
F_S	horizontal slosh force, lb
g	vertical acceleration, 32.174 ft/sec^2
h	liquid depth, ft
$h/2R$	liquid-depth ratio

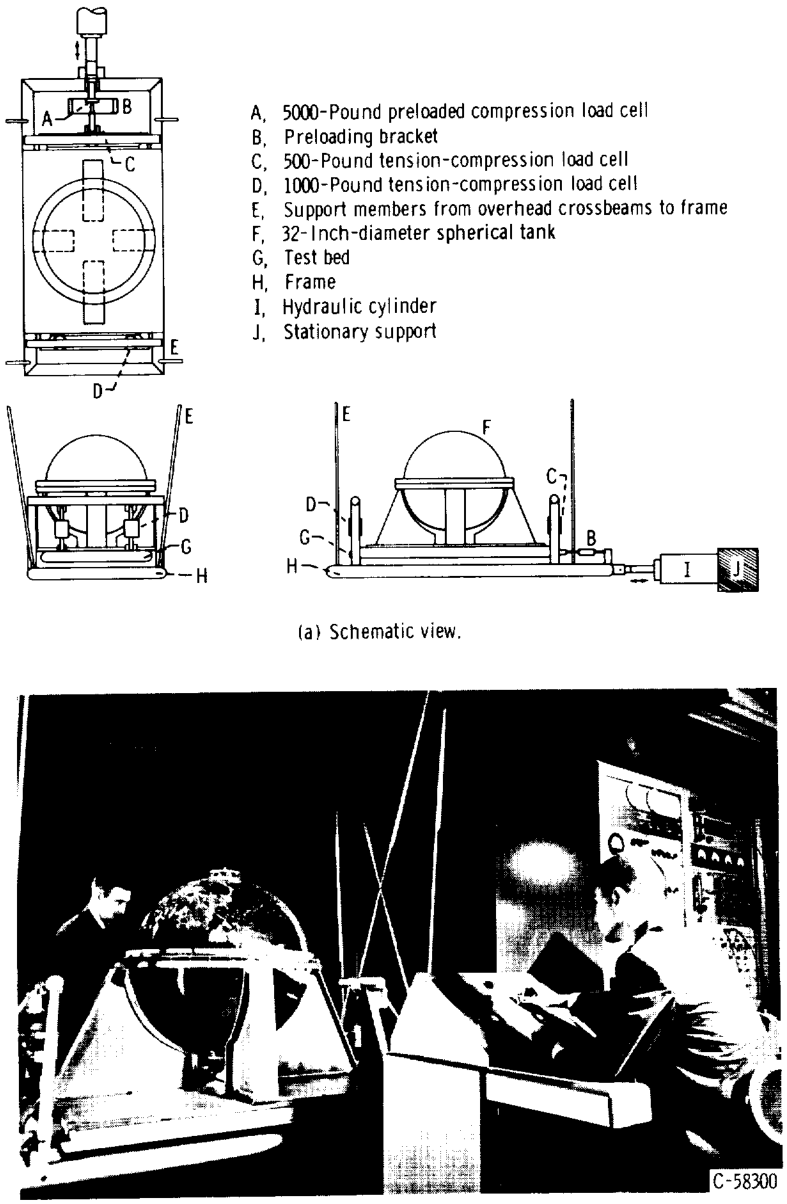
h_b	distance from bottom of tank to baffle, ft
$h_b/2R$	baffle location
R	radius of spherical tank, ft
W	baffle width, ft
W/R	baffle width ratio
X_0	excitation amplitude, ft
X_0/D	excitation amplitude parameter
α	oscillatory excitation frequency, rad/sec
α_l	liquid fundamental (first natural mode) frequency, rad/sec
δ	damping ratio (logarithmic decrement), $\ln\left[\frac{(F_s)_n}{(F_s)_{n+1}}\right]$
η	excitation frequency parameter, $\alpha\sqrt{R/g}$
η_l	liquid fundamental frequency parameter, $\alpha_l\sqrt{R/g}$
λ	horizontal slosh-force parameter, $F_s/\rho g D^3$
ρ	liquid mass density, slugs/ft^3

Subscript:

n	cycle number, 1, 2, 3, . . .

APPARATUS AND INSTRUMENTATION

The large experimental test facility, which is identical to that described in references 3 and 4, is shown in figure 1. A 32.0-inch-diameter spherical tank fabricated from clear plastic was mounted on a test bed that was suspended from a frame through three vertically oriented load cells and one horizontally oriented load cell. 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. The excitation amplitude could be varied from 0 to 1 inch, and the excitation frequency could be varied from 0 to 20 cycles per second. A sinusoidal excitation wave form was used for this investigation. The electric and hydraulic control circuits for the driving mechanism were designed to enable the oscillatory motion of the frame, test bed, and tank to be "quick-stopped" at a point of zero velocity during any given cycle of oscillation so that only the residual horizontal forces resulting from the liquid sloshing could be measured. The horizontal slosh forces were sensed by the horizontal load cell (a piezoelectric quartz crystal that had been preloaded in compression), and the signal was displayed on a continu-



(a) Schematic view.

(b) Pictorial view.

Figure I. - Large expeimental test facility for annular-ring baffles.

ously recording strip chart. Experimental data are not presented from the vertical load cells because they did not possess sufficient accuracy and sensitivity.

The smaller test facility shown in figure 2 was identical to that described in references 2 to 4 and 13. A 9.5-inch-diameter spherical tank was formed in a laminated clear plastic block. When placed on the test facility, the tank was mounted on four ball bearings and was free to oscillate in one direction in the horizontal plane. The sinusoidal motion of the tank was produced by a slider-crank mechanism driven through a variable-speed transmission by an alternating-current electric motor. The excitation amplitude was fixed at 0.100 inch; the excitation frequency could be varied from 0 to 5 cycles per second. The electric driving motor was wired so that the alternating current could be removed from the field and a direct current could be applied to one of the field windings. This enabled the oscillatory motion of the tank to be quick-stopped so that only the residual horizontal forces resulting from the liquid sloshing could be measured. These residual slosh forces were sensed by a strain gage mounted between the tank and the slider-crank mechanism. The signal from the strain gage was displayed by means of a continuously recording strip chart.

A summary of the baffle configurations investigated is presented in table I, and diagrams are shown in figure 3. The rigid single-ring and three-ring baffle configurations utilized in the 32.0-inch-diameter tank were fabricated from 1/8-inch-thick aluminum. The single-ring baffles ($W/R = 0.0625$, 0.125, 0.250, and 0.375) were each located at a depth ratio $h_b/2R$ of 0.50.

The baffles of the three-ring configuration ($W/R = 0.125$) were located at depth ratios of 0.35, 0.50, and 0.65. The flexible single-ring baffle ($W/R = 0.375$) was fabricated from 0.012-inch-thick spring brass and consisted of four overlapping segments (as shown in fig. 4) to achieve a high degree of flexibility.

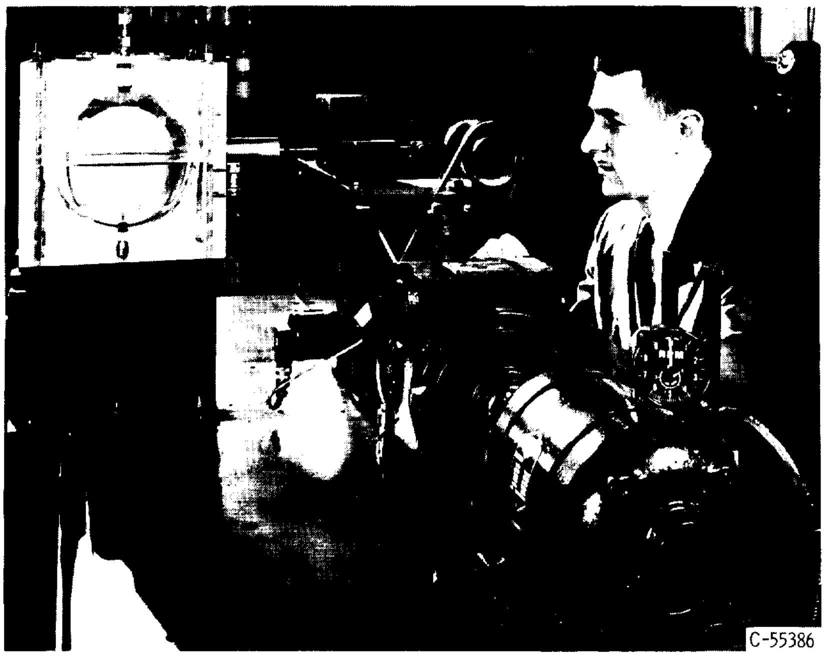


Figure 2. - Small experimental test facility for annular-ring baffles.

The rigid single-ring baffles utilized in the 9.5-inch-diameter tank were fabricated from 0.012-inch-thick spring brass. Baffle width ratios of 0.125 and 0.250 were investigated; each baffle was located at a depth ratio $h_b/2R$ of 0.50.

Water was used as the contained liquid in all cases.

TABLE I. - BAFFLE CONFIGURATIONS

Tank diameter, D, in.	Baffle location, $h_b/2R$	Baffle width, W, in.	Baffle width ratio, W/R	Type baffle
32.0	0.5	1.0	0.0625	Single ring, rigid
32.0	.5	2.0	.125	Single ring, rigid
32.0	.5	4.0	.250	Single ring, rigid
32.0	.5	6.0	.375	Single ring, rigid
32.0	.5	6.0	.375	Single ring, flexible
32.0	0.35, 0.5, 0.65	2.0	.125	Three ring, rigid
9.5	.5	.593	.125	Single ring, rigid
9.5	.5	1.186	.250	Single ring, rigid

PROCEDURE

For each data point taken on either test facility, the tank was oscillated sinusoidally at a preselected excitation frequency and amplitude until the wave height of the liquid at the tank wall had reached the maximum value that could be obtained without the liquid surface breaking up and showering liquid throughout the tank. The oscillatory motion of the tank was then quick-stopped, and the residual horizontal slosh forces were

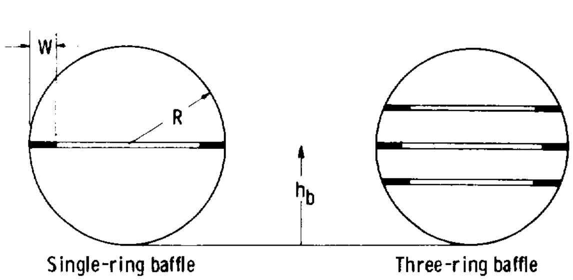


Figure 3. - Side views of baffles.

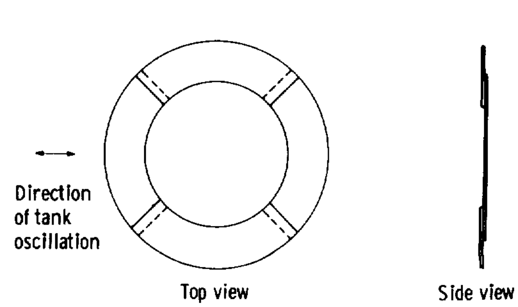


Figure 4. - Flexible single-ring baffle.

recorded. Excitation amplitudes from 0.050 to 0.900 inch and excitation frequencies from 0.5 to 2.0 cycles per second were investigated with the larger test facility. An excitation amplitude of 0.100 inch and excitation frequencies from 0.9 to 2.1 cycles per second were investigated with the smaller test facility. Experimental data were obtained for each baffle configuration over a range of liquid-depth ratios encompassing the baffle location.

DATA REDUCTION

The initial input conditions of excitation amplitude and frequency were reduced to dimensionless parameters X_0/D and $\eta = \alpha\sqrt{R/g}$, respectively. The fundamental frequency of the contained liquid was determined from the first several cycles of the slosh-force oscillograph trace occurring immediately after the quick stop and was reduced to the dimensionless parameter $\eta_l = \alpha_l\sqrt{R/g}$. The slosh-force parameter $\lambda = F_s/\rho g D^3$ was calculated by using the magnitude of the first slosh-force peak occurring immediately after the oscillatory motion of the tank had been quick-stopped. The damping ratios were calculated by averaging the first two successive values of the logarithmic decrement $\delta = \ln[(F_s)_n/(F_s)_{n+1}]$ on each oscillograph trace, where $(F_s)_n$ was the peak force on one slosh cycle and $(F_s)_{n+1}$ was the peak force on the succeeding cycle.

RESULTS AND DISCUSSION

Rigid Single-Ring Baffles, Baffle Width Ratio $0 \leq W/R \leq 0.375$, 32.0-Inch-Diameter Tank

Liquid-depth ratio of 0.50. - The liquid fundamental frequency parameter η_l is presented as a function of the excitation frequency parameter η in

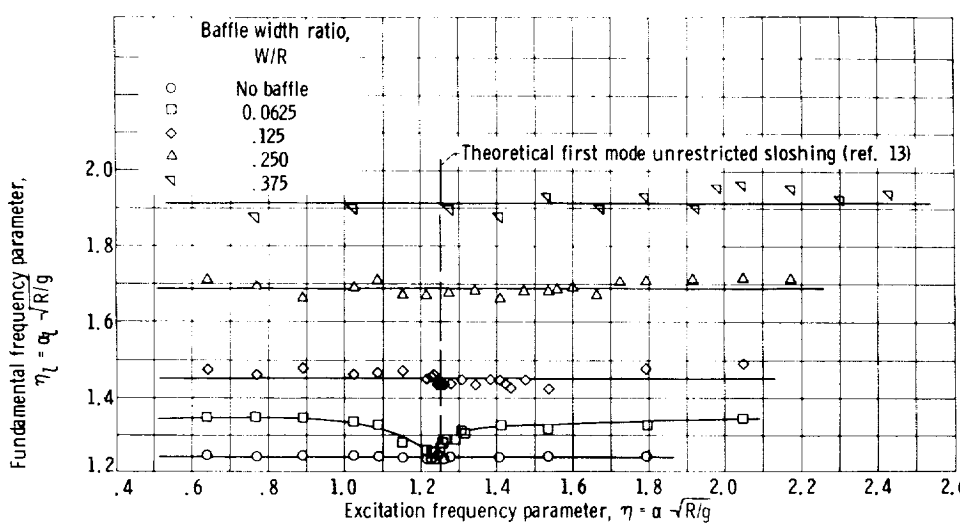
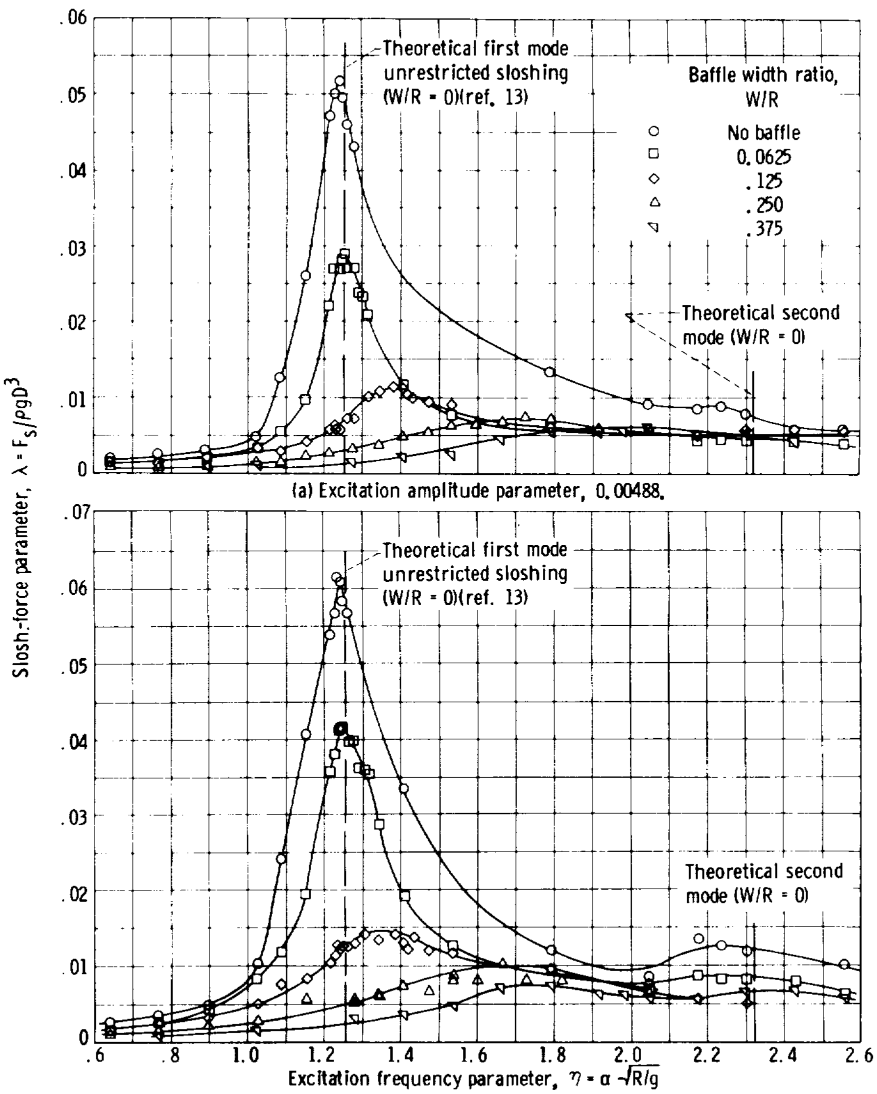


Figure 5. - Variation of fundamental frequency parameter with excitation frequency parameter for rigid single-ring baffles. 32-Inch-diameter tank; liquid-depth ratio, 0.50.

figure 5. The fundamental frequency of the liquid oscillations generally increased with baffle width ratio; the fundamental frequency for each baffle width was somewhat greater than the calculated frequency (ref. 13) for an equivalent tank with a diameter equal to the inside diameter of the baffle. The fundamental frequency tended to be independent of the excitation frequency for all baffle width ratios investigated with the exception of $W/R = 0.0625$, for which the fundamental frequency approached that of an unbaffled tank ($W/R = 0$) as the excitation frequency approached the fundamental frequency and the wave height of the liquid oscillations became large.

The slosh-force parameter λ is presented in figure 6 as a function of the excitation frequency parameter for excitation amplitude parameters X_0/D of 0.00488 and 0.00975. The slosh-force parameter attained a maximum value at



(b) Excitation amplitude parameter, 0.00975.

Figure 6. - Slosh-force parameter as function of excitation frequency parameter for rigid single-ring baffles. 32-inch-diameter tank; liquid-depth ratio, 0.50.

an excitation frequency equal to or near the fundamental frequency of liquid oscillation associated with each baffle width ratio; these maximum slosh forces are hereafter referred to as the first or fundamental mode slosh forces. The first mode slosh forces were reduced by approximately 90 percent as the baffle width ratio was increased from 0 to 0.375; however, little additional decrease in the first mode slosh forces was noted for baffle width ratios greater than 0.125. In some cases a small force peak occurred as the excitation frequency approached the second natural frequency of the liquid oscillations. The characteristic second mode wave form became less clearly defined and more difficult to obtain as the baffle width ratio increased; consequently, the second mode slosh forces were reduced or eliminated.

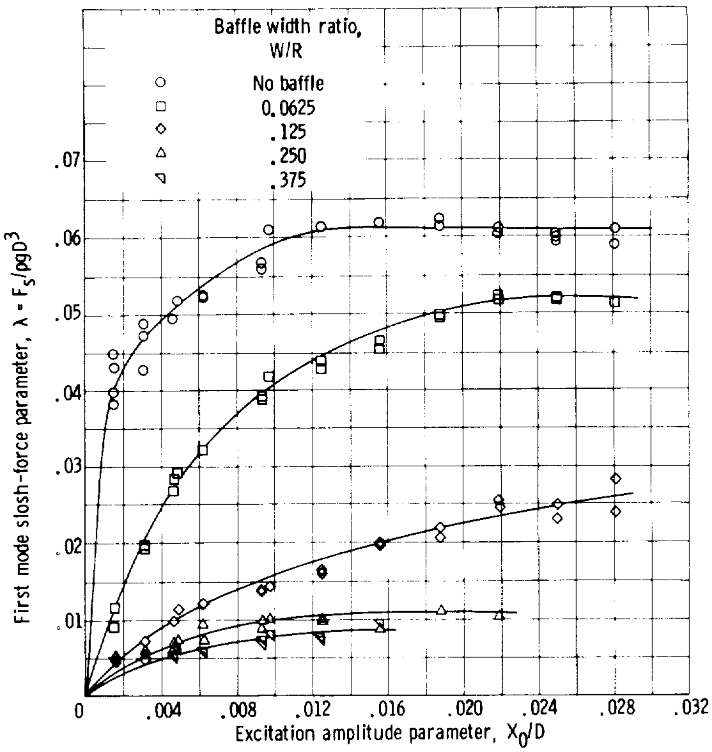


Figure 7. - Variation of first mode slosh-force parameter with excitation amplitude parameter for rigid single-ring baffles. 32-inch-diameter tank; liquid-depth ratio, 0.50.

The first mode slosh-force parameter is presented in figure 7 as a function of the excitation amplitude parameter. For each baffle width ratio investigated, the force parameter tended to increase to a maximum value

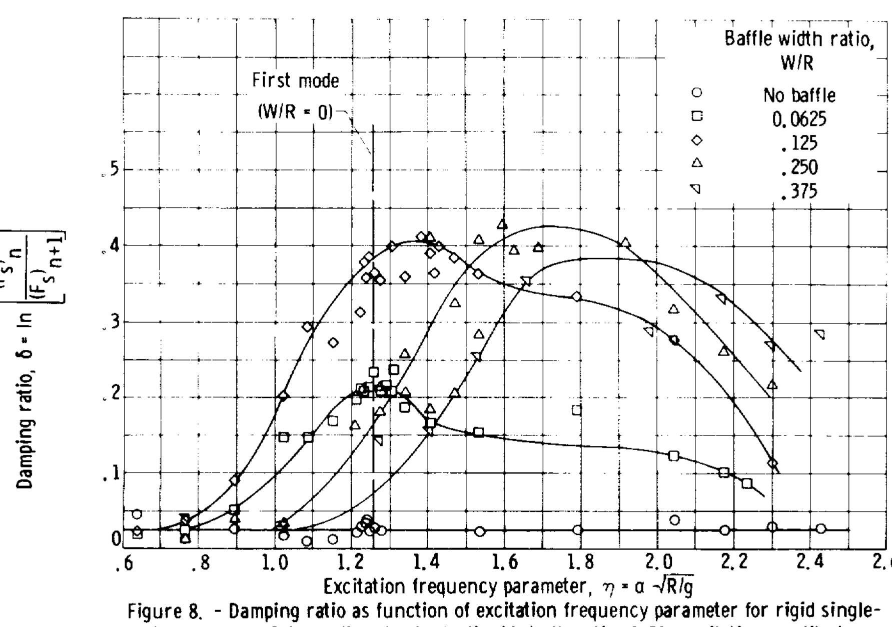


Figure 8. - Damping ratio as function of excitation frequency parameter for rigid single-ring baffles. 32-inch-diameter tank; liquid-depth ratio, 0.50; excitation amplitude parameter, 0.00975.

and then remain constant as X_0/D increased. At a given value of X_0/D, the force parameter decreased as the baffle width ratio increased; the unrestricted slosh-forces were reduced by as much as 85 percent by the $W/R = 0.375$ baffle at the maximum excitation amplitudes investigated.

The effect of a variation in excitation frequency on the damping ratio δ for each of the rigid single-ring baffle configurations is shown in figure 8 for a value of X_0/D of 0.00975. The damping ratio for $W/R = 0$ was independent of the excitation frequency, and therefore of the wave height of the liquid surface, as previously noted in reference 4. The damping ratio for each baffle configuration was strongly dependent upon the wave height and reached a maximum when the excitation frequency was approximately equal to the fundamental frequency. Little or no increase in the first mode damping ratio was found as the baffle width ratio increased beyond a value of 0.125.

Liquid depth ratio $0.25 \leq h/2R \leq 0.75$. - The effect of a variation in liquid-depth ratio on the fundamental frequency parameter for each of the rigid single-ring baffles is shown in figure 9. The excitation frequency was equal to the fundamental frequency for each liquid-depth and baffle width ratio. The experimentally determined fundamental frequencies obtained in the unbaffled tank were slightly lower than those predicted by reference 13 except at the higher liquid-depth ratios, where agreement was good. The presence of the $W/R = 0.0625$ baffle generally caused little variation in the fundamental frequencies from those values noted in the unbaffled tank. The fundamental frequencies obtained for the $0.125 \leq W/R \leq 0.375$ baffles increased rapidly to maximum values for liquid-depth ratios equal to or somewhat greater than that of the baffle location ($h_b/2R = 0.50$); this increase was apparently due to an effective reduction in the tank diameter that was created by the baffle and a turbulent flow region near the edge of the baffle. A sharp decrease of the fundamental frequencies was then observed for the $0.125 \leq W/R \leq 0.375$ baffles when the liquid-depth ratio increased slightly farther above the baffle location; this decrease is probably caused by a tendency of the baffle to reduce the apparent liquid-depth ratio so that the sloshing liquid acted

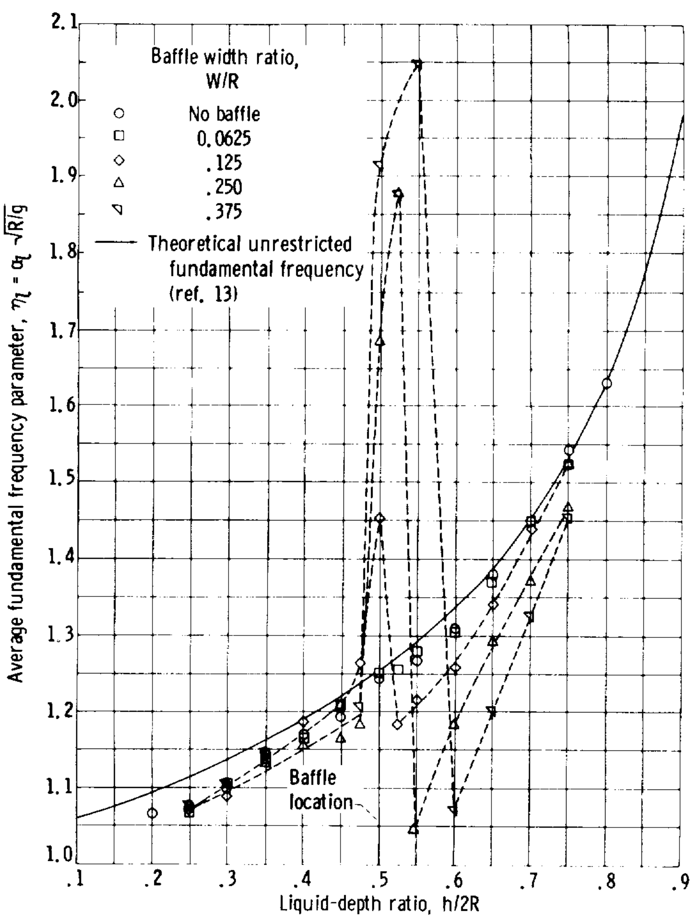


Figure 9. - Variation of fundamental frequency parameter with liquid-depth ratio for rigid single-ring baffles. 32-inch-diameter tank.

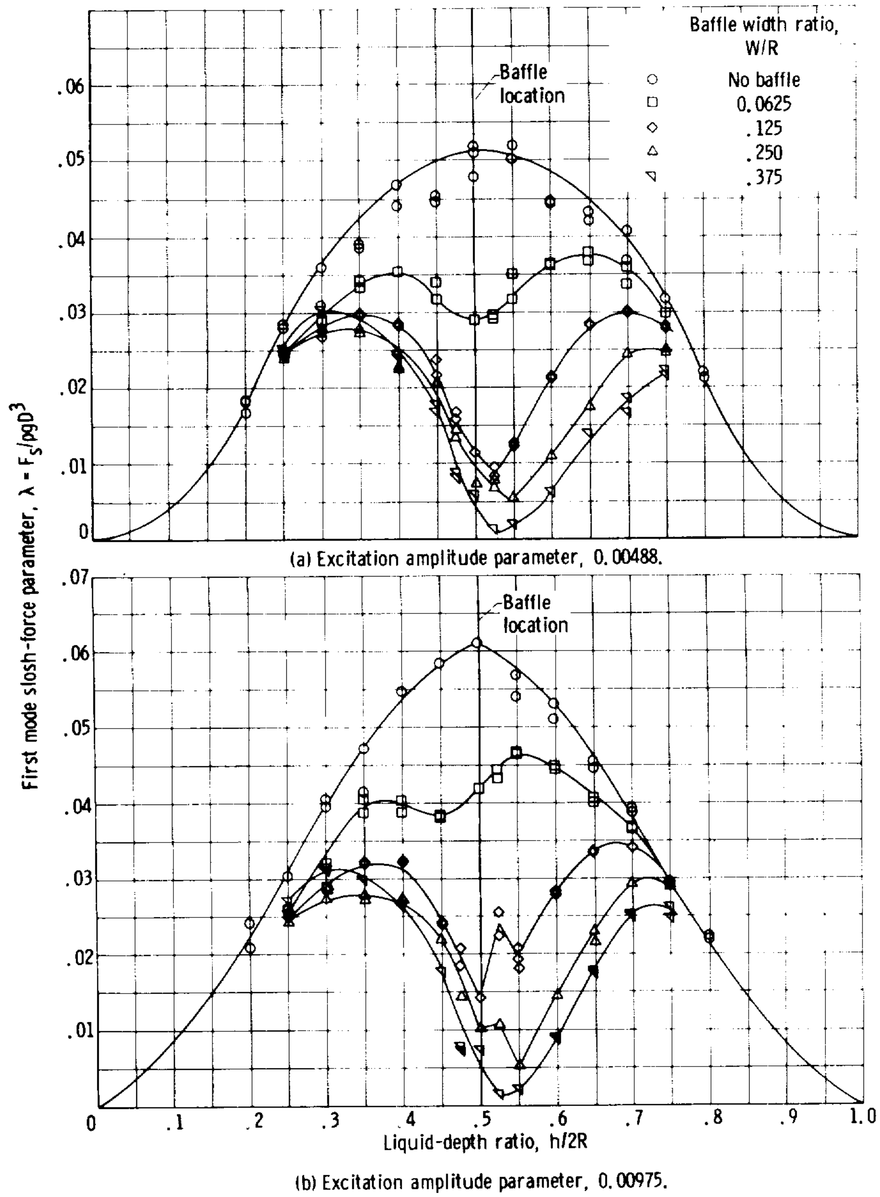


Figure 10. - Variation of first mode slosh-force parameter with liquid-depth ratio for rigid single-ring baffles. 32-inch-diameter tank.

as though it were contained in a flat-bottom hemispherical tank. These variations in the fundamental frequency with liquid-depth ratio became more pronounced as the baffle width ratio increased. A similar variation in fundamental frequencies has been observed for baffled cylindrical tanks (ref. 9). Each of the data points presented in figure 9 represents an average of several values; the maximum deviation from the average was ±3.5 percent.

The first mode slosh-force parameters for each baffle width ratio are presented as a function of the liquid-depth ratio in figure 10 for values of X_0/D of 0.00488 and 0.00975. The force parameter decreased at almost all liquid-depth ratios investigated as the baffle width ratio increased. It was observed that, generally, each baffle configuration was most effective when the baffle was submerged just below the liquid surface when the wave height reached a maximum as shown in figure 11. The increase in the force parameter at $h/2R = 0.525$ and $X_0/D = 0.00975$ for the $W/R = 0.125$ and 0.250 baffles apparently occurred because the baffles did not remain completely submerged during the liquid oscillatory cycle. The slosh baffles became relatively ineffective in reducing the slosh forces at liquid-depth ratios $0.35 > h/2R > 0.70$.

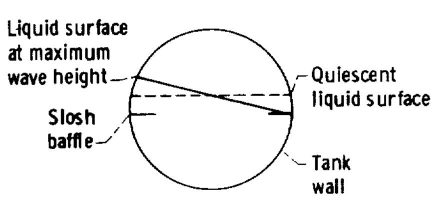


Figure 11. - Liquid surface configuration at maximum baffle efficiency.

The first mode damping ratios for each baffle width ratio are presented as a function of liquid-depth ratio in figure 12 for a value of X_0/D of 0.00975. The maximum damping ratio ($\delta \approx 0.75$) was obtained with the $W/R = 0.125$ baffle at a liquid-depth ratio of 0.525. The damping ratios for the $W/R = 0.375$ baffle were relatively high at liquid-depth ratios of 0.50 and 0.60 but were sharply reduced for $0.50 < h/2R < 0.60$; this apparently occurred because the baffle was extremely effective in restricting the wave height of the slosh liquid, and since the damping ratio decreases with reduced wave height, the damping ratio was also low. The baffles were generally ineffective in providing high damping ratios when the liquid surface was below or appreciably above the baffle location ($0.45 > h/2R > 0.75$).

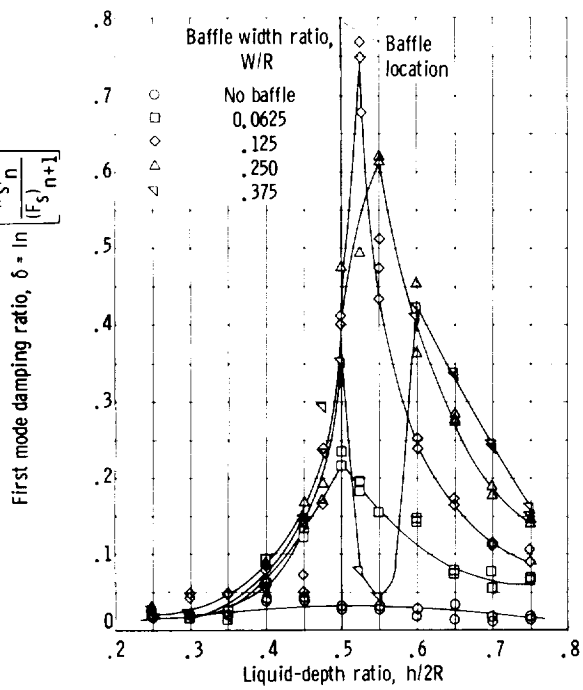


Figure 12. - Variation of first mode damping ratio with liquid-depth ratio for rigid single-ring baffles. 32-Inch-diameter tank. Excitation amplitude parameter, 0.00975.

Rigid Three-Ring Baffle, Baffle Width Ratio of 0.125, 32.0-Inch-Diameter Tank

It was desired to achieve a high degree of slosh suppression over a wider range of liquid-depth ratios than that previously obtained with single-ring baffles. From the experimental data previously presented, it appeared that, in general, the $W/R = 0.125$ baffle provided the maxi-

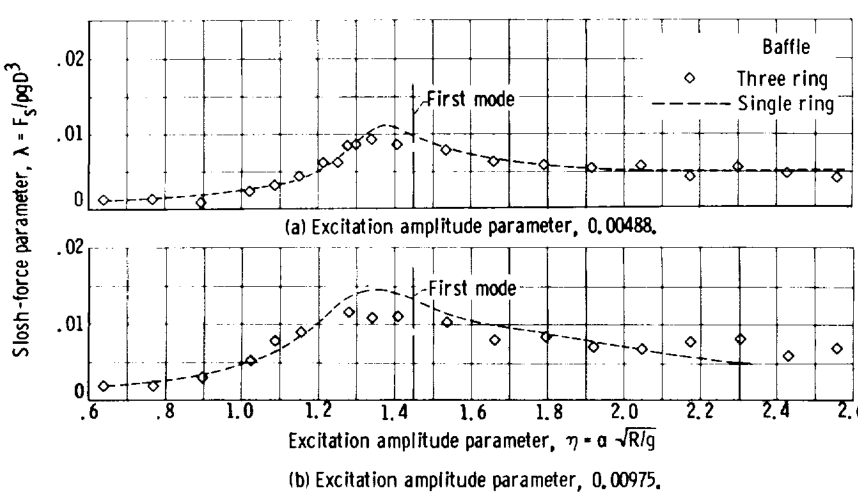


Figure 13. - Slosh-force parameter as function of excitation frequency parameter for rigid three-ring baffle. 32-Inch-diameter tank; liquid-depth ratio, 0.50; baffle width ratio, 0.125.

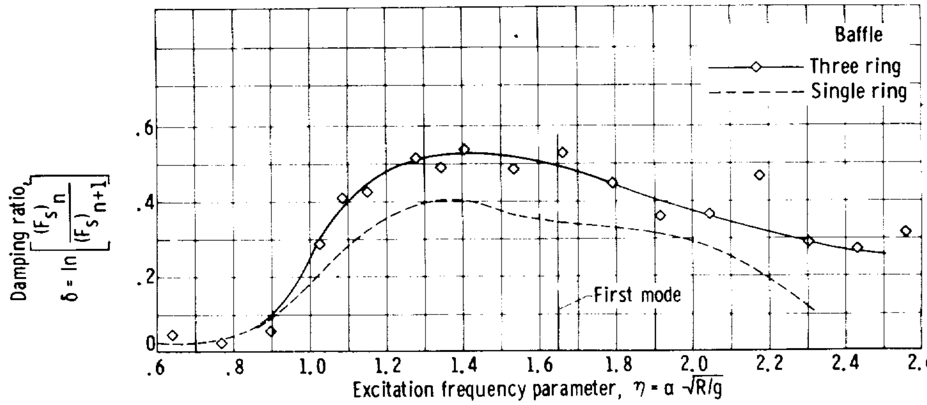


Figure 14. - Damping ratio as function of excitation frequency parameter for rigid three-ring baffle. 32-inch-diameter tank; liquid-depth ratio, 0.50; baffle width ratio, 0.125; excitation amplitude parameter, 0.00975.

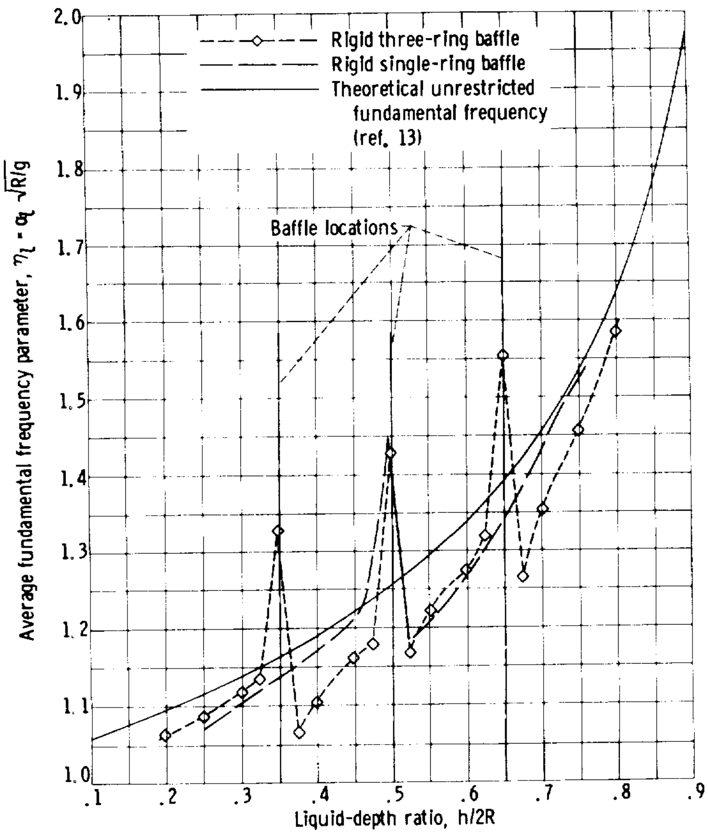


Figure 15. - Variation of average fundamental frequency parameter with liquid-depth ratio for rigid three-ring baffle. 32-inch-diameter tank; baffle width ratio, 0.125.

mum slosh-suppression effectiveness for a minimum weight penalty. The optimum vertical spacing between baffles for a three-ring configuration appeared to be about 0.15 tank diameter (figs. 10 and 12).

Liquid-depth ratio of 0.50. - The first mode slosh-force parameter is presented as a function of the excitation frequency parameter in figure 13 for values of X_0/D of 0.00488 and 0.00975. The results were similar to those obtained for the single-ring baffle configuration except at excitation frequencies near the fundamental frequency, where the wave height of the liquid oscillations became large enough for the $h_b/2R = 0.35$ baffle to provide a small amount of slosh-force suppression.

The effect of a variation in excitation frequency parameter on the damping ratio is shown in figure 14 for a value of X_0/D of 0.00975. Comparing figure 14 with figure 13(b) indicates that, while the $h_b/2R = 0.35$ baffle reduced the force parameter over only a small range of excitation frequencies, the lower baffle did increase the damping over a relatively large range of excitation frequencies.

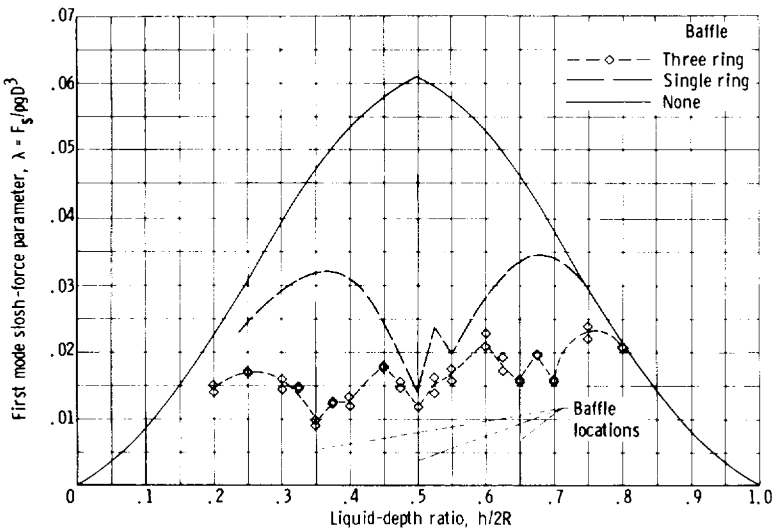
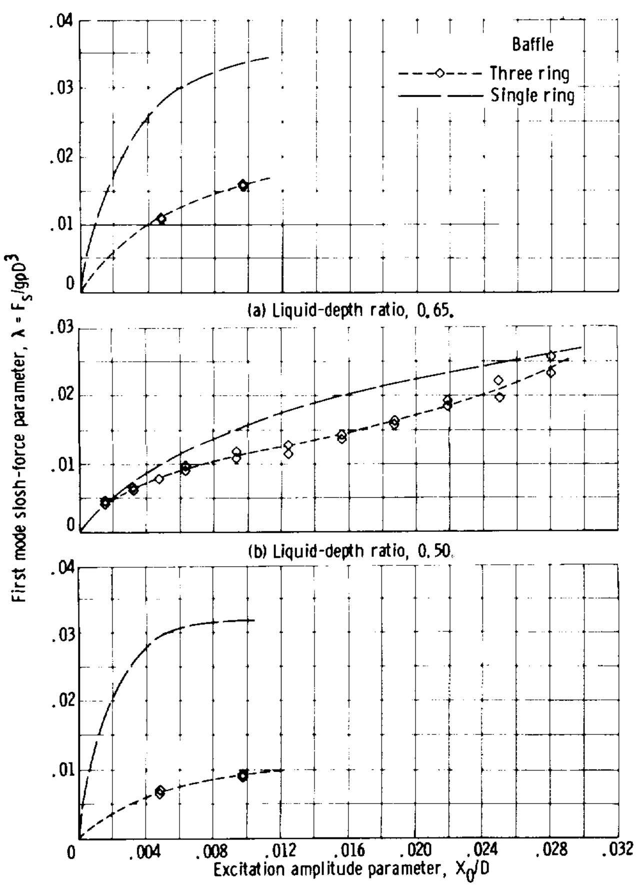


Figure 16. - Variation of first mode slosh-force parameter with liquid-depth ratio for rigid three-ring baffle. 32-Inch-diameter tank; baffle width ratio, 0.125; excitation amplitude parameter, 0 00975.



(c) Liquid-depth ratio, 0.35.

Figure 17. - Variation of first mode slosh-force parameter with excitation amplitude parameter for rigid three-ring baffle. 32-Inch-diameter tank; baffle width, 0.125.

<u>Liquid-depth ratio $0.20 \leq h/2R \leq 0.80$.</u> - Figure 15 presents the fundamental frequency parameter as a function of the liquid-depth ratio. As expected from the experimental data already presented (fig. 9, p. 9), the fundamental frequency of the contained liquid was greater than that of an unbaffled tank for $h/2R = h_b/2R$ and less than that of an unbaffled tank for $h/2R > h_b/2R$ at each baffle location.

The effectiveness of the slosh-force suppression provided by the three-ring baffle configuration is shown in figure 16 for a value of $X_0/D = 0.00975$. The first mode slosh-force parameter was again reduced to a minimum value when the liquid surface was even with each baffle location, as would be expected from consideration of the results presented in figure 10(b), page 10. The slosh-force peaks which had previously occurred at liquid-depth ratios of 0.35 and 0.70 with the single-ring baffle had been effectively reduced by the three-ring baffle configuration.

The additional slosh-force suppression provided by the $h_b/2R = 0.35$ and 0.65 baffles in the three-ring configuration is also shown in figure 17. The three-ring baffle configuration provided only slightly better slosh-force suppression than the single-ring configuration at a liquid-depth ratio of 0.50, but provided a significant increase in the slosh-force suppression at liquid-depth ratios of 0.35 and 0.65.

The first mode damping ratios are presented for a range of liquid-

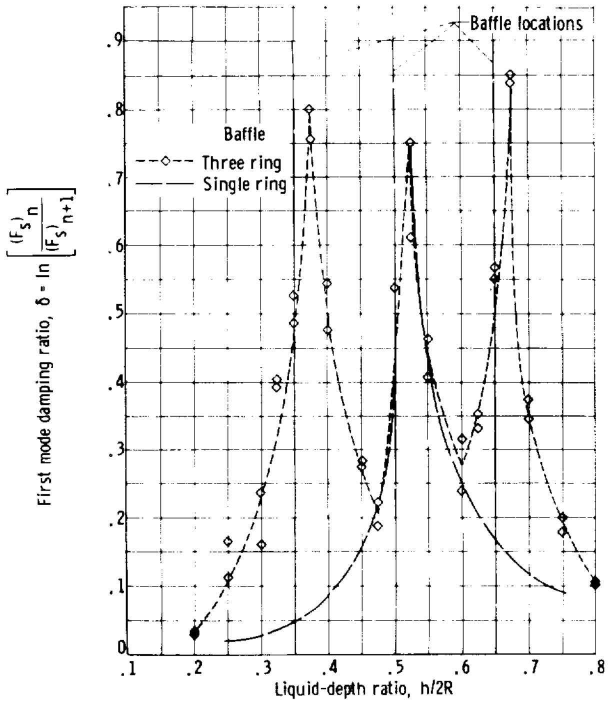


Figure 18. - Variation of first mode damping ratio with liquid-depth ratio for rigid three-ring baffles. 32-Inch-diameter tank; baffle width ratio, 0.125; excitation amplitude parameter, 0.00975.

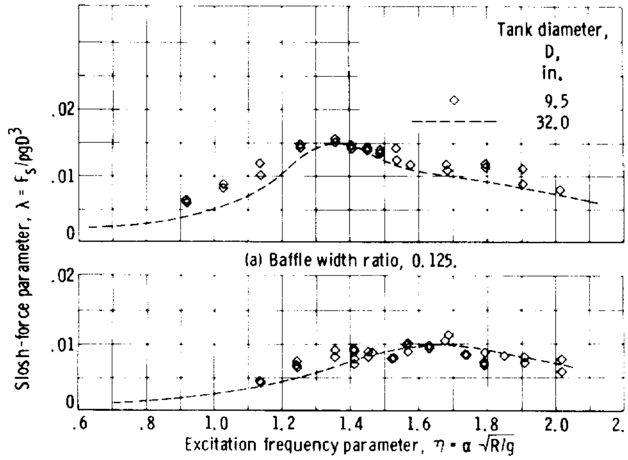


Figure 19. - Slosh-force parameter as function of excitation frequency parameter for rigid single-ring baffle. 9.5-Inch-diameter tank; liquid-depth ratio, 0.50; excitation amplitude parameter, approximately 0.01.

depth ratios in figure 18 for a value of X_0/D of 0.00975. As expected, the damping ratios increased to peak values when the liquid surface was 0.025 tank diameter above each baffle location. The three-ring baffle configuration provided damping ratios $\delta \geq 0.1$ over a range of depth ratios $0.25 \leq h/2R \leq 0.80$.

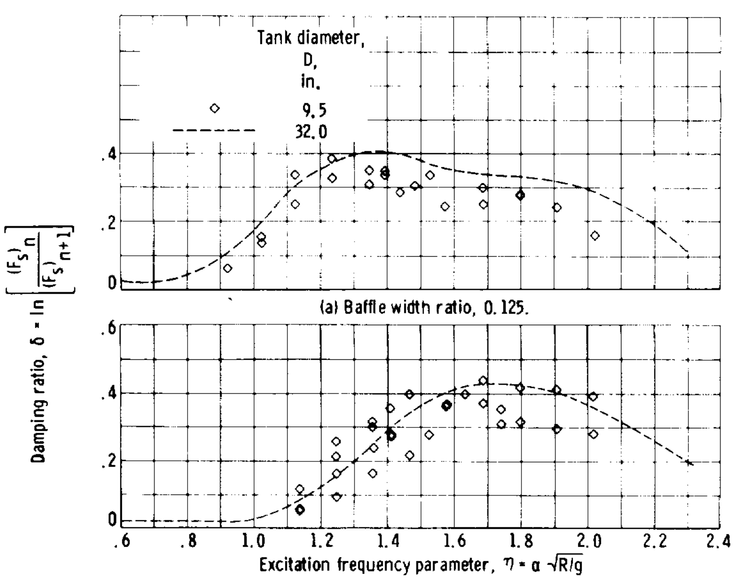


Figure 20. - Damping ratio as function of excitation frequency parameter for rigid single-ring baffles. 9.5-Inch-diameter tank; liquid-depth ratio, 0.50; excitation amplitude parameter, approximately 0.01.

The vertical load cells on the large test facility were used in this investigation only to determine comparatively if the use of annular-ring baffles to suppress liquid sloshing would result in large vertical forces which would be exerted on the tank. In every case where vertical force measurements were made, however, a decrease in the horizontal slosh forces also resulted in a decrease in the vertical forces.

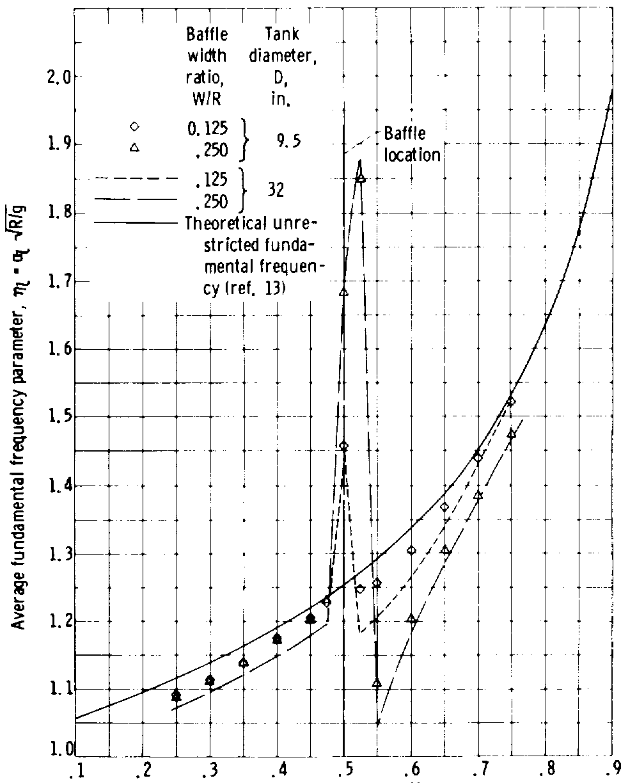


Figure 21. - Variation of fundamental frequency parameter with liquid-depth ratio for rigid single-ring baffles. 9.5-inch-diameter tank; excitation amplitude parameter, approximately 0.01.

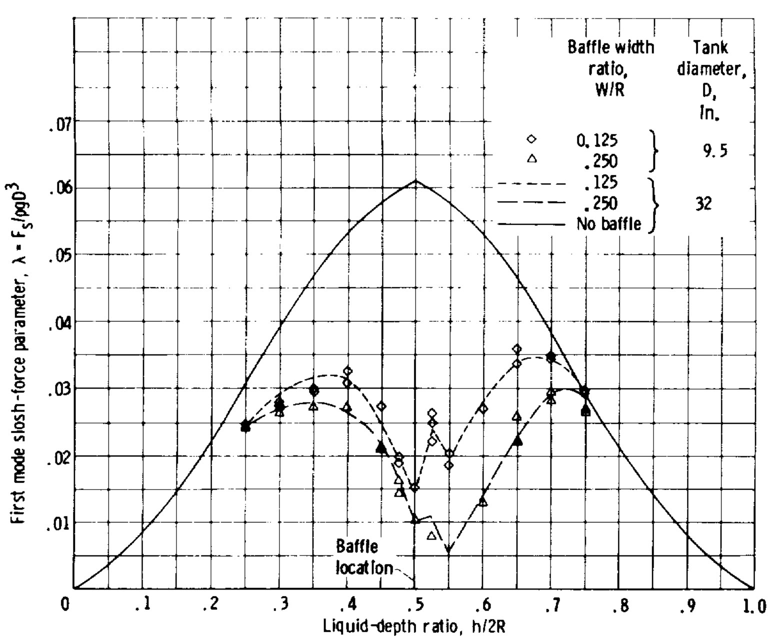


Figure 22. - Variation of first mode slosh-force parameter with liquid-depth ratio for rigid single-ring baffles. 9.5-inch-diameter tank; excitation amplitude parameter, approximately 0.01.

Rigid Single-Ring Baffles, Baffle Width Ratios of 0.125 and 0.250, 9.5-Inch-Diameter Tank

To evaluate the scaling factors necessary to predict the fundamental frequencies, slosh forces and damping ratios resulting from the use of annular-ring baffles in spherical tanks of varying size, rigid single-ring baffles having baffle width ratios of 0.125 and 0.250 were investigated in a 9.5-inch-diameter tank. The ratio of wave height to tank diameter was maintained nearly constant in the two tanks by oscillating them at nearly constant values of X_0/D (ref. 4). A value of $X_0/D = 0.0105$ was used for the 9.5-inch-diameter tank while a value of $X_0/D = 0.00975$ was used for the 32.0-inch-diameter tank; the effect of this small difference in the values of X_0/D on the liquid sloshing characteristics is negligible for this investigation.

The following results are presented and compared with those obtained in the 32.0-inch-diameter tank: (1) the slosh-force parameter and damping ratio as functions of the excitation frequency parameter for a liquid-depth ratio of 0.50 (figs. 19 and 20, respectively) and (2) the fundamental frequency parameter, first mode slosh-force parameter, and first mode damping ratio as functions of the liquid-depth ratio (figs. 21, 22, and 23, respectively). Generally, the experimental results obtained in the 9.5-inch-diameter tank for each of the baffle width ratios (0.125 and 0.250) investigated showed good agreement

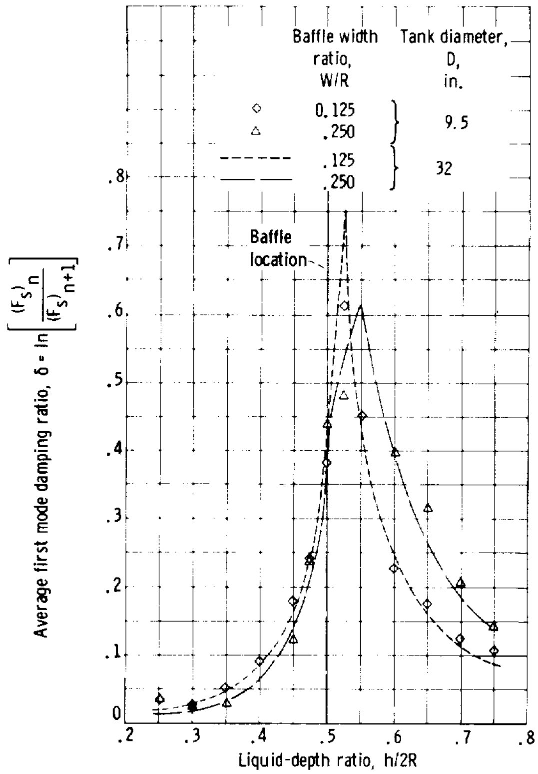


Figure 23. - Variation of first mode damping ratio with liquid-depth ratio for rigid single-ring baffles. 9.5-Inch-diameter tank; excitation amplitude parameter, approximately 0.01.

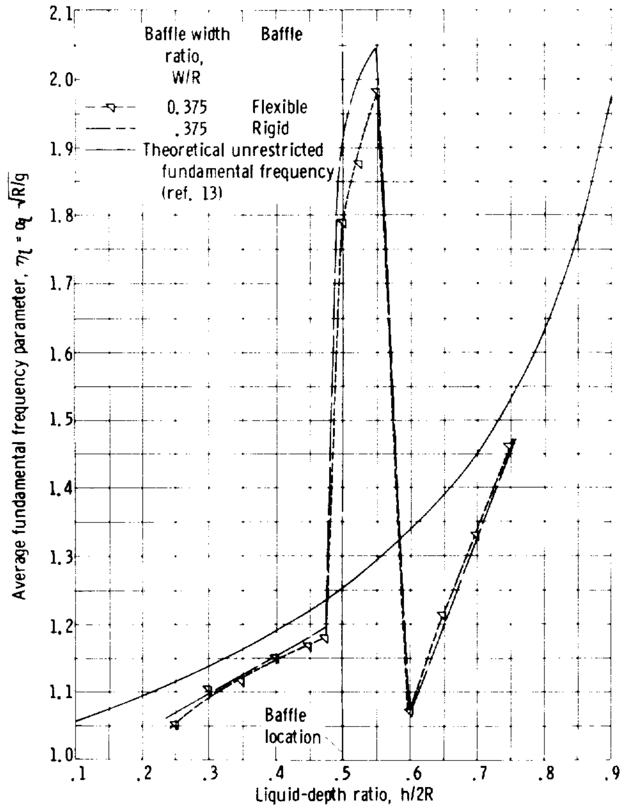


Figure 24. - Variation of average fundamental frequency parameter with liquid-depth ratio for flexible single-ring baffle. 32-Inch-diameter tank; baffle width ratio, 0.375.

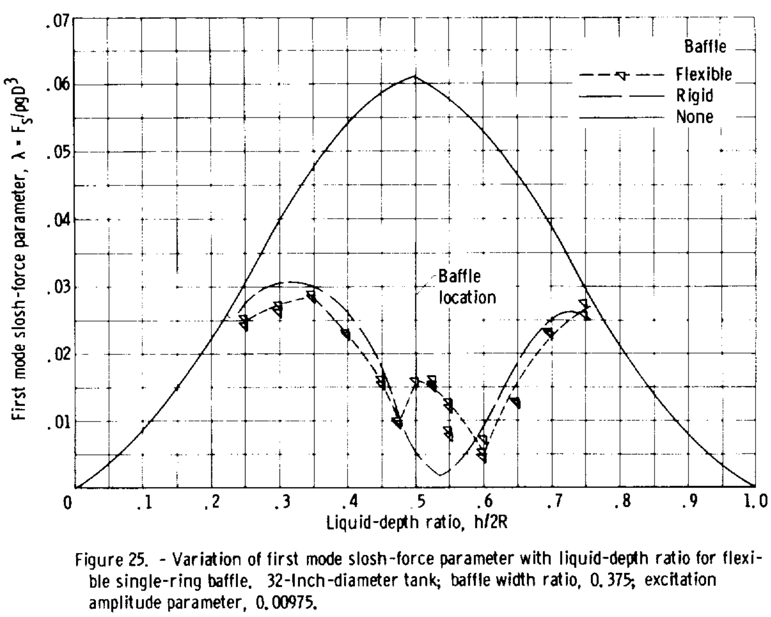


Figure 25. - Variation of first mode slosh-force parameter with liquid-depth ratio for flexible single-ring baffle. 32-Inch-diameter tank; baffle width ratio, 0.375; excitation amplitude parameter, 0.00975.

with the results obtained in the 32.0-inch-diameter tank. Values of the fundamental frequency parameter $(\eta_l = \alpha_l \sqrt{R/g})$, first mode slosh-force parameter $(\lambda = F_s/\rho g D^3)$, and first mode damping ratio $\delta = [(F_s)_n/(F_s)_{n+1}]$ were generalized at each liquid-depth ratio for spherical tanks of varying diameters that contained flat-plate annular-ring baffles having a constant baffle width ratio (W/R) and that were oscillated at a constant value of the excitation amplitude parameter (X_0/D).

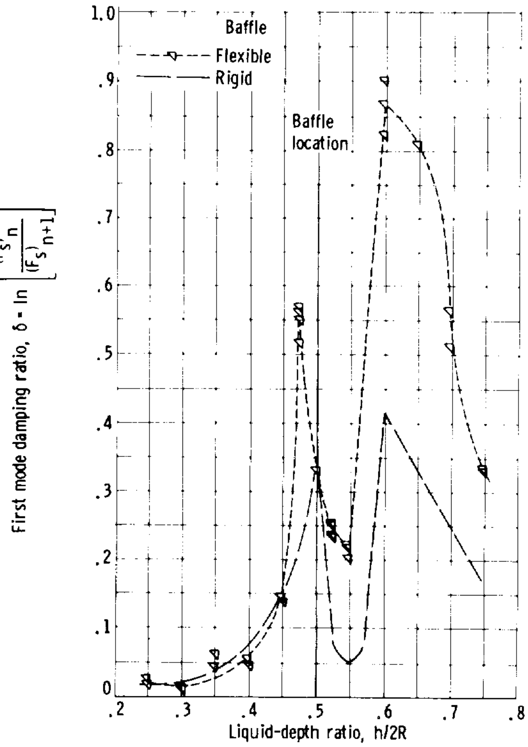


Figure 26. - Variation of first mode damping ratio with liquid-depth ratio for flexible single-ring baffle. 32-inch-diameter tank; baffle width ratio, 0.375; excitation amplitude parameter, 0.00975.

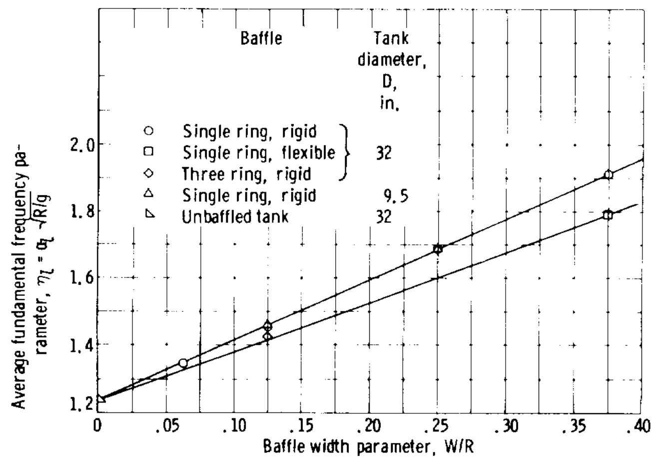


Figure 27. - Variation of average fundamental frequency parameter with baffle width parameter for various baffle configurations, liquid-depth ratio, 0.50.

Flexible Single-Ring Baffle, W/R = 0.375, 32.0-Inch-Diameter Tank

It was indicated in reference 9 that some flexibility of an annular-ring baffle might be an important factor in increasing the damping of liquid oscillations in cylindrical tank configurations. To evaluate this factor experimentally in a spherical tank configuration, a $W/R = 0.375$ baffle was fabricated from 0.012-inch-thick spring brass in four overlapping quarters or segments so that a high degree of flexibility was achieved.

The variation of the fundamental frequency parameter with liquid-depth ratio was similar to that obtained for the $W/R = 0.375$ rigid baffle, as shown in figure 24. Each data point is the average of several values; the maximum deviation from the average was ±3.5 percent.

The flexible baffle provided slightly better first mode slosh-force suppression than the rigid baffle over most of the range of liquid-depth ratios investigated, as shown in figure 25 for a value of X_0/D of 0.00975. Large deflections of the flexible baffle were observed for depth ratios $0.475 < h/2R < 0.60$; however, the baffle thus presented a smaller cross-sectional area normal to the liquid motion and undoubtedly changed the flow characteristics of the liquid past the baffle to the extent that the slosh forces were larger than those obtained for the rigid baffle.

The first mode damping ratios obtained for the flexible baffle over a range of liquid-depth ratios (fig. 26) were generally larger in magnitude but showed trends that were similar to those obtained for the comparable rigid baffle.

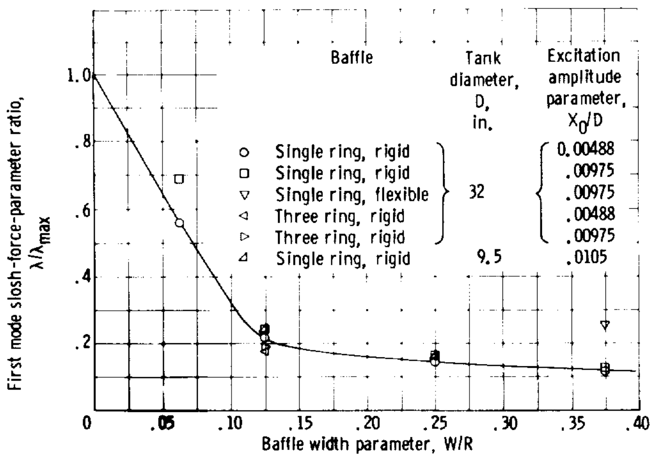


Figure 28. - Effect of baffle configuration and baffle width parameter on reduction of first mode slosh-force parameter, liquid-depth ratio, 0.50.

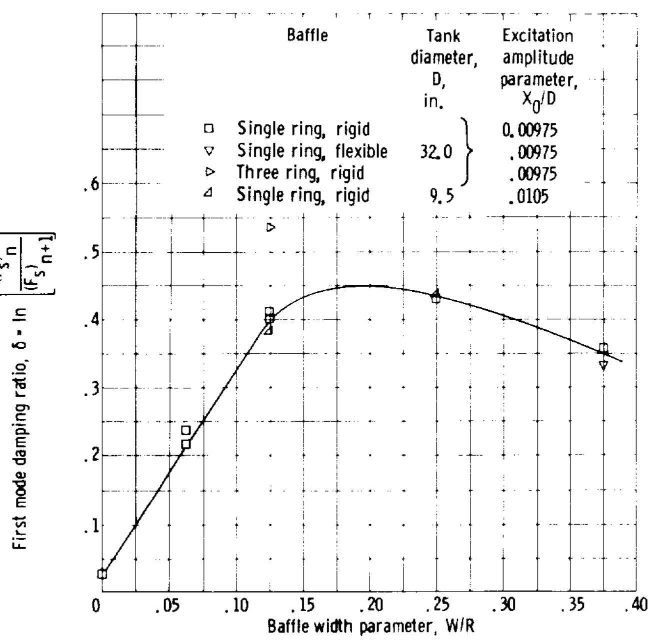


Figure 29. - Effect of baffle configuration and baffle width parameter on first mode damping ratio, liquid-depth ratio, 0 50.

Summary Comparison for Liquid-Depth Ratio of 0.50

The fundamental frequency parameter is presented as a function of the baffle width ratio in figure 27. The value of the frequency parameter used for the $W/R = 0.0625$ rigid single-ring baffle is that value obtained when the wave height of the liquid oscillations was small. The frequency parameter increased linearly with baffle width ratio. The fundamental frequency of liquid oscillation obtained for each baffle width ratio was somewhat greater than that of an equivalent spherical tank having a diameter equal to the inside diameter of the baffle.

The effect of the baffle width ratio on the first mode slosh-force parameter ratio (λ/λ_{max}) is shown in figure 28, where λ_{max} is the value of the force parameter for $W/R = 0$ and λ is the value of the force parameter at any value of W/R. The first mode slosh forces were reduced to about 21 percent of the forces obtained in the unbaffled tank when the baffle width ratio was increased from 0 to 0.125. The slosh forces were reduced by only an additional 10 percent when the baffle width ratio was increased to 0.375. The flexible baffle was less effective than the rigid baffle ($W/R = 0.375$) in reducing the slosh forces at this particular liquid depth. The force parameter ratio λ/λ_{max} tended to be independent of the excitation amplitude parameter and tank diameter for the values investigated.

The first mode damping ratios obtained for the rigid single-ring baffles increased to a value of about 0.40 as the baffle width ratio increased from 0 to 0.125; little or no increase in the damping ratio was observed at this particular depth ratio as the baffle width ratio was increased to 0.375 (fig. 29). The rigid three-ring baffle configuration provided somewhat higher damping than the $W/R = 0.125$ rigid single-ring baffle; the flexible baffle provided about the same damping as the $W/R = 0.375$ rigid single-ring baffle.

A baffle width ratio of 0.125 appeared to provide the most slosh-suppression effectiveness for a minimum weight penalty in spherical tanks.

SUMMARY OF RESULTS

An experimental investigation was conducted to determine the slosh-suppression effectiveness of several flat-plate annular-ring baffle configurations in spherical tanks having diameters of 32.0 and 9.5 inches. Experimentally determined values of the fundamental frequencies of liquid oscillations, horizontal slosh forces, and damping ratios were obtained for each baffle configuration over a range of excitation frequencies and liquid-depth ratios. The dimensionless parameters used to present the experimental data were evaluated as scaling factors for the two tank diameters investigated. The results are summarized as follows:

1. The values of the fundamental frequency parameter obtained in a baffled tank increased rapidly above that of an unbaffled tank when the liquid surface was at a depth ratio equal to or slightly above that of the baffle location (no variation, however, was observed for the baffle with a width ratio of 0.0625). A further increase in the liquid-depth ratio above the baffle location resulted in a sharp decrease in the fundamental frequency parameter to a value less than that found in an unbaffled tank. The magnitude of the variation in the fundamental frequency parameter increased as the baffle width ratio increased; this variation is believed to be caused by the baffle effectively changing the tank geometry. The frequency parameters approached that of an unbaffled tank when the liquid-depth ratio was slightly less or appreciably greater than the depth ratio of the baffle.

2. The maximum slosh-force parameter for a specific liquid-depth ratio and baffle configuration was obtained when the excitation frequency was approximately equal to the fundamental frequency of the liquid oscillations. The first mode slosh-force parameter (1) increased with excitation amplitude and (2) decreased by approximately 90 percent as the baffle width ratio increased from 0 to 0.375; however, little additional decrease was generally noted for baffle width ratios greater than 0.125. Each baffle configuration generally appeared to be most effective in reducing the slosh forces when the quiescent liquid surface was even with or slightly above the baffle so that it remained completely submerged during the liquid oscillations. The rigid baffles were ineffective in reducing the slosh forces when the liquid surface was more than 0.15 to 0.20 tank diameter above and below the baffle location. The rigid three-ring baffle configuration provided a relatively low slosh-force level throughout the range of liquid-depth ratios investigated. The flexible baffle was slightly more effective than the comparable rigid baffle in reducing the slosh forces except when the liquid surface was near the baffle location.

3. The maximum damping ratios for a specific liquid-depth ratio and baffle configuration were obtained when the excitation frequency was approximately equal to the fundamental frequency of the liquid oscillations. Maximum damping

ratios were obtained for each baffle configuration (except the baffles with a width ratio of 0.375) when the liquid surface was even with or slightly above the baffle. The rigid baffles were generally ineffective in providing a high value of damping when the liquid surface was more than 0.05 tank diameter below or 0.25 tank diameter above the baffle location. The rigid three-ring baffle configuration provided damping ratios greater than 0.1 through a range of liquid-depth ratios $0.25 \leq h/2R \leq 0.80$. The flexible baffle provided higher damping ratios than the comparable rigid baffle.

4. Little additional slosh-force suppression or increase in damping was obtained for baffle width ratios greater than 0.125, and this was adjudged to be an optimum value.

5. The values of the fundamental frequency parameter, slosh-force parameter, and damping ratio obtained for a relatively nonviscous liquid were generalized for spherical tanks of varying diameter over a range of liquid-depth ratios when the baffle width ratio and excitation amplitude parameter remained constant.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, September 9, 1964

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