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TECHNICAL NOTE

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AN EXPERIMENTAL INVESTIGATION OF THE DAMPING OF LIQUID OSCILLATIONS IN AN OBLATE SPHEROIDAL TANK WITH AND WITHOUT BAFFLES

By David G. Stephens, H. Wayne Leonard, and Milton A. Silveira

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AN EXPERIMENTAL INVESTIGATION OF THE DAMPING OF LIQUID OSCILLATIONS IN AN OBLATE SPHEROIDAL TANK WITH AND WITHOUT BAFFLES

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SUMMARY

An experimental investigation was conducted to determine the damping of the fundamental antisymmetric mode of oscillation of liquids contained in an oblate spheroidal tank. The decay of the fundamental mode was studied for a range of liquid depths in tanks with and without baffles. In the investigation of baffle effects, ring and cruciform baffles of various sizes were fixed at different locations within the tank. Data presented show the variation of the damping factor with tank fullness and with baffle type, width, location, and orientation as well as the effects of the amplitude of the liquid oscillations and of small variations in the liquid kinematic viscosity on the damping factor. The results of the investigation indicate that the addition of ring baffles to the tank results in an increase in the available effective damping when the baffle plane is in a region near the equilibrium liquid surface, and that cruciform baffles are effective in the damping of the fundamental mode in the near-empty tank. No apparent changes in damping for the tanks having ring baffles were observed as the kinematic viscosity of the liquid was varied over a small range.

INTRODUCTION

Current problems associated with liquid-fueled propulsion systems used in missiles and space-flight boosters indicate a need for further basic research to broaden the knowledge of the damping of oscillating liquids in tanks of various shapes and sizes. Of fundamental importance is the effectiveness of various baffle configurations on the liquid damping characteristics. The problem area includes variations of damping with tank fullness; baffle configuration, edge shape, width, location, and orientation; amplitude of the liquid oscillation; liquid flow rates; accelerations of the tank; and kinematic viscosity of the contained liquid. Available methods for the prediction of the damping characteristics of such baffles is limited to a semiempirical method applicable to ring baffles in right-circular cylindrical tanks. The experimental results of reference 1 showed excellent agreement with the values obtained by this semiempirical relationship which is developed in references 2 and 3 and is based on the data of reference 4.

Some boost systems currently in the development stage are employing oblate spheroidal propellant storage tanks. Experimental investigations of the liquid natural frequencies in tanks of this type (ref. 5) have been made but no known information is available concerning the damping characteristics of liquids so contained.

In order to obtain information necessary for the prediction of the damping in these tanks, an experimental investigation of the damping of the fundamental antisymmetric mode of water in a representative oblate spheroidal tank was made. The measured damping values obtained are unique for this representative tank but it is felt that these values reflect the trends which could be expected in similar tanks of different sizes. The tests were conducted in tanks with and without baffles, and the tanks were oriented such that the plane of the major axis was horizontal. Prime variables considered were: tank fullness; baffle configuration, width, location, and orientation; amplitude of the liquid oscillation; and small changes in the kinematic viscosity of the liquid. The results of this investigation are reported herein.

SYMBOLS

a	semimajor spheroid axis
b	semiminor spheroid axis
h	liquid depth
h_B	vertical distance of baffle from tank bottom
M_n	amplitude of terminal moment
M_o	amplitude of initial moment
n	number of cycles
w	width of baffle annulus

δ damping factor, $\frac{1}{n} \log_e \frac{M_o}{M_n}$

ζ amplitude of liquid oscillation

APPARATUS

Tanks and Mountings

The investigations were conducted with water in several identical oblate spheroidal tanks having major and minor axes of 26.3 inches and 19.8 inches, respectively, and constructed of 1/8-inch Plexiglas. The mounting, which was constructed to permit interchanging of the several tanks, consisted of a contour support framework rigidly attached to a flat disc as shown in figure 1.

Baffles

All baffles used in this investigation were constructed of 1/8-inch Plexiglas and were rigidly cemented to the tank wall. The positions and dimensions of the baffles are given in the table in figure 2. In all cases, rectangular edges were maintained.

Instrumentation

The moments resulting from the liquid oscillations were sensed by a load cell which was used as one leg of a three-point rigid support system for the mounting disc. The load cell was positioned so that a vertical plane passing through the load cell and the center of the tank would be perpendicular to the node line of the fundamental mode whereas the other two supports are located on a line parallel to the node line. The signal from the load cell was amplified and used to measure the damping factor and frequency of the decaying oscillations.

PROCEDURE

The fundamental antisymmetric mode of liquid oscillation was excited by means of induced pitching motions to the tank mounting assembly. When the desired amplitude of oscillation was reached, the pitching motions were stopped and the decay of the moments resulting from the liquid motions was observed. The decay of the oscillation specified by the damping factor δ is defined as

$$\delta = \frac{1}{n} \log_e \frac{M_o}{M_n} \tag{1}$$

where n is the number of cycles over which the decay was measured, M_o is the amplitude of a selected initial moment, and M_n is the amplitude of a selected terminal moment after n cycles. Throughout this investigation a constant value of M_n of $0.7M_o$ was maintained. All damping values presented represent the average of five or more measured values for the given condition.

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The change in damping factor with tank fullness was examined for tanks with and without baffles. The value of M_o, held constant through all portions of the test except the investigation of the effects of liquid amplitude, was selected as slightly below the maximum moment for which the fundamental mode could be defined for all the baffle test conditions. The damping afforded by the various ring baffles was measured for liquid depths ranging from well above the baffle to some depth below the baffle at which the liquid surface was never in contact with the baffle. The damping afforded by the cruciform baffles was measured from $\frac{h}{2b} = 0.551$ to the minimum depth at which the predetermined initial moment could be induced.

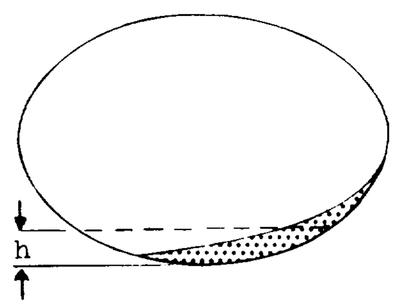
The variation of damping with amplitude of the liquid oscillation was studied at fixed liquid depths corresponding to $\frac{h}{2b} = 0.374$, 0.551, and 0.732 for a tank with no baffles and for tanks with a single ring baffle of $\frac{w}{a} = 0.057$ located 1 inch below the liquid level, that is, at $\frac{h_B}{2b} = 0.322$, 0.500, and 0.682, respectively. The amplitude, measured visually from the equilibrium surface along an arc of the tank wall, was taken as the maximum distance traversed by the oscillating liquid surface in generating the initial moment.

The effects of changes in liquid kinematic viscosity on the damping were examined by varying the temperature of the liquid between 38° F and 180° F at $\frac{h}{2b} = 0.551$ in the tank fitted with the $\frac{w}{a} = 0.057$ ring baffle at $\frac{h_B}{2b} = 0.500$.

DISCUSSION OF RESULTS

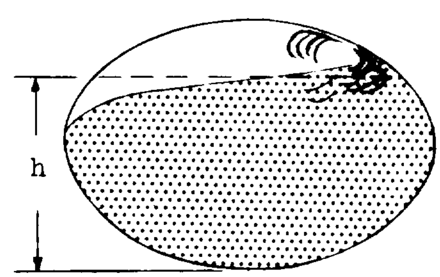
Tank Without Baffles

The experimentally determined damping of the fundamental antisymmetric mode of water in an oblate spheroidal tank without baffles is presented in figure 3 in terms of the damping factor δ. Values of the damping factor are shown as a function of the tank fullness $h/2b$ where h is the liquid depth and $2b$ is the minor axis of the spheroid. The initial amplitudes of the liquid oscillations were such that at all depths the moments imposed on the tank by the oscillating liquid at the beginning of the damping measurements were the same. Figure 3 indicates that relatively high damping exists at the lower liquid depths, but the damping gradually decreases to a minimum at a value of $h/2b$ of approximately 0.75 and then increases rapidly as the near-full condition is approached. The increase in damping at the low liquid depths may be attributed to the small liquid mass oscillating over a comparatively large tank wall area as shown in the following sketch:



Sketch 1.- Near-empty condition.

The damping increase in the near-full condition is possibly a result of the change in direction generated in the oscillating liquid by the tank wall. At these depths, the slope of the tank wall toward the center of the equilibrium surface tends to force the oscillating liquid inward during the upward half-cycle of oscillation. In many instances, the liquid was observed to spill over into the center region of the oscillating surface as shown in the following sketch:



Sketch 2.- Near-full condition.

Ring Baffles

The effects of ring baffles on the liquid damping are shown in figures 4 to 6 for three baffle locations. In each figure the damping factor is presented as a function of tank fullness over the range of maximum baffle effectiveness. The baffle locations are given in the dimensionless form $h_B/2b$ where h_B is the vertical distance from the plane of the ring to the tank bottom and 2b is the minor axis of the spheroid. Ring-baffle locations for this test were $\frac{h_B}{2b} = 0.322$, 0.500, and 0.682. The data for rings of three different widths are shown at each location, the width being specified by w/a, where w is the radial width of the baffle annulus and a is the semimajor axis of the spheroid.

The damping factor for each of three different width ring baffles is shown in figure 4 for an $h_B/2b$ of 0.322. The damping trends for each of the rings are similar; that is, the damping factor increases as the liquid depth approaches the vertical distance of the baffle from the tank bottom h_B, reaches a maximum at a liquid depth slightly above the baffle, and decreases as the distance between the baffle and the equilibrium surface is increased. The liquid depth at maximum damping was observed to correspond approximately to the minimum depth above the baffle at which the baffle did not break the liquid surface during the liquid oscillation. In the region of baffle effectiveness, a substantial increase in damping with increasing baffle width is also noted.

The damping factor as a function of tank fullness for each of three ring baffles at an $h_B/2b$ of 0.500 is plotted in figure 5. The trends exhibited and the maximum damping values obtained are comparable to those of figure 4. At liquid depths below the baffle such that the liquid surface is not in contact with the baffle during any portion of the oscillations, the values of damping are compatible with those of a tank without baffles. As in figure 4, the liquid depth at which maximum damping occurs is such that the baffle is near the surface but does not break the liquid surface during the oscillations. As the baffle is further submerged the values of damping decrease and approach the values measured in the tank without baffles.

The variation of the damping factor with tank fullness for each of three ring baffles at an $h_B/2b$ of 0.682 is presented in figure 6. This figure shows that although the general trends of the values of damping for this configuration are similar to those of figures 4 and 5, a marked dissimilarity in the damping characteristics exists in that the curve exhibits two peaks. The higher peak, and hence the maximum damping, occurs at a liquid depth slightly below the baffle. The second peak occurs at a liquid depth slightly above the baffle as was observed in the previous cases. This deviation from the previous trends is apparently due to the change in flow conditions around the baffle as the included angle between the tank wall and the baffle decreases.

A composite of the data obtained for the $\frac{w}{a} = 0.057$ ring baffle of figures 4 to 6 is presented in figure 7 where the ring data are superimposed on the data for the tank without baffles to facilitate a comparison of the magnitude of the damping values throughout the depth range. This comparison shows that the addition of ring baffles to the tank effectively increases the damping of the liquid oscillations when the baffle is in a region near the equilibrium surface. The baffle locations are specified by the vertical dashed lines and only data taken where the liquid surface is located near the baffle are shown.

Cruciform Baffles

The damping factor is shown as a function of tank fullness in figure 8 for two tanks, each fitted with a different width cruciform baffle. Damping factors for two different orientations of each cruciform with respect to the node line of the oscillating liquid are presented. The damping trends for each configuration examined appear similar. The values of the damping factor decrease from a maximum at the near-empty condition and approach the damping values obtained for a tank with no baffles as the depth increases. As observed with the ring-baffles, the magnitude of the damping factor increases as the width of the baffle is increased.

Relationship Between Moment and Surface-Wave Amplitude

The damping factors shown in figures 3 to 8 were measured from the decay of the moments produced by the liquid oscillations between predetermined moment limits. As would be anticipated, the amplitude of the surface wave necessary to produce the required initial moments varied as the liquid depth was changed. The surface-wave amplitude necessary to produce the required moment is presented in figure 9 as a function of tank fullness. The figure indicates that the surface-wave amplitude necessary to produce the required moment output is highly dependent on tank fullness, being much greater at the near-full and near-empty conditions than for liquid depths near the midregion of the tank.

Effect of Surface-Wave Amplitude

Tank without baffles.- The variation of the damping factor with the amplitude ratio $\zeta/2b$ is shown for three liquid depths in figure 10.

The amplitude, measured from the equilibrium surface along an arc of the spheroid, was taken as the maximum distance traversed by the oscillating surface in generating the initial moment. The figure indicates that the damping trends for the liquid at each of the three depths are similar. In each case, the damping factor remains essentially constant throughout most of the amplitude range but increases at the lower amplitudes. This increase in damping at the lower amplitudes is possibly due to surface-tension effects. The slight increase in the damping factor with increasing amplitude ratio for the $\frac{h}{2b} = 0.732$ data may be attributed to the radial motions of the liquid induced by the tank wall. As indicated previously in sketch 2, higher amplitudes result in a more violent inward liquid motion, even to the extreme case of the liquid being forced completely around the upper tank surface.

A comparison of the data of figures 10 and 3 indicates that the data of figure 3 were obtained in the range where the damping is not highly amplitude dependent.

Tanks with ring baffles.- The variation of the damping factor with the amplitude ratio for each of three tanks fitted with the $\frac{w}{a} = 0.057$ ring baffle and having a liquid depth such that the baffles were submerged 1 inch below the equilibrium surface is shown in figure 11. These data indicate that, for the liquid depths examined, the damping is highly amplitude dependent throughout the amplitude range. An increase in amplitude ratio is accompanied by an increase in damping. This phenomenon was also noted when ring baffles were employed in a right-circular cylindrical tank. (See ref. 1.)

Effect of Liquid Kinematic Viscosity

The values of the damping factor associated with variations in liquid kinematic viscosity are presented in figure 12. Variations in kinematic viscosity were accomplished by varying the temperature of the contained liquid (water). The damping factors presented were taken in a tank fitted with the $\frac{w}{a} = 0.057$ ring baffle at an $h_B/2b$ of 0.500. The figure shows no apparent change in damping factor throughout the test range which includes temperature variations from 38° F to 180° F.

Frequency

The frequency of the fundamental antisymmetric mode of liquid oscillation was measured simultaneously with the damping factor and is shown as a function of tank fullness in figure 13. Natural frequencies are presented for three tanks with a $\frac{w}{a} = 0.057$ ring baffle at $\frac{h_B}{2b} = 0.322$, 0.500, and 0.682 and are compared with the natural liquid frequency in a tank with no baffles. (See ref. 5.) The data indicate that there is no appreciable change in the first liquid natural frequency with the addition of the baffles to the tank.

CONCLUSIONS

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An experimental investigation of the damping characteristics of the fundamental antisymmetric mode of liquid oscillation in an oblate spheroidal tank has been conducted. The damping provided by the addition of ring baffles of different widths at various locations and the damping provided by cruciform baffles located in the bottom of the tank at various orientations with respect to the direction of the liquid oscillation were determined for variations of liquid depth. The effect of the amplitude of the oscillation and the effect of small variations in the kinematic viscosity of the liquid on the measured damping values were studied. The results of this investigation are as follows:

1. The addition of ring baffles to the tanks effectively increases the damping of the liquid oscillations when the baffle is in a region near the equilibrium surface.

2. The increase in damping with the width of the ring baffle is limited to baffle locations near the liquid surface; however, for baffle locations well below the liquid surface, increases in baffle width do not result in substantial increases in damping.

3. The cruciform baffles located in the bottom of the tank provide greater damping as the liquid level is decreased and as the width of the baffle is increased.

4. The measured damping values for the tank without baffles do not seem to be amplitude dependent except for the relatively low amplitudes, whereas the measured damping values for the tanks with baffles exhibited a strong amplitude dependence.

5. Small variations in the liquid kinematic viscosity do not seem to affect the trends of the damping values for the tanks fitted with ring baffles.

6. The frequency of the fundamental antisymmetric mode was not appreciably altered by the addition of ring baffles.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., April 6, 1961.

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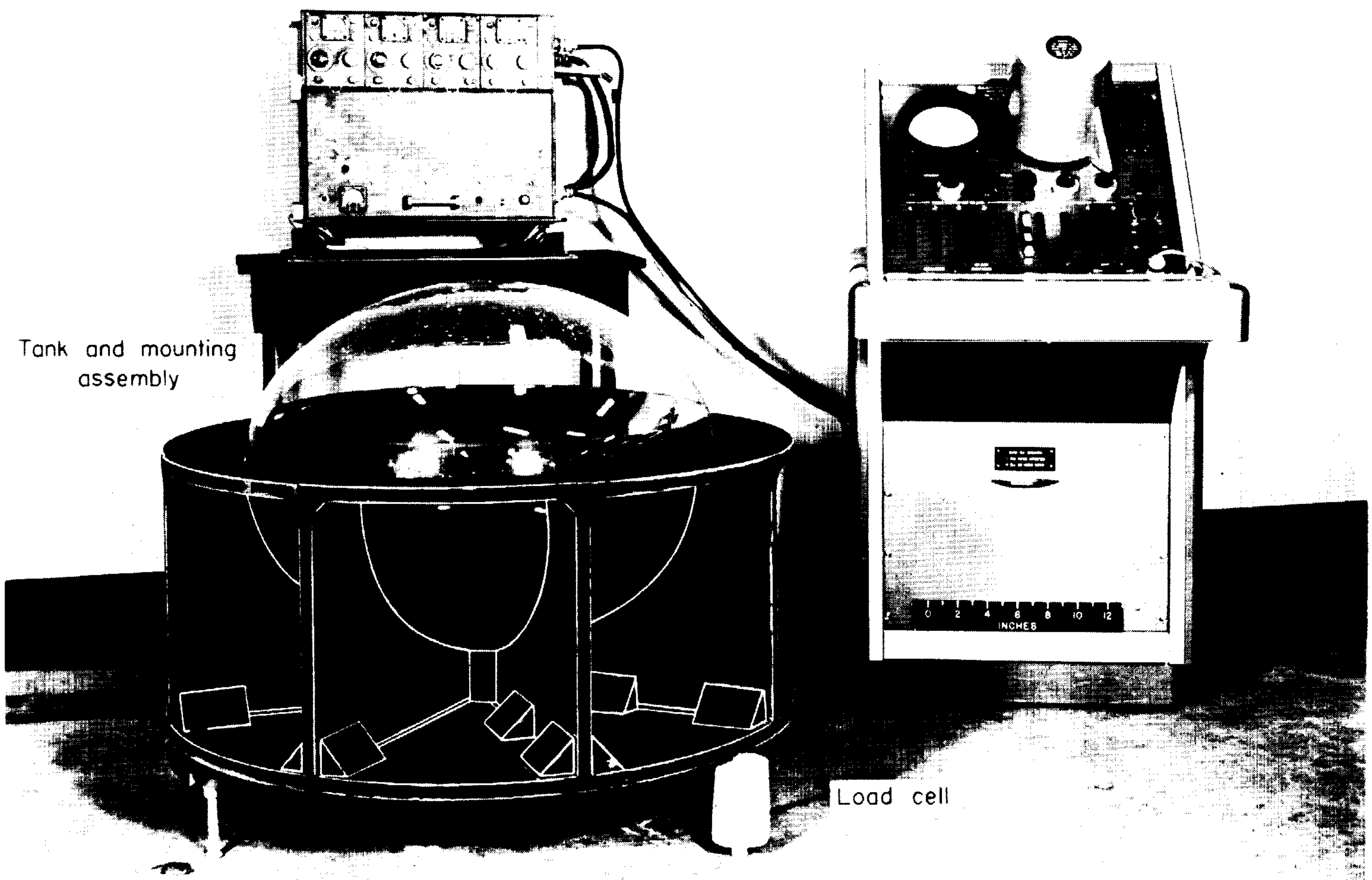

Figure 1.- Apparatus used in damping investigation. L-60-5758.1

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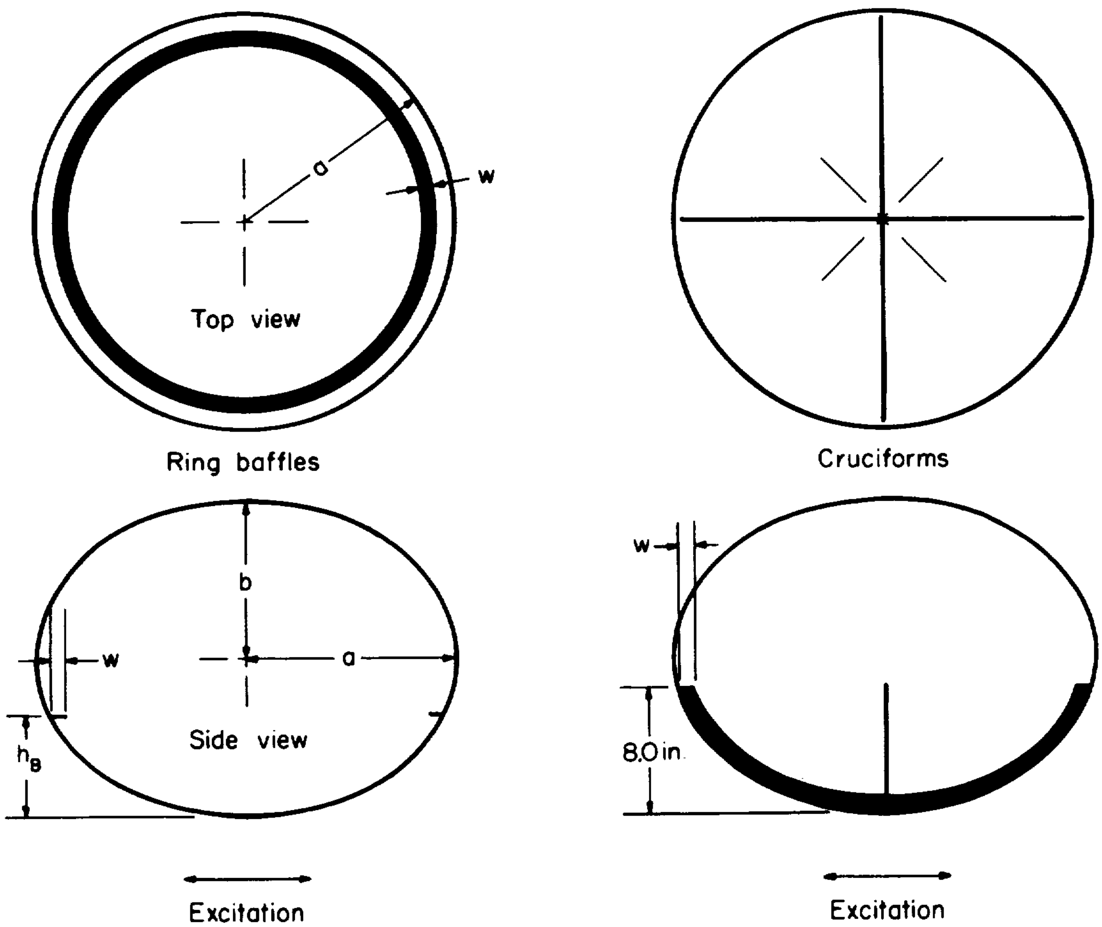

Ring-baffle dimensions

h_B, in.	w, in.	w/a
6.40	1.0 .75 .50	0.076 .057 .038
9.90	1.0 .75 .50	0.076 .057 .038
13.50	1.0 .75 .50	0.076 .057 .038

Cruciform dimensions

Orientation, deg	w, in.	w/a
90	0.75 .50	0.057 .038
45	0.75 .50	0.057 .038

Figure 2.- Sketch showing the width, location, and orientation of the baffle configurations. a = 13.15 inches; b = 9.90 inches.

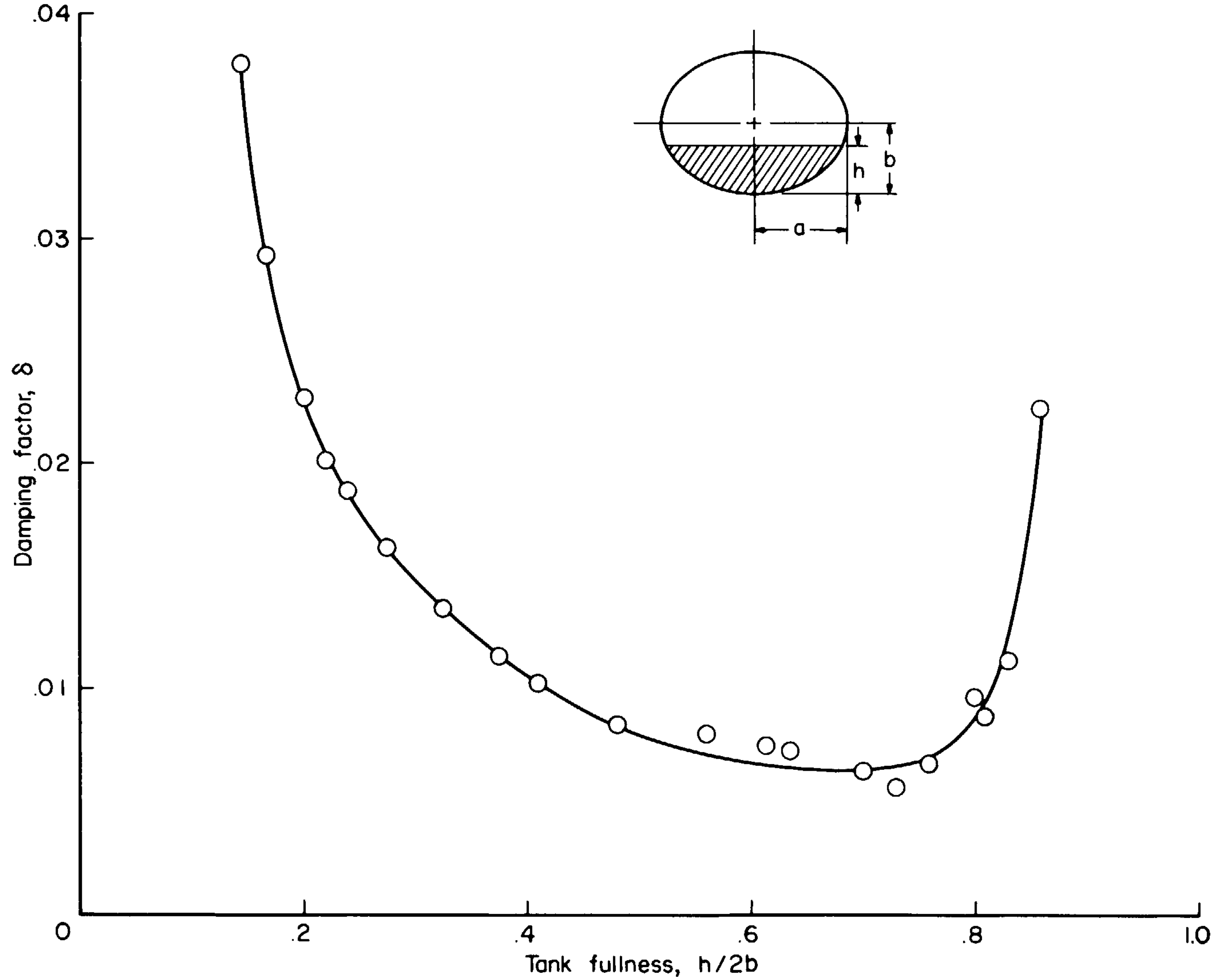

Figure 3.- Variation of damping factor with tank fullness for tank with no baffles.

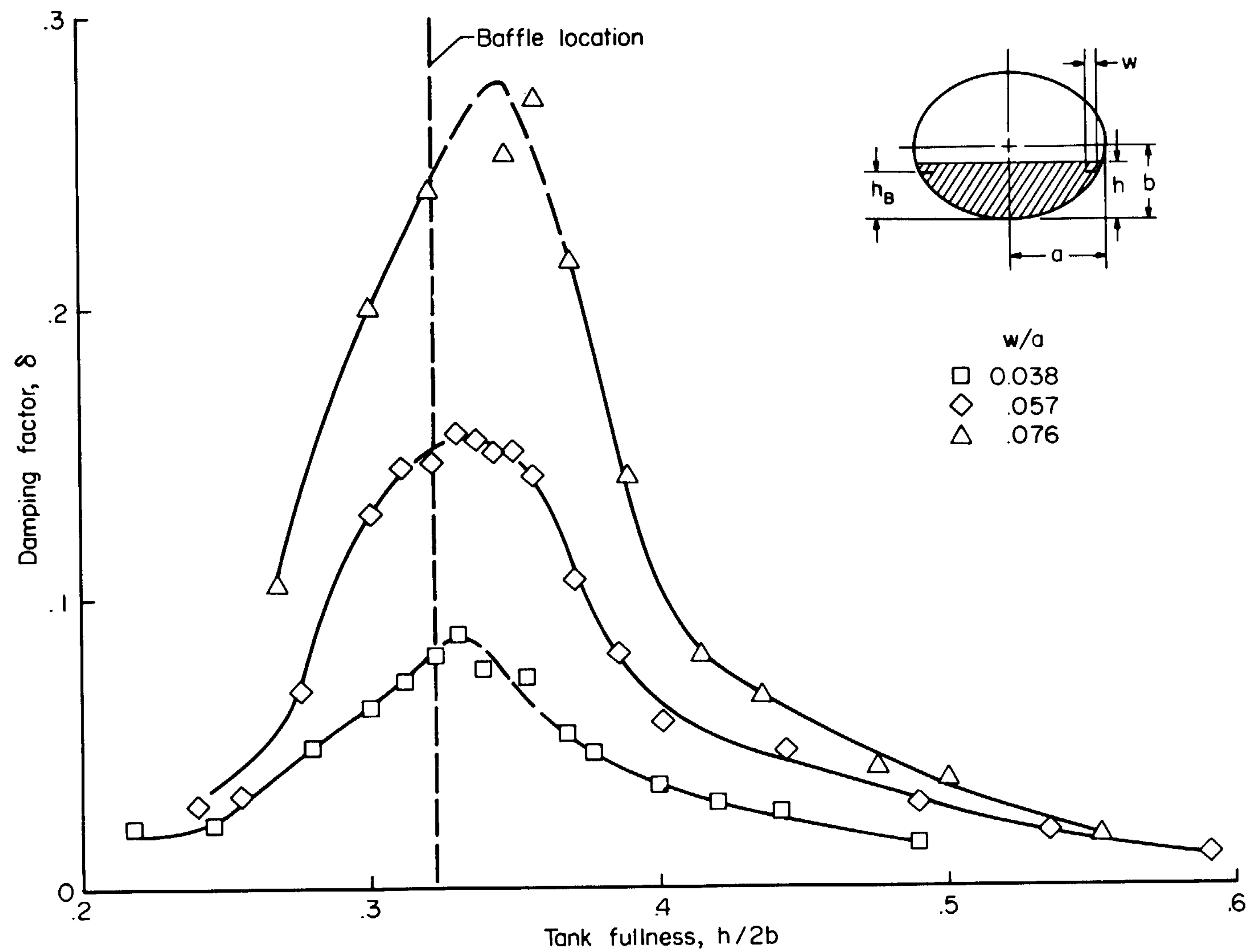

Figure 4.- Variation of damping factor with tank fullness for ring baffles at $h_B/2b = 0.322$.

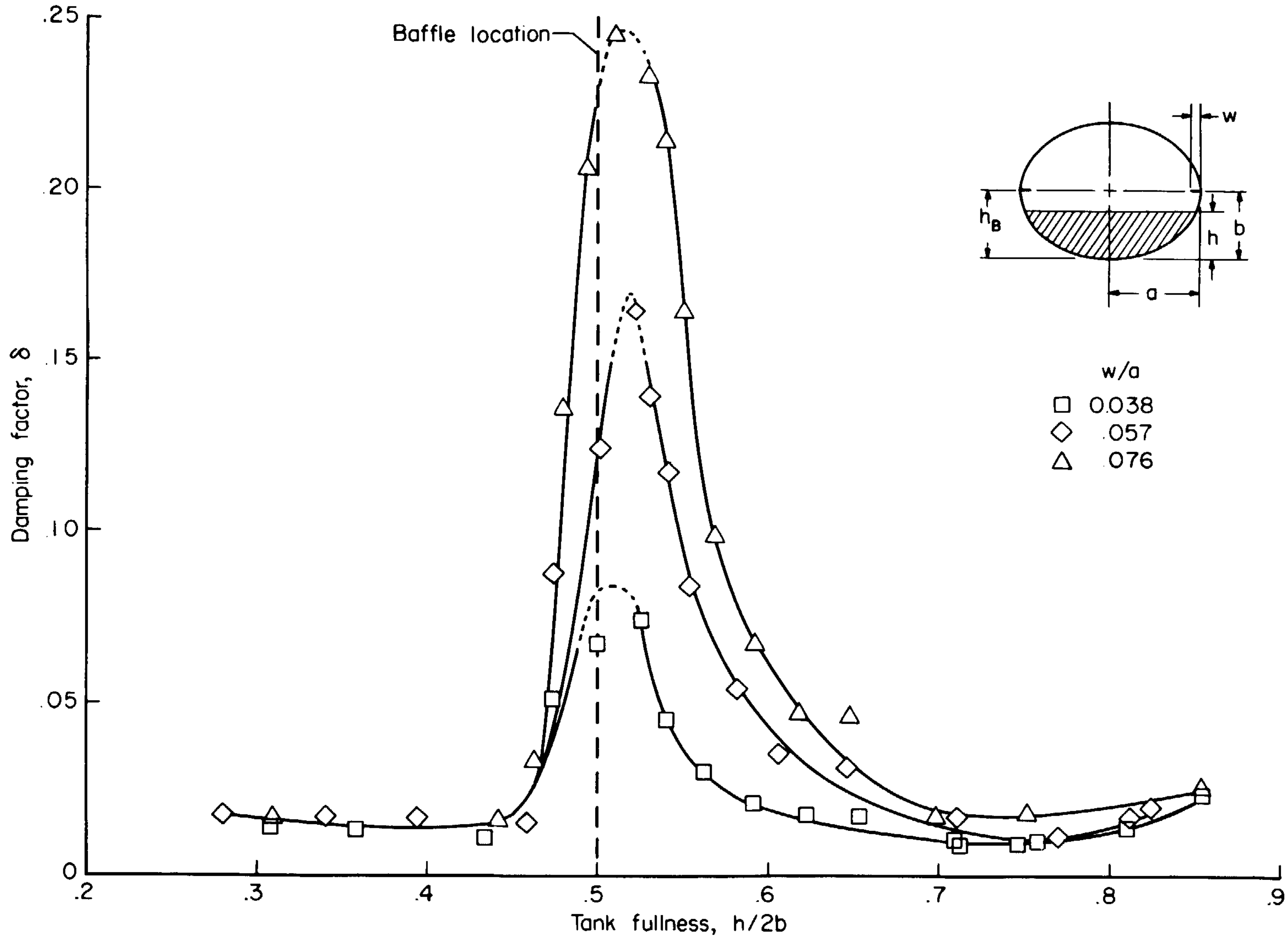

Figure 5.- Variation of damping factor with tank fullness for ring baffles at $h_B/2b = 0.500$.

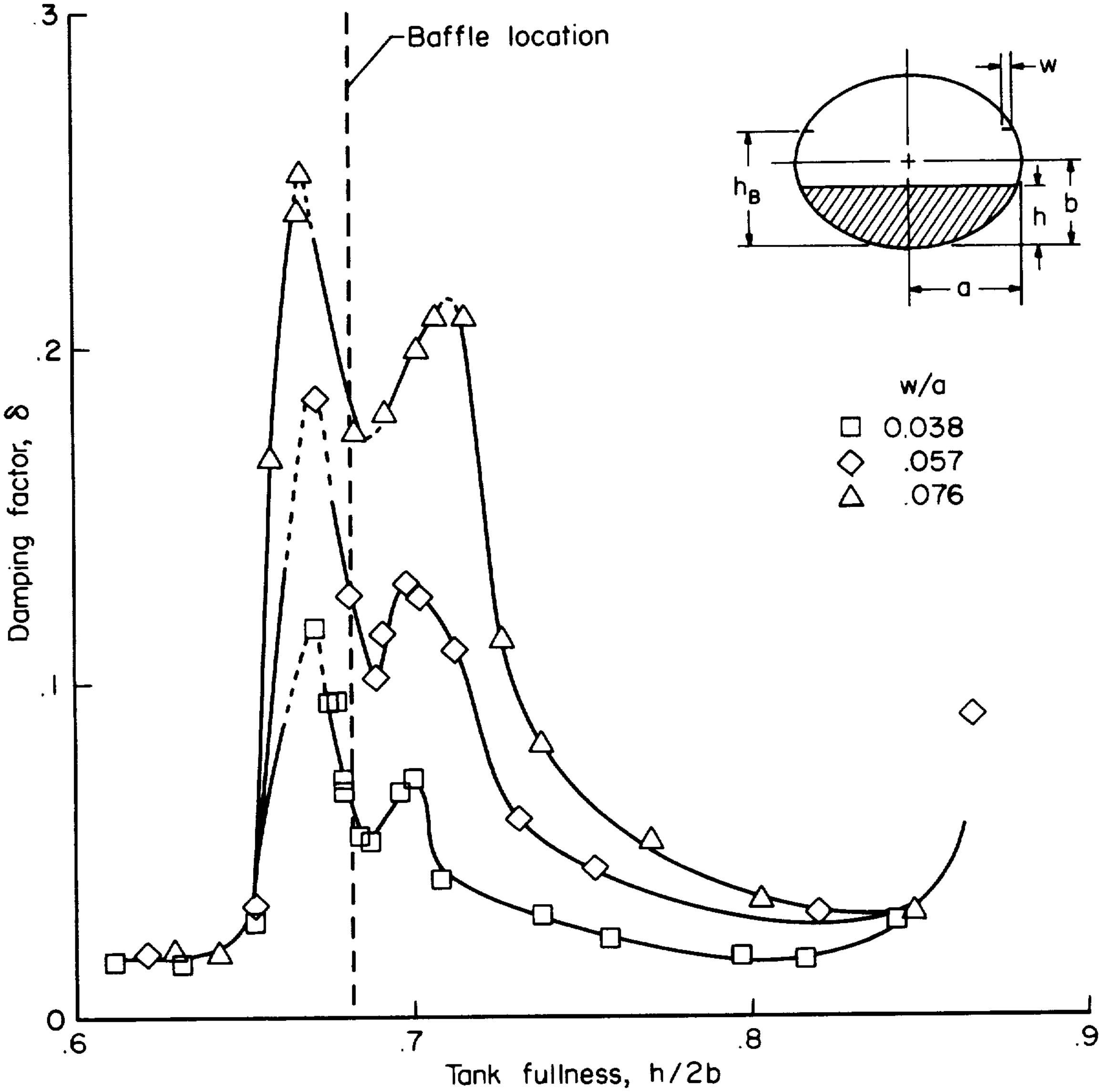

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Figure 6.- Variation of damping factor with tank fullness for ring baffles at $h_B/2b = 0.682$.

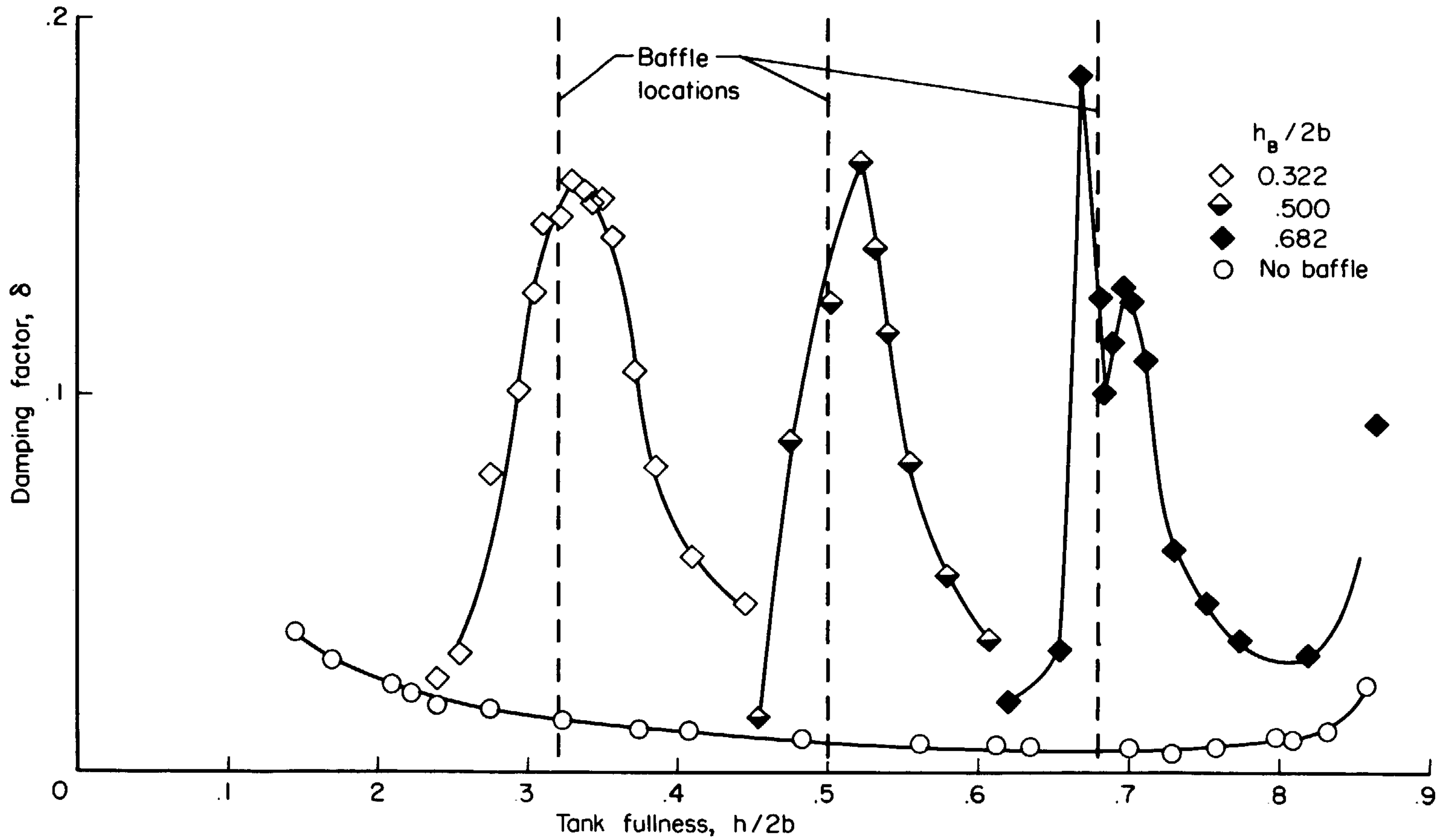

Figure 7.- Variation of damping factor with tank fullness for tank with ring baffles and for tank without baffles. w/a = 0.057. (Data for each baffle taken separately.)

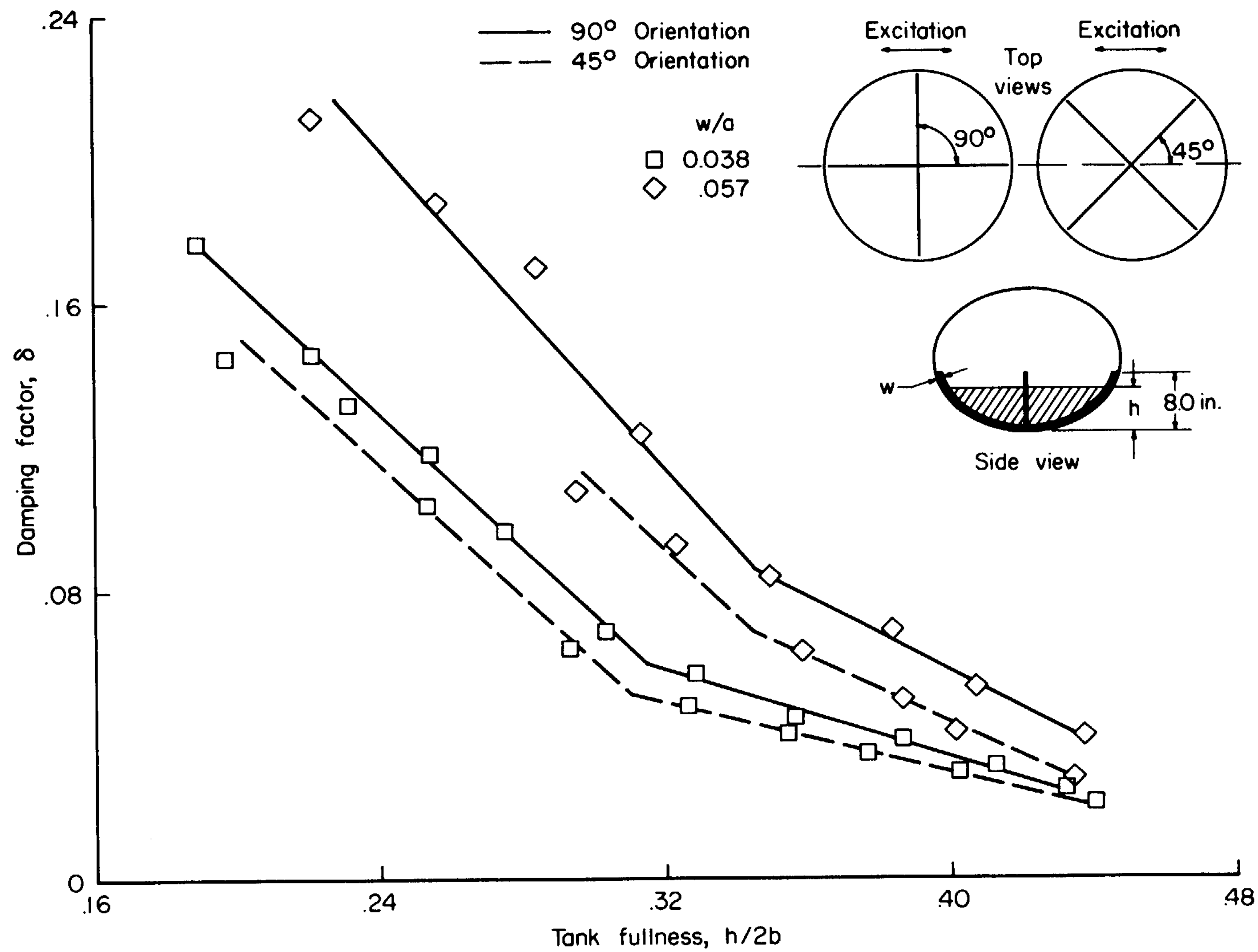

Figure 8.- Variation of damping factor with tank fullness for cruciform baffles.

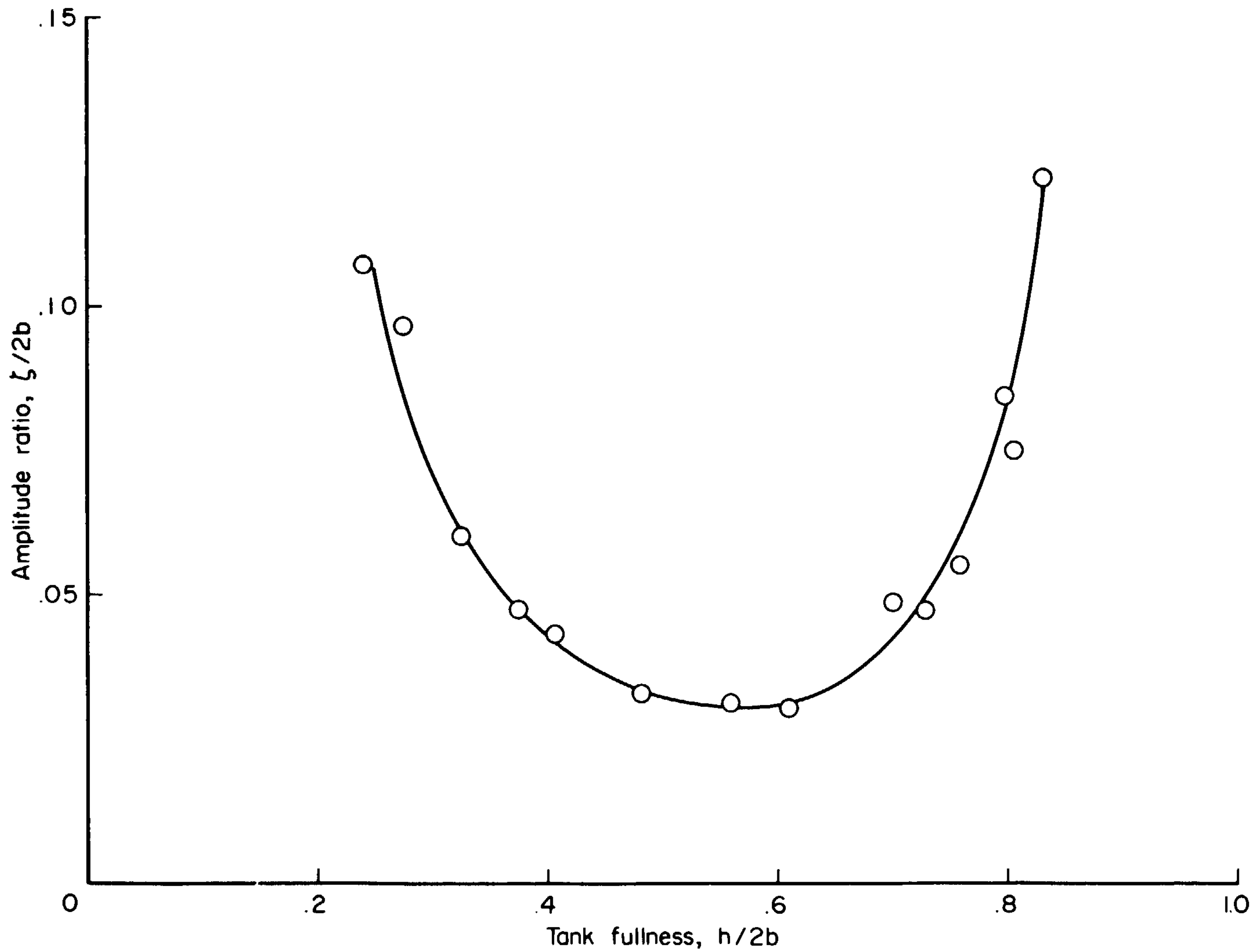

Figure 9.- Variation of amplitude ratio with tank fullness required to produce moment M_o for tank with no baffles.

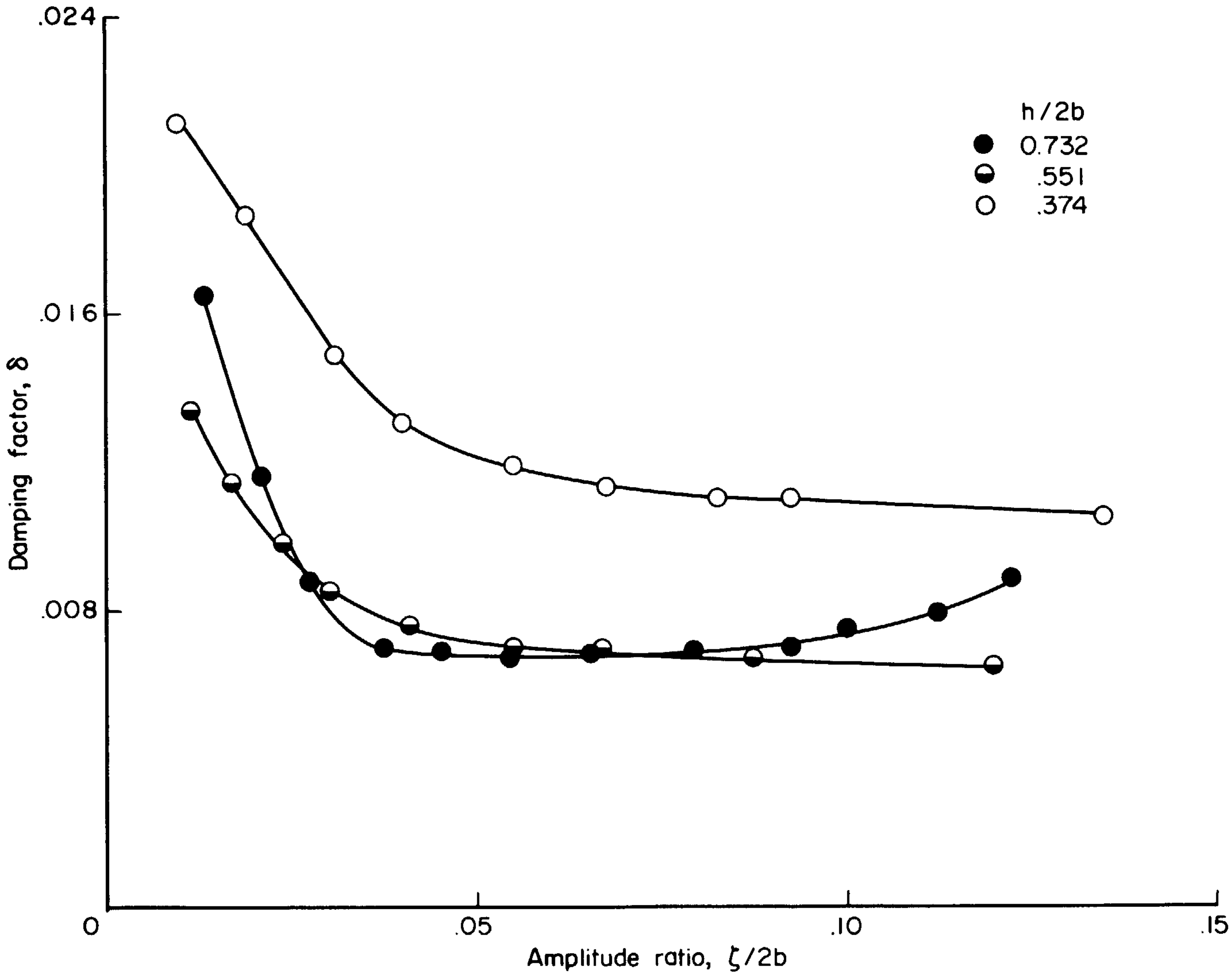

Figure 10.- Variation of damping factor with amplitude ratio for tank with no baffles.

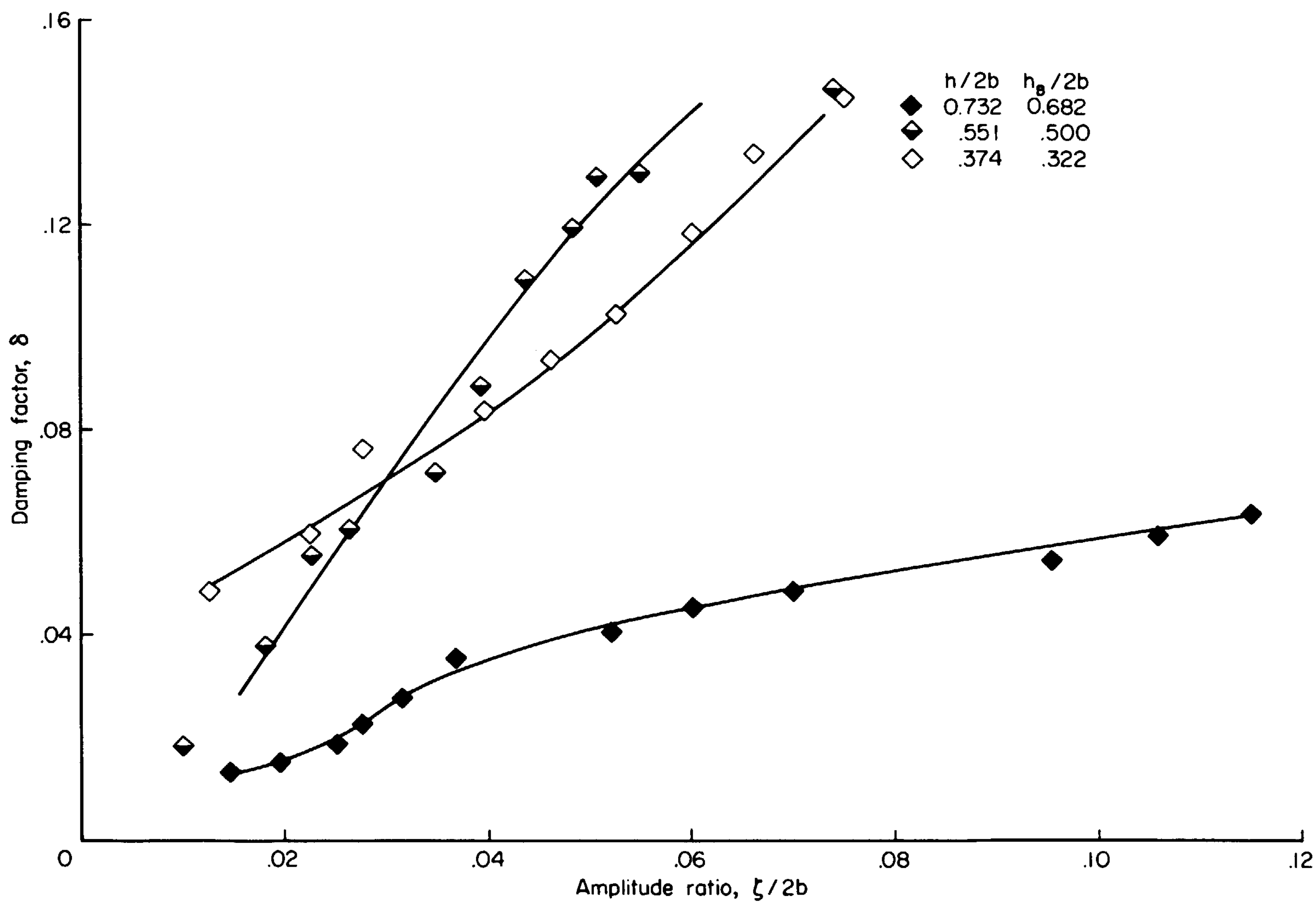

Figure 11.- Variation of damping factor with amplitude ratio for tanks with ring baffles. $w/a = 0.057$.

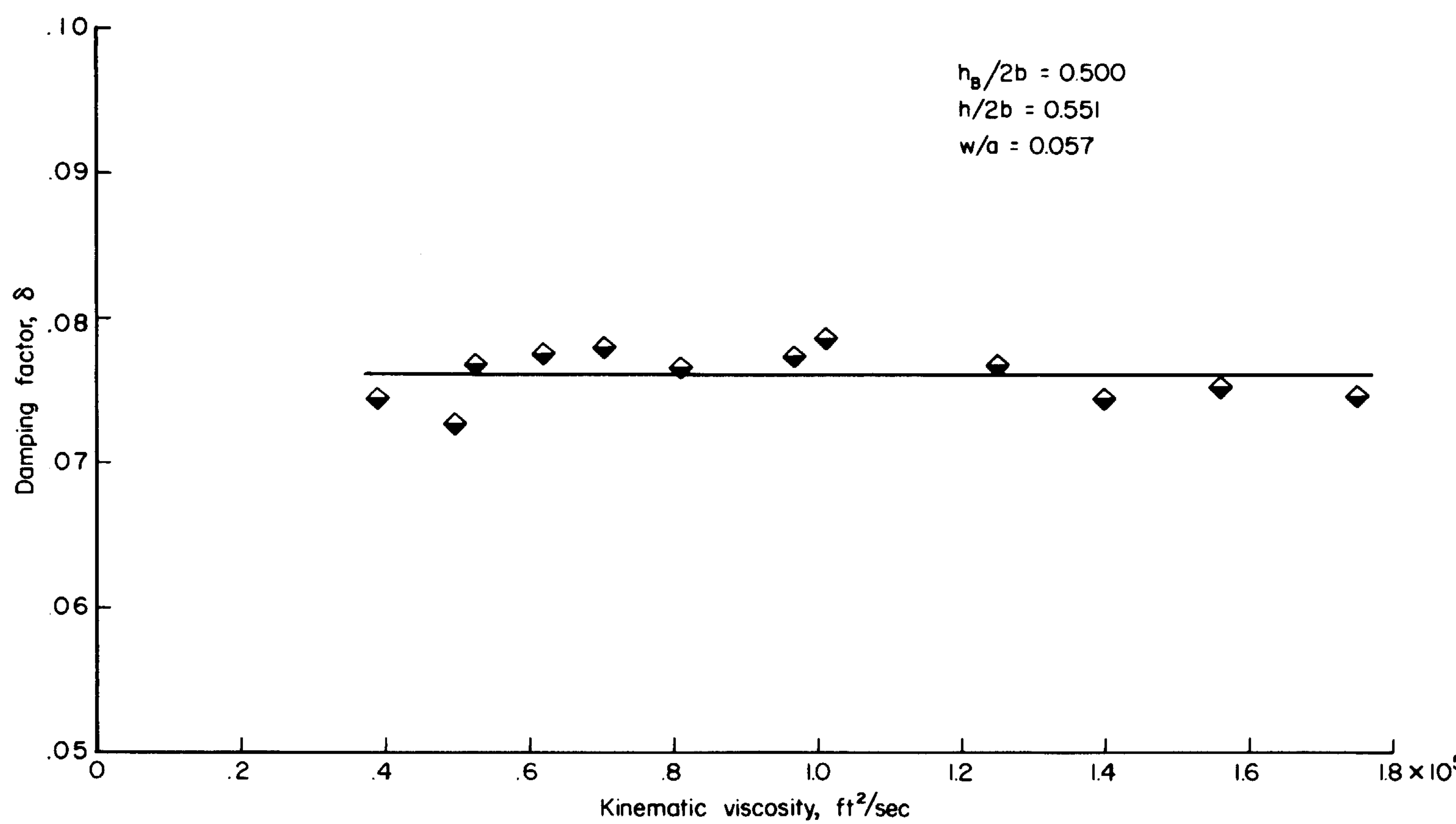

Figure 12.- Variation of damping factor with kinematic viscosity of water for a tank with a ring baffle.

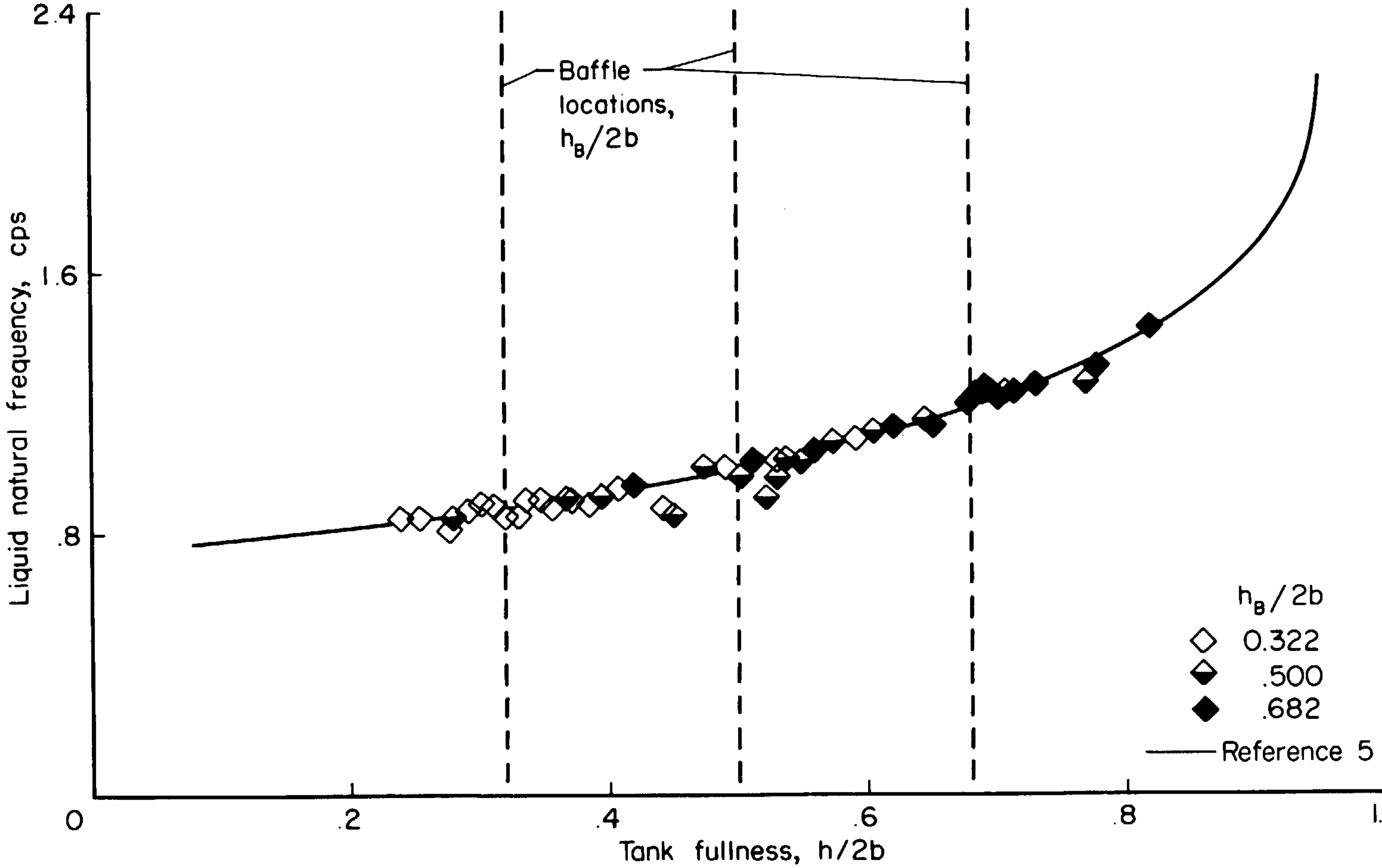

Figure 13.- Variation of fundamental liquid natural frequency with tank fullness for three oblate spheroidal tanks fitted with a ring baffle. w/a = 0.057.

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