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COMPARISON OF PROPELLANT SLOSHING PARAMETERS OBTAINED FROM MODEL AND FULL-SIZE CENTAUR LIQUID-OXYGEN TANKS

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SUMMARY

Propellant sloshing and pendulum analogy parameters are compared for a scale-model and a full-scale Centaur liquid-oxygen tank. Experimental data were obtained in a 1/3.75 scale-model tank and a full-size tank in both an unbaffled and a baffled configuration with water as the contained liquid. The full-size baffled tank configuration was also tested with liquid oxygen as the contained liquid. The fundamental-frequency and damping-ratio parameters show good agreement between the scale-model and full-size tanks for both the unbaffled and baffled tank configurations. The fundamental-frequency and damping-ratio parameters for the baffled tank configuration show no apparent difference between liquid oxygen and water. The pendulum analogy parameters, obtained for the unbaffled tank configuration only, also show good agreement between the model and full-size tanks.

INTRODUCTION

Propellant (or liquid) sloshing is a potential source of disturbance critical to the stability and/or structural integrity of space vehicles or boosters containing relatively large masses of liquid propellants. Considerable difficulty is encountered, however, when an attempt is made to include the complex hydrodynamic equations of liquid motion in a computer simulation of the vehicle motion for a stability analysis. Therefore, it is desirable to represent propellant sloshing as a mechanical analogy (e.g., either a pendulum or a spring mass system) for which linear second-order differential equations of motion are readily adaptable to digital or analog computer simulations.

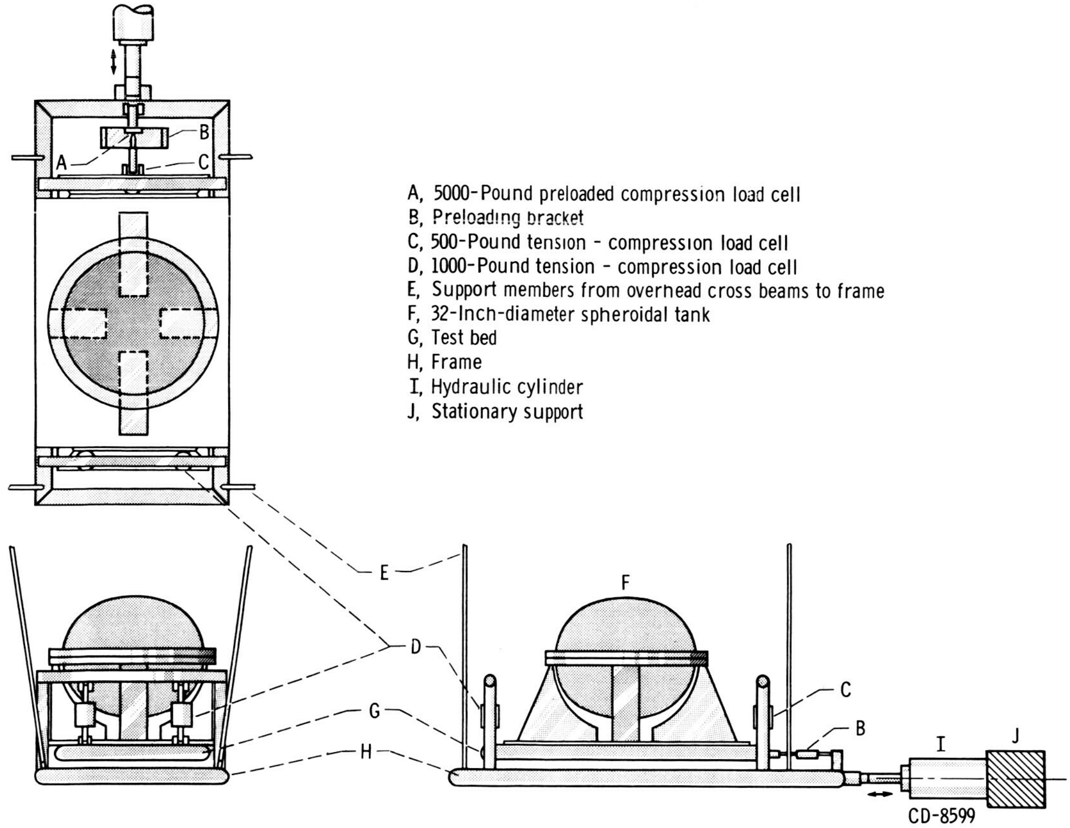
The fundamental mode of liquid sloshing is usually the most critical because the resulting slosh forces are much larger than the forces produced for the higher natural modes. Also, the fundamental mode frequency of the liquid oscillations may be close to either the attitude control frequency or a body-bending frequency of the vehicle.

A pendulum model of the fundamental mode of liquid sloshing generally consists of a pendulum mass suspended from a given point in each propellant tank to represent the liquid sloshing mass, and a fixed mass to represent the nonsloshing mass. Most pendulum analogy parameters necessary to simulate the fundamental mode of propellant sloshing may be obtained from experimental programs conducted for any particular tank configuration. Testing full-size propellant tanks with actual propellants, however, is often very expensive and/or impractical. Therefore, it is desirable to test scale-model tanks with water to define the necessary pendulum analogy parameters for the actual vehicle tanks. The scaling parameters used to adapt the pendulum analogy parameters from the model tanks to the actual full-size tanks, however, may often be questionable when the model and full-size tanks are much different in size, or when water is used to simulate the propellant.

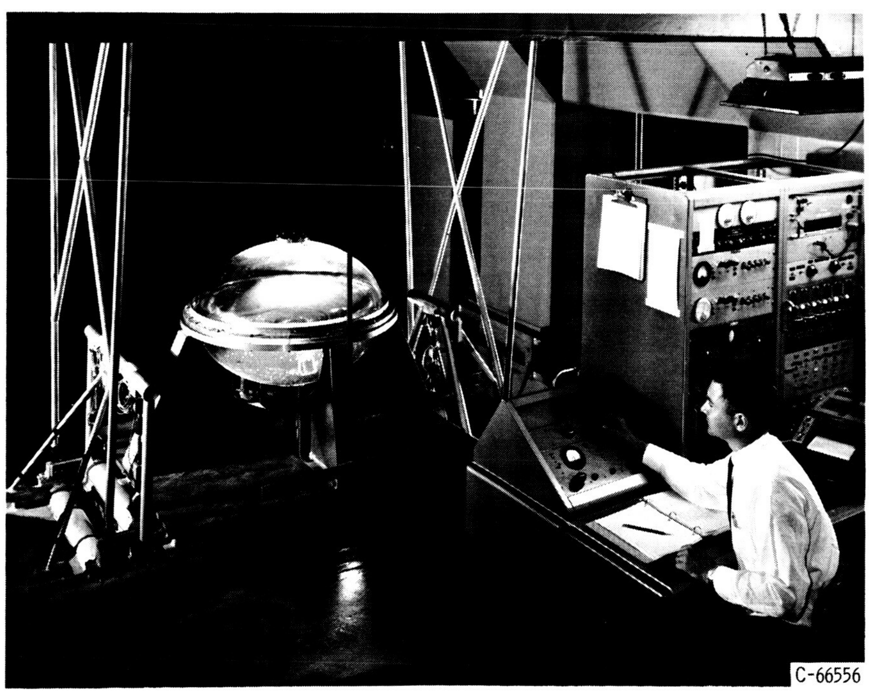
An experimental program was previously conducted at the Lewis Research Center to (1) investigate propellant sloshing characteristics, (2) determine the effectiveness of a proposed slosh baffle design, and (3) determine several pendulum analogy parameters in a 1/3.75 scale-model Centaur liquid-oxygen tank with water as the contained liquid (ref. 1). Subsequently, a limited experimental program was conducted by General Dynamics/Convair with a full-size (major axis 10 ft) Centaur liquid-oxygen tank with both water and liquid oxygen as the contained liquids (ref. 2) to verify the parameters obtained in the scale-model tests. The results of the scale-model and the full-size experimental investigations are compared herein. The following propellant sloshing and pendulum analogy parameters are compared: (1) fundamental frequency, (2) liquid-damping ratio, (3) pendulum mass, (4) length of pendulum arm, and (5) hinge-point location of pendulum arm.

SYMBOLS

a	major axis of tank, ft
b	tank height, ft
F	force on tank producing propellant sloshing, lb
F_s	horizontal slosh force, lb
g	vertical acceleration of tank, 32.174 ft/sec^2
h	liquid depth (measured from bottom of tank to liquid surface), ft
L_p	length of pendulum arm, ft
ℓ_p	distance from center of tank to pendulum hinge point, ft



(a) Schematic view.



(b) Overall view.

Figure 1. - Experimental scale-model contour liquid-oxygen tank test facility.

M_o	fixed or nonsloshing mass, slugs
M_p	pendulum or liquid sloshing mass, slugs
M_T	total liquid mass present in completely filled tank, slugs
M_t	total liquid mass present in tank at given liquid-depth ratio, slugs
r	radius of liquid surface of partly filled tank, ft
δ	damping ratio or logarithmic decrement, $\ln(F_{s,n}/F_{s,n+1})$
η	fundamental frequency parameter, $\omega\sqrt{r/g}$
ω	fundamental frequency of liquid oscillations, rad/sec

Subscript:

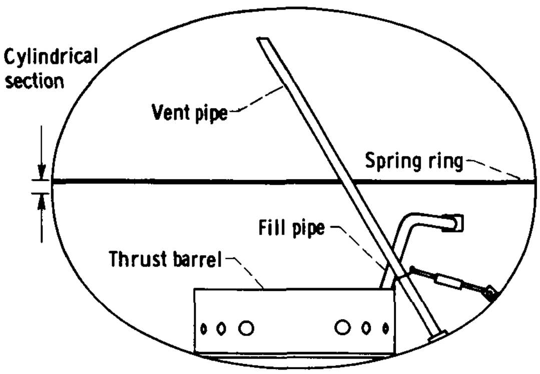
n = 1, 2	corresponding to first two oscillations of liquid surface occurring immediately when motion of tank is quick-stopped

APPARATUS AND PROCEDURE

Model Tank

The experimental test facility, described in references 1 and 3, is shown in figure 1. The scale-model tank 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 cross beams and was free to oscillate in one direction on the horizontal plane. A hydraulic piston and a servocylinder provided the driving forces.

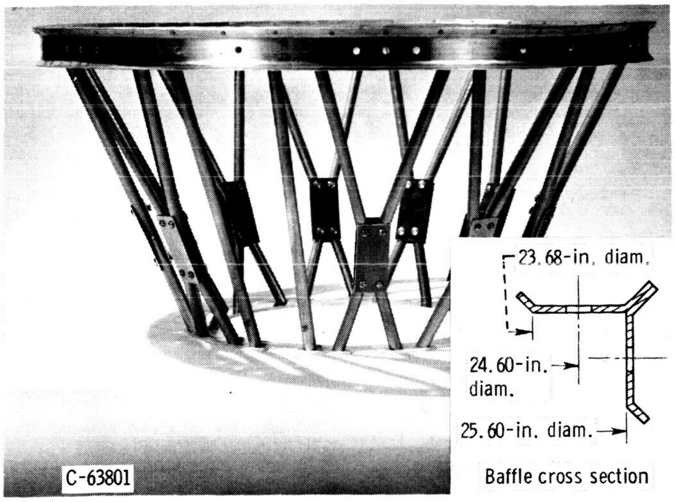
The scale-model liquid-oxygen tank is shown schematically in figure 2(a) for the unbaffled configuration and in figures 2(b) to (d) for the baffled tank configuration. The model tank and baffle were geometrically similar to the full-size tank and baffle. The tank was oscillated sinusoidally at a preselected excitation frequency and ampli-



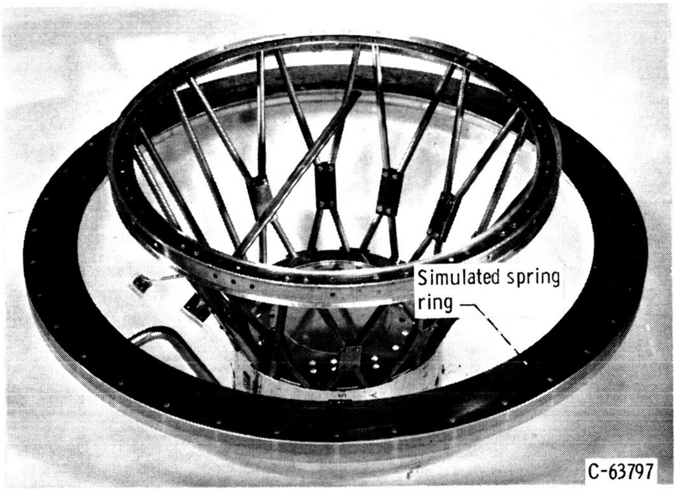
Width of spring ring, in.	0.73
Diameter of thrust barrel, in.	13.31
Height of thrust barrel, in.	4.38
Outside diameter of vent pipe, in.	0.63
Length of vent pipe, in.	22.5
Outside diameter of fill pipe, in.	0.75
Tank major axis, in.	32.0
Tank height, in.	23.74
Height of cylindrical section, in.	0.88

(a) Unbaffled configuration.

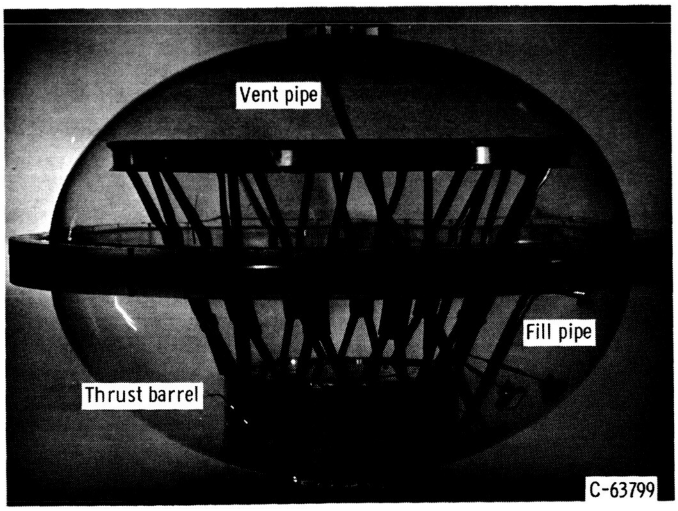
Figure 2. - Scale model of Centaur liquid-oxygen tank.



(b) Baffle configuration, side view.

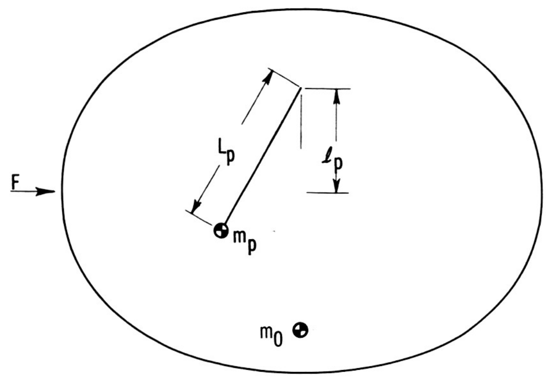


(c) Baffle installation, oblique view.



(d) Baffle installation, side view.

Figure 2. - Concluded.



F	force restraining horizontal motion of tank in test facility, equal to slosh force
L_p	length of pendulum arm
ℓ_p	distance from center of tank to pendulum hinge point
m_p	pendulum mass
m_0	fixed mass

Figure 3. - Quantities used to describe pendulum analogy of liquid sloshing.

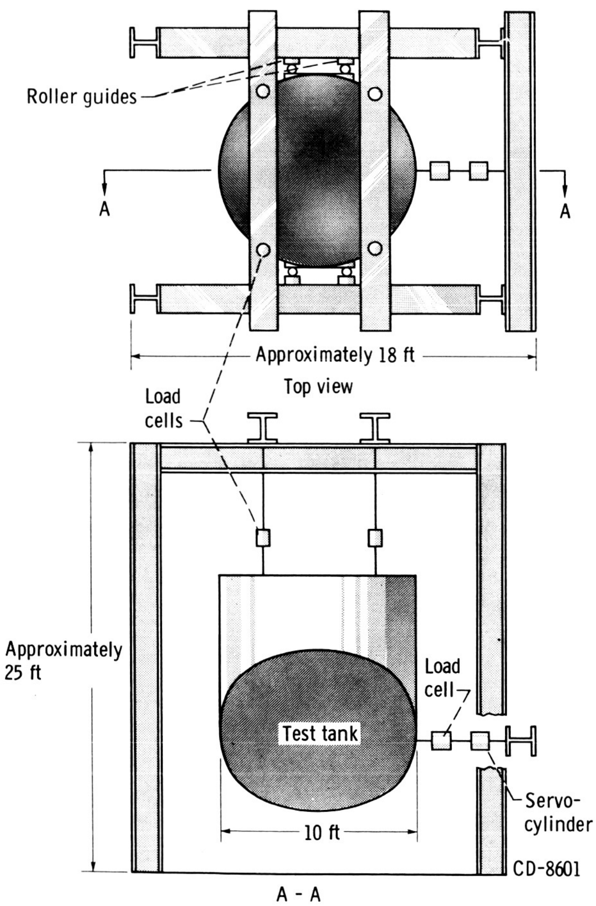


Figure 4. - Schematic diagram of experimental full-size Centaur liquid-oxygen tank test facility.

tude. The sloshing parameters (frequency and damping) were determined by oscillating the tank at an excitation frequency, equal to the fundamental frequency for that particular liquid depth, in order to obtain the maximum wave heights and slosh forces. The oscillatory motion of the tank was then "quick-stopped," and the residual slosh forces were recorded. The excitation amplitude of the tank was held constant at a value of 0.100 inch for these tests. The pendulum hinge-point location was determined by oscillating the tank at the fundamental frequency of the liquid oscillations at a very low excitation amplitude (0.01 to 0.03 in.). The pendulum mass quantities were determined by oscillating the tank at a frequency less than the fundamental frequency of the contained liquid so that the liquid would oscillate at the excitation frequency. A complete derivation of the equations of pendulum motion in a propellant tank is presented in appendix B of reference 1. The quantities used to describe the pendulum analogy are shown in figure 3.

Full-Size Tank

The experimental test facility for the full-size Centaur liquid-oxygen tank, which is described in detail in reference 2, is shown schematically in figure 4. The test tank was suspended from a structure by four rods that were pivoted at each end. The tank was free to translate horizontally in one direction when driven by a hydraulic servo-cylinder. The motion of the tank was restrained to one direction in the horizontal plane by roller guides located in the horizontal plane of the center of gravity of the

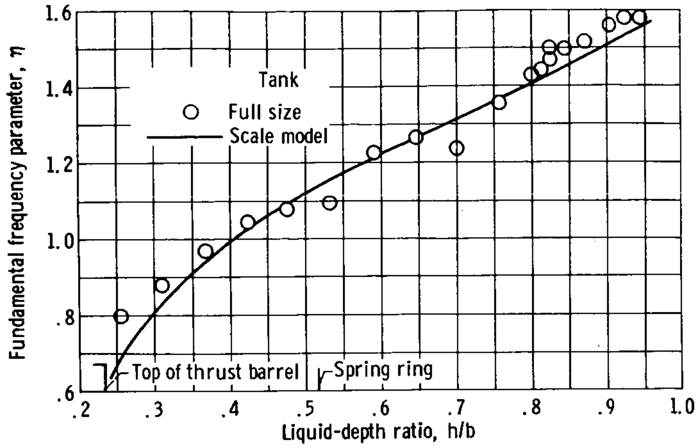


Figure 5. - Fundamental frequency parameter for varying liquid-depth ratio for unbaffled tank with water as contained liquid.

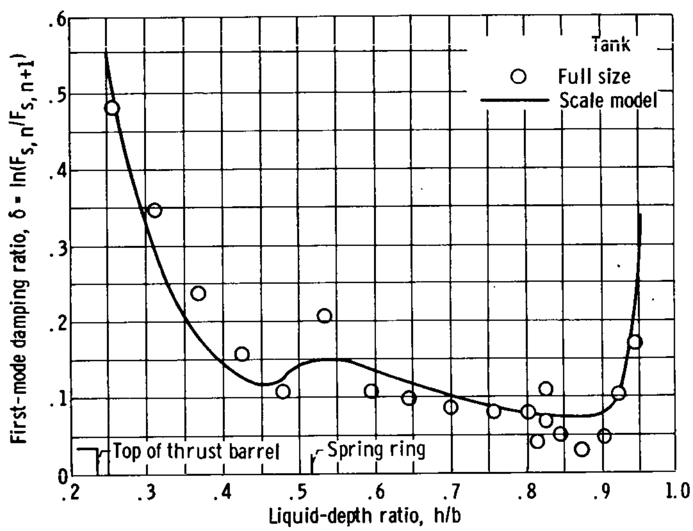


Figure 6. - Damping ratio as function of liquid-depth ratio for unbaffled tank with water as contained liquid.

empty tank. The driving servocylinder was located in the horizontal and vertical planes of the center of gravity of the empty tank to minimize torques about the transverse and longitudinal axes of the tank. The tank was filled with fluid to the desired level and was oscillated sinusoidally at a frequency less than the fundamental mode frequency so that fluid would not splash. The tank was then quick-stopped at the zero velocity point of the excitation cycle and rigidly restrained against the tower structure by the servocylinder. The measurements were recorded before cessation of tank excitation and continued for sufficient time to record the pertinent slosh data. The excitation amplitude was held nearly constant at 1.5 inches for all the testing. The tests were conducted with water as the contained liquid for the unbaffled tank configuration and with water and liquid oxygen for the baffled tank configuration.

Although the experimental procedures in obtaining the data for the scale-model and the full-size tanks were not identical in all cases, the comparison of the sloshing and pendulum analogy parameters presented herein for the two tanks, nevertheless, is valid.

PROPELLANT SLOSHING PARAMETERS

Unbaffled Tank Configuration

The fundamental frequency parameter and the damping ratio (or logarithmic decrement) are shown in figures 5 and 6, respectively, for the scale-model and full-size Centaur liquid-oxygen tanks. The contained liquid in both cases was water. The fundamental frequency parameter and the damping ratios show good agreement between the scale-model and full-size tanks.

Generally, the damping ratios (fig. 6) scale directly with no correction for tank size. The direct scaling shown in figure 6 is due to the thrust barrel, spring ring, and the top of the tank acting in the same manner as the slosh baffles that scale directly to tank size (refs. 4 to 7). Reference 1 indicated that the damping ratio should be scaled to tank size on the basis of a viscosity parameter in the regions of the tank where the liquid damping was primarily dependent on a wall-wiping action. The damping ratios at a given liquid-depth ratio, however, were nearly the same for the two tanks investigated indicating that, in general, there were no regions in the tank where a wall-wiping action was predominant in damping the liquid oscillations. The one possible exception where wall-wiping action may have been predominant is in the region of liquid-depth ratios $0.8 \leq h/b \leq 0.9$, where the experimental data tend to agree fairly well with the predicted damping ratio of 0.055 (ref. 1).

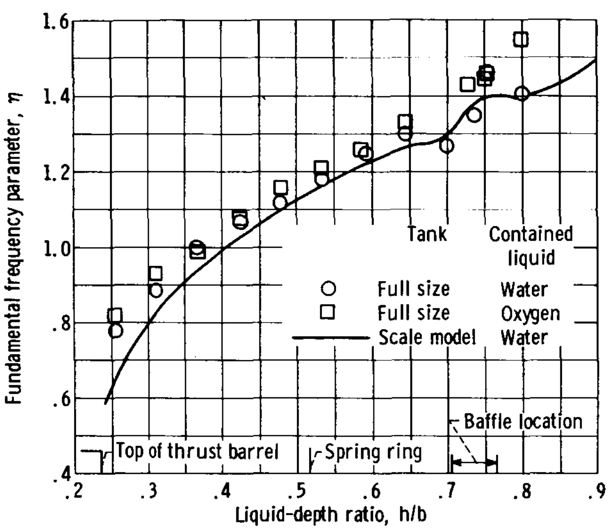


Figure 7. - Fundamental frequency parameter for varying liquid-depth ratios for baffled tank.

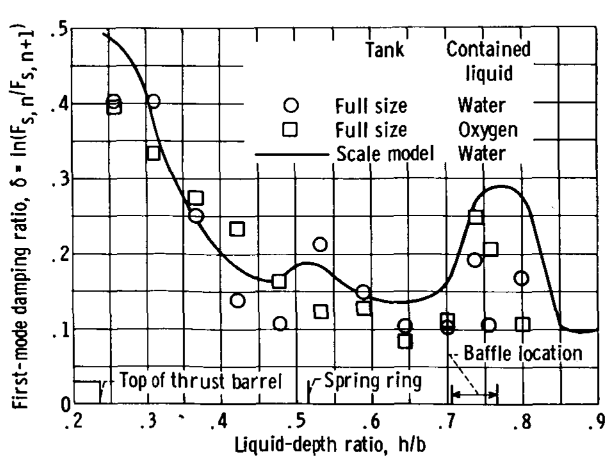


Figure 8. - Damping ratio as function of liquid-depth ratio for baffled tank.

Baffled Tank Configuration

The fundamental frequency parameter and the damping ratios for the baffled tank configurations are shown in figures 7 and 8, respectively. The contained liquid was water for the scale-model tank and water and liquid-oxygen in the full-size tank. The fundamental frequency parameter and the damping ratios are nearly the same for the model and full-size tanks, although there appears to be more data scatter for the damping ratios. The effects of the thrust barrel, spring ring, and the slosh baffle on the first-mode damping ratio for the model tank (fig. 8) are very pronounced. The damping ratios for the full-size tank for both water and liquid oxygen follow the same trend as the model tank, but there is a large degree of data scatter at the baffle location

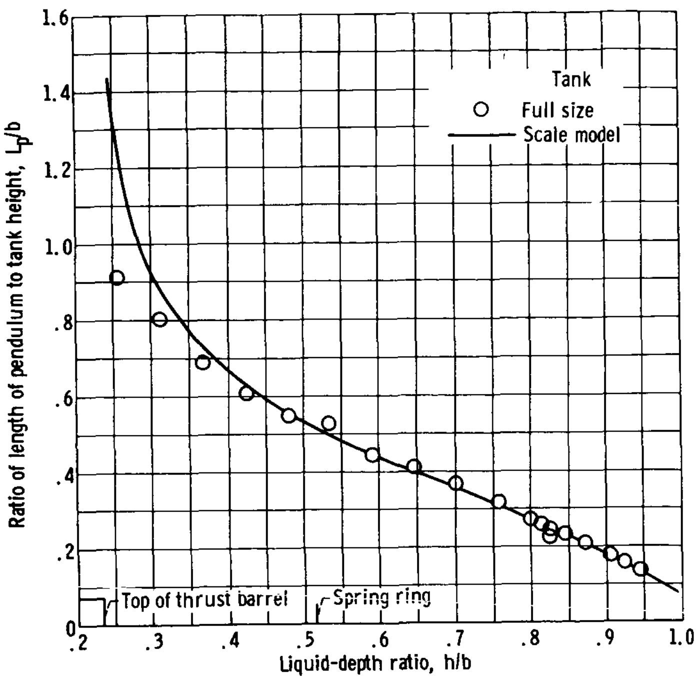


Figure 9. - Ratio of length of pendulum arm to tank height as function of liquid-depth ratio for unbaffled tank with water as the contained liquid.

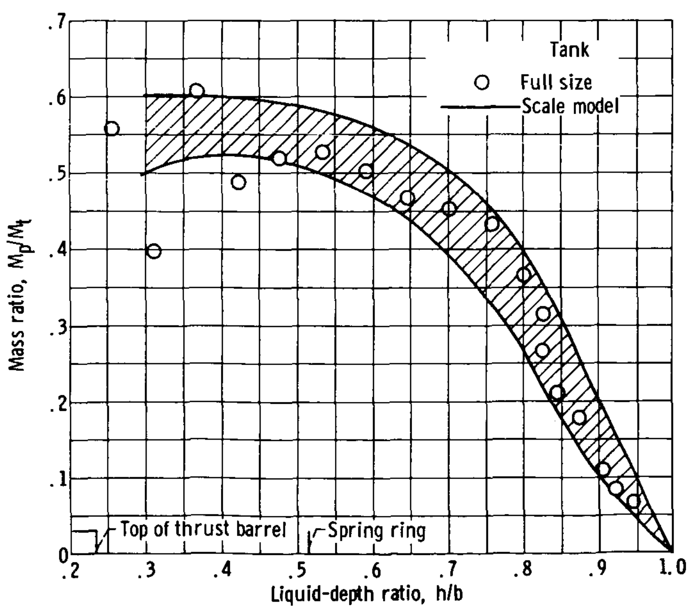


Figure 10. - Ratio of pendulum or liquid sloshing mass to mass present at each depth ratio as function of liquid-depth ratio for unbaffled tank with water as contained liquid.

for the full-size tank. The data in the full-size tank for water and liquid oxygen show no appreciable difference within the limits of experimental accuracy for the large test facility.

Pendulum Analogy Parameters

The pendulum analogy parameters determined for the Centaur liquid-oxygen tank are compared in figures 9 to 12 for the unbaffled tank configuration. The ratio of the length of the pendulum arm to tank height, shown in figure 9, shows excellent agreement between the model and full-size tanks.

The ratio of pendulum or sloshing mass to the liquid mass in the tank at each liquid depth is shown in figure 10 as a function of liquid-depth ratio. The band in figures 10 to 12 represents the range of data scatter for the scale-model tank. The data for the model and full-size tanks show excellent agreement except near the thrust barrel.

The pendulum or sloshing mass divided by the total liquid mass in a completely filled tank is shown as a function of liquid-depth ratio in figure 11. The full-size-tank data appear to be slightly higher than the model-tank data for depth ratios between 0. 80 and 0. 65.

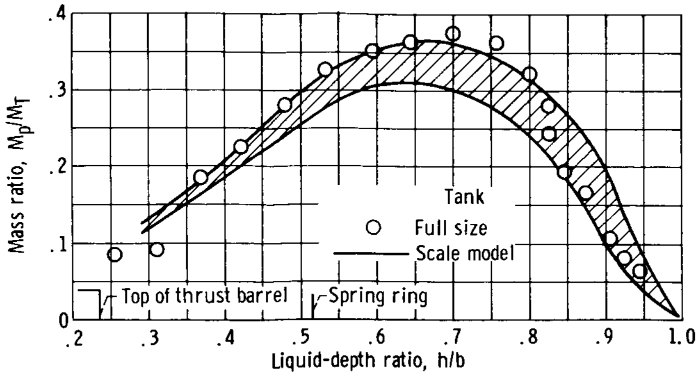


Figure 11. - Ratio of pendulum or sloshing mass to total mass in completely filled tank as function of liquid-depth ratio for unbaffled tank with water as contained liquid.

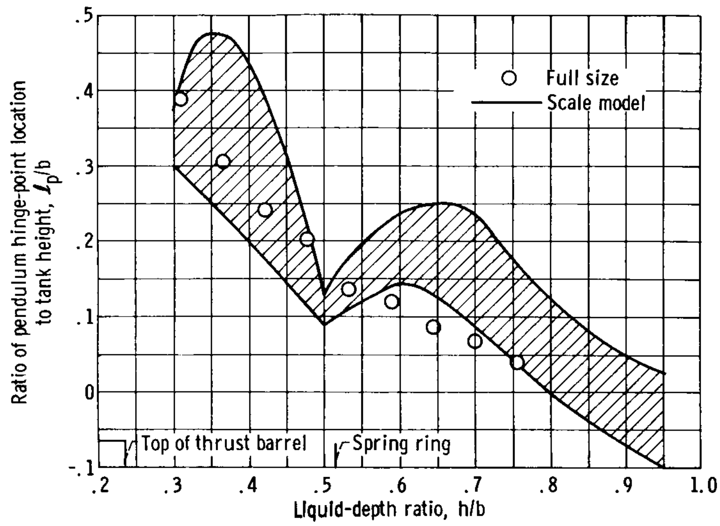


Figure 12. - Ratio of pendulum hinge point location to tank height as function of liquid-depth ratio for unbaffled tank with water as contained liquid.

The ratio of the pendulum hinge-point location to the tank height is shown as a function of liquid-depth ratio in figure 12. The scale-model tank test results show a large degree of scatter due to difficulty encountered in accurately measuring the small slosh forces with the vertical load cells on the test facility for this investigation.

SUMMARY OF RESULTS

Propellant sloshing and pendulum analogy parameters are compared for a scale-model tank and a full-scale Centaur liquid-oxygen tank. Experimental data were obtained in a 1/3.75 scale-model tank and in a full-size tank in the baffled and unbaffled configuration with water as the contained liquid. The full-size baffled tank configuration was also tested with liquid oxygen as the contained liquid.

The fundamental-frequency and the damping-ratio parameters show good agreement between the scale-model and full-size tank for both the baffled and unbaffled configurations. The fundamental-frequency and the damping-ratio parameters show no appreciable difference between liquid oxygen and water for the baffled tank configuration. The slosh baffle increased the damping ratio over that of the unbaffled tank configuration.

The ratios of the length of pendulum arm to tank height, the pendulum or sloshing mass to the liquid mass in the tank at each liquid depth, and the pendulum or sloshing mass to the total liquid mass in a completely filled tank show good agreement for both scale-model and full-size tanks for the unbaffled tank configuration. The ratio of pendulum-hinge point to tank-height data shows a large amount of scatter for the scale-model tank; however, the same general trend between the model and the tank is apparent.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 13, 1966,
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