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EXPERIMENTAL DETERMINATION OF LIQUID OSCILLATION FREQUENCY IN AN INCLINED RIGHT CIRCULAR CYLINDER

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16. Abstract

An experimental investigation was performed to determine the frequency of liquid oscillations in a right circular cylinder tank tilted at 0°, 30°, 45°, and 60° to the local vertical. The liquid depth was also varied. Two modes of oscillation were studied, one with its nodal line along the minor axis of the liquid free surface and one with its nodal line along the major axis of the surface. The frequency of each of these modes was decreased by increasing the tank tilt, with the frequency of the former being decreased much more than the frequency of the latter.

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DEFINITION OF SYMBOLS

Symbol	Definition
C	frequency parameter correction factor
g	the acceleration due to gravity, cm/sec^2
h	liquid depth measured along the tank axis, cm
R	tank radius, cm
α	tilt angle of tank axis relative to the local vertical, deg
ω	liquid oscillation frequency, rad/sec

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EXPERIMENTAL DETERMINATION OF LIQUID OSCILLATION FREQUENCY IN AN INCLINED RIGHT CIRCULAR CYLINDER

SUMMARY

An experimental investigation was performed to determine the frequency of liquid oscillations in a right circular cylindrical tank tilted at 0°, 30°, 45°, and 60° to the local vertical. The liquid depth was also varied. Two modes of oscillation were studied, one with its nodal line along the minor axis of the liquid free surface and one with its nodal line along the major axis of the surface. The frequency of each of these modes was decreased by increasing the tank tilt, with the frequency of the former being decreased much more than the frequency of the latter.

I. INTRODUCTION

Body force dominated propellant dynamics in axisymmetric tanks with the body force vector parallel to the tank axis has been studied extensively (references 1, 2, and 3). The conditions, axisymmetry and body force vector parallel to the tank axis, have applied to nearly all rocket vehicles of interest until consideration of the Shuttle vehicle, booster and orbiter. Shuttle configurations being studied are aircraft-type vehicles launched vertically and having horizontal fly-back capability. To have fly-back capability in all situations, including abort, the vehicle must be controllable during transition from vertical to horizontal flight with any propellant fill level. Knowledge of propellant dynamics during flight at these various vehicle orientations is required for proper control system design.

The purpose of this study was to determine the effect on liquid oscillation frequency of changes in the angle between the tank axis and the body force vector (the liquid weight vector in this investigation). An experimental approach was chosen. The tank tilt angle was varied from 0° to 60° and the liquid depth to tank radius ratio from 0.5 to 3.25.

II. APPARATUS AND PROCEDURE

The test set-up is shown in figure 1. The apparatus consisted of a 20 centimeter inside diameter plexiglass right circular cylindrical tank 38 centimeters tall bolted to an aluminum framework which held the tank at the desired tilt angle. The test liquid was distilled water with two parts per thousand Aerosol MA. The kinematic viscosity of the liquid at the test temperature, 27.8°C, was .0084 cm^2/sec with viscosity measured by an Oswalt-type viscometer and assuming the density to be that of water, 1 gm/cm^3. The surface tension at this temperature was 48 dynes/cm (reference 4). A stop watch was used to measure the period of liquid oscillation.

The tank was set at the desired tilt angle and filled to the test depth, h. The free surface was not allowed to contact the tank bottom or to spill over the tank top, and these restrictions set the lower and upper limits, respectively, on liquid depth. Two modes were studied, one having its nodal line along the minor axis of the elliptical free surface and one along the major. Liquid oscillations were excited by rocking the tank and framework. During free decay of the oscillations, and after disappearance of initial disturbances, the time required for completion of 50 cycles was measured with a stop watch and used to calculate frequency.

III. DISCUSSION

The liquid oscillation mode having its nodal line along the minor axis of the elliptical free surface will be called the longitudinal mode, and the mode with nodal line along the major axis will be called the lateral mode.

A. Experimental

Frequency data for the longitudinal mode are shown in figure 2. Three or more measurements were taken at each test condition, and the data were repeatable within approximately ±1.5 percent.

The theoretical curve for $\alpha = 0°$ (i.e., for an untilted right circular cylinder) follows the expression,

$$\frac{\omega^2 R}{g} = 1.841 \tanh \left(1.841 \frac{h}{R}\right),$$

taken from reference 2 and shows excellent agreement with the $\alpha = 0°$ experimental results. Dashed lines are faired through data taken at other angles. The frequency parameter, ω^2R/g, at $\alpha = 60°$ is approximately 27 percent of the maximum value at $\alpha = 0°$.

Figure 2 shows that the measured frequencies were affected only slightly by changes in liquid depth for angles other than 0°; however, the appearance of the liquid surface, as it oscillated, changed considerably with liquid depth. With the surface very near the tank bottom, a geyser of liquid formed at the overhanging tank wall and fell back into the surface once each cycle. This geyser disappeared with increased liquid depth and may have been due to the occurrence of traveling waves at the small depth.

The frequency data for lateral oscillations are shown in figure 3. The effect of tank tilt on frequency parameter is seen to be much less for lateral oscillations than for longitudinal, with the value of ω^2R/g at $\alpha = 60°$ equal to approximately 75 percent of the maximum value at $\alpha = 0°$. The lateral mode did not exhibit any obvious differences in appearance due to liquid depth as did the longitudinal mode. The locus of maximum amplitudes for the lateral mode appeared to be the two cylinder elements one cylinder diameter apart, measured horizontally. This mode might contribute forces in both the lateral and longitudinal directions, whereas, the longitudinal mode probably does not exert unbalanced lateral forces.

Figure 4 shows the change in longitudinal mode frequency parameter with tilt angle and gives the ratio of ω^2R/g at a particular α to ω^2R/g at $\alpha = 0°$ for depths at which changes in depth do not appreciably affect ω^2R/g. Interpolation between the data at $\alpha = 0°$ and $\alpha = 30°$ indicates that the frequency, ω, would be reduced by a very small amount for a 10° tank tilt. (Ten degrees is roughly the largest angle expected between thrust vector and tank axis during boost for some currently studied Shuttle vehicles.)

B. Comparison with Theory

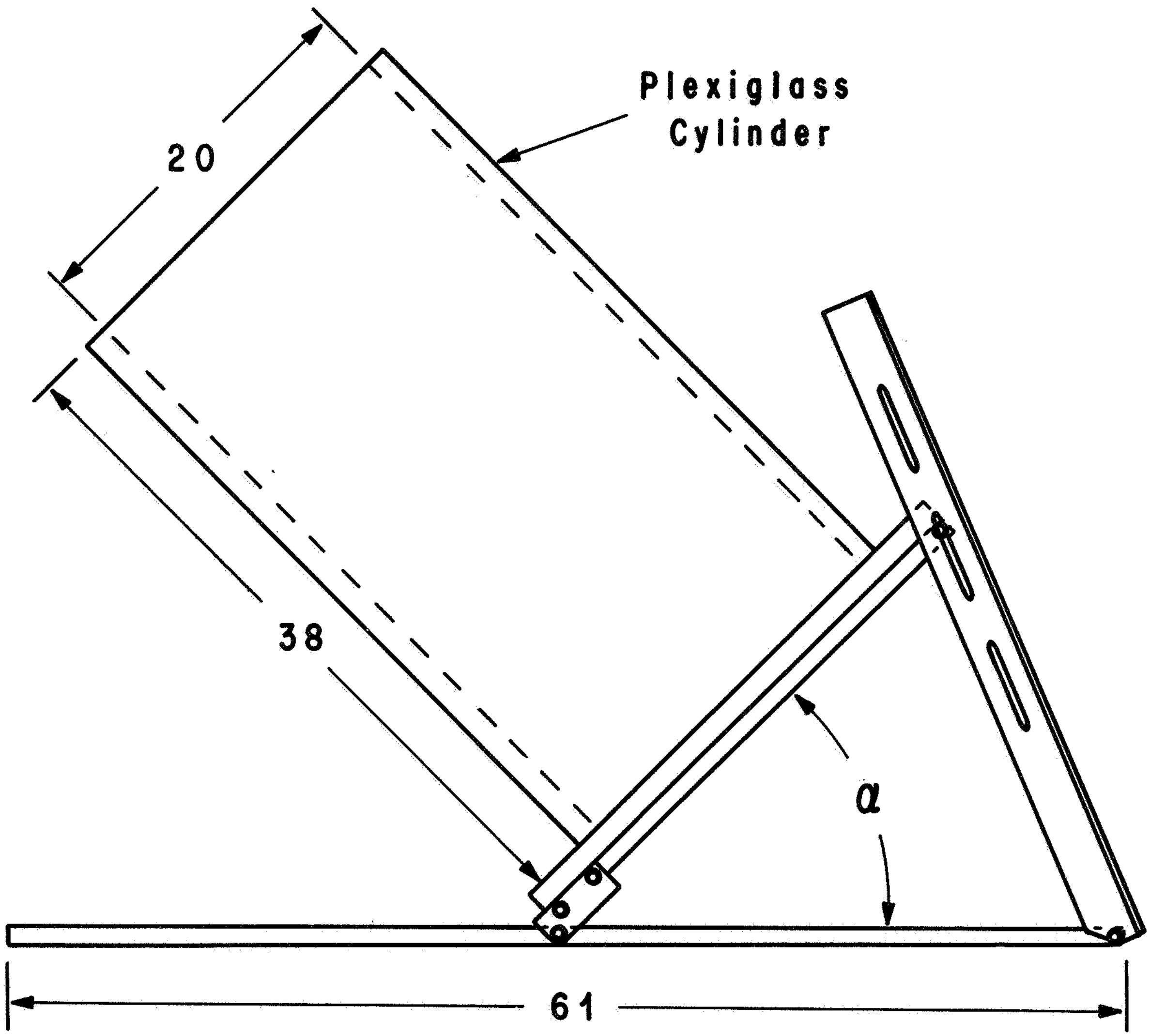
In figure 5, the data are compared with the theory of references 2 and 5. The theory of reference 5 predicts values of ω^2R/g which are 10 percent and 14 percent lower than the measured values for $\alpha = 30°$ and $\alpha = 45°$, respectively, and agrees well with experiment at $\alpha = 60°$. The development of the theory used the assumption that the oscillating free surface remained flat. But the real free surface appeared flat only at very small amplitudes, and this may be one cause of discrepancy between the theory and experiment.

IV. CONCLUDING REMARKS

An experiment was performed to measure the frequency of liquid oscillations in an inclined right circular cylinder. Inclination angles of 0°, 30°, 45°, and 60° were used. For the mode with its nodal line lying along the minor axis of the elliptical free surface, the longitudinal mode, the frequency parameter (proportional to frequency squared) was reduced, by inclining the tank at 60°, to 27 percent of its value with the tank upright. For the mode with nodal line along the major axis of the free surface ellipse, the lateral mode, the frequency parameter at 60° inclination was 75 percent of the value at 0° inclination.

Comparison with available theory showed good agreement except at the 30° and 45° inclinations, where the predicted values were 10 percent and 14 percent, respectively, below the measured values of frequency parameter.

The results indicate that tank tilt should have only a small effect on Shuttle propellant dynamics during launch for the expected 10° or less angle between thrust vector and tank axis.



Note: Dimensions are in Centimeters

FIG. 1. TEST SET-UP

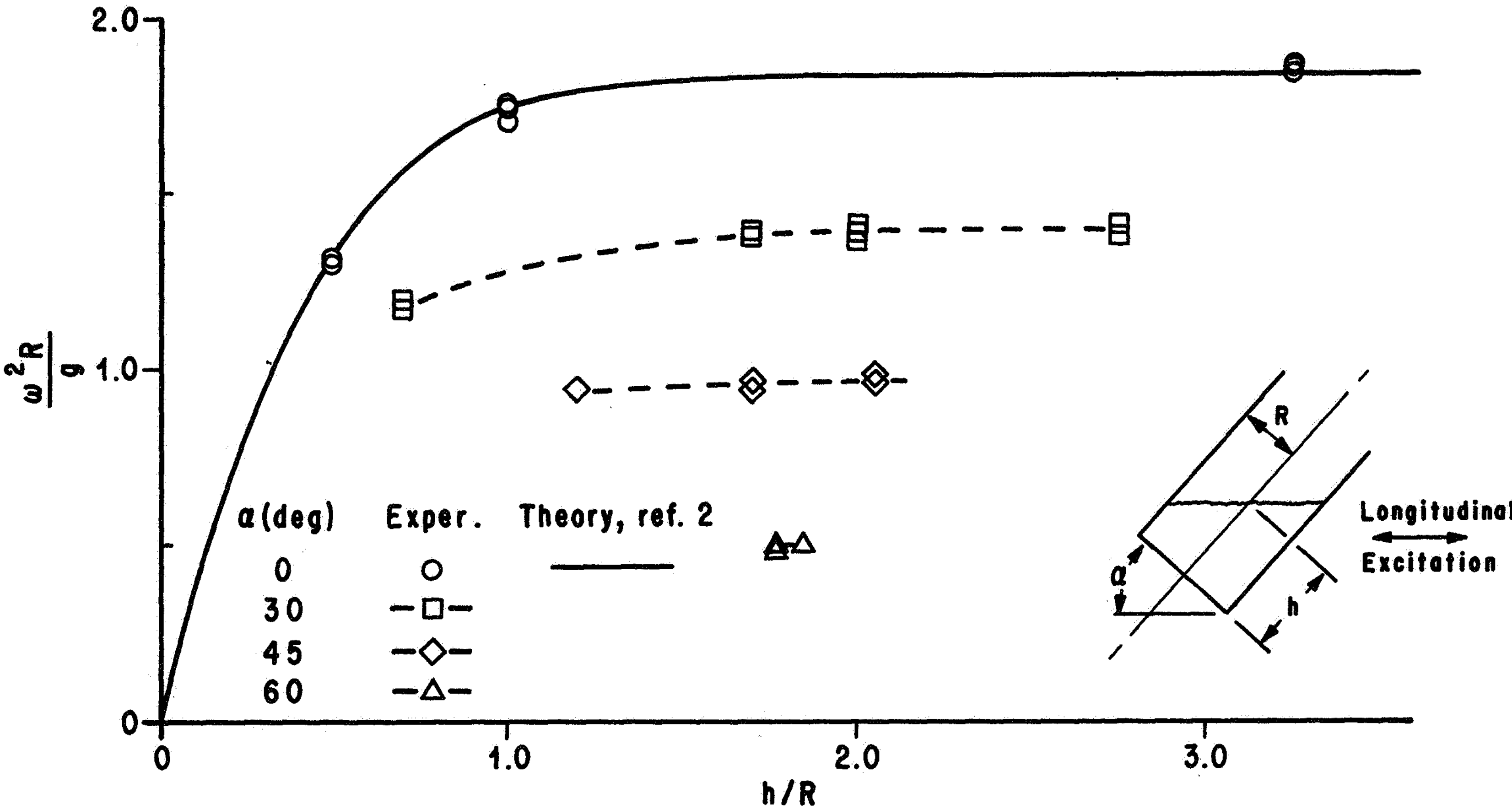


FIG. 2. EFFECT OF LIQUID DEPTH AND TILT ANGLE ON LONGITUDINAL FREQUENCY

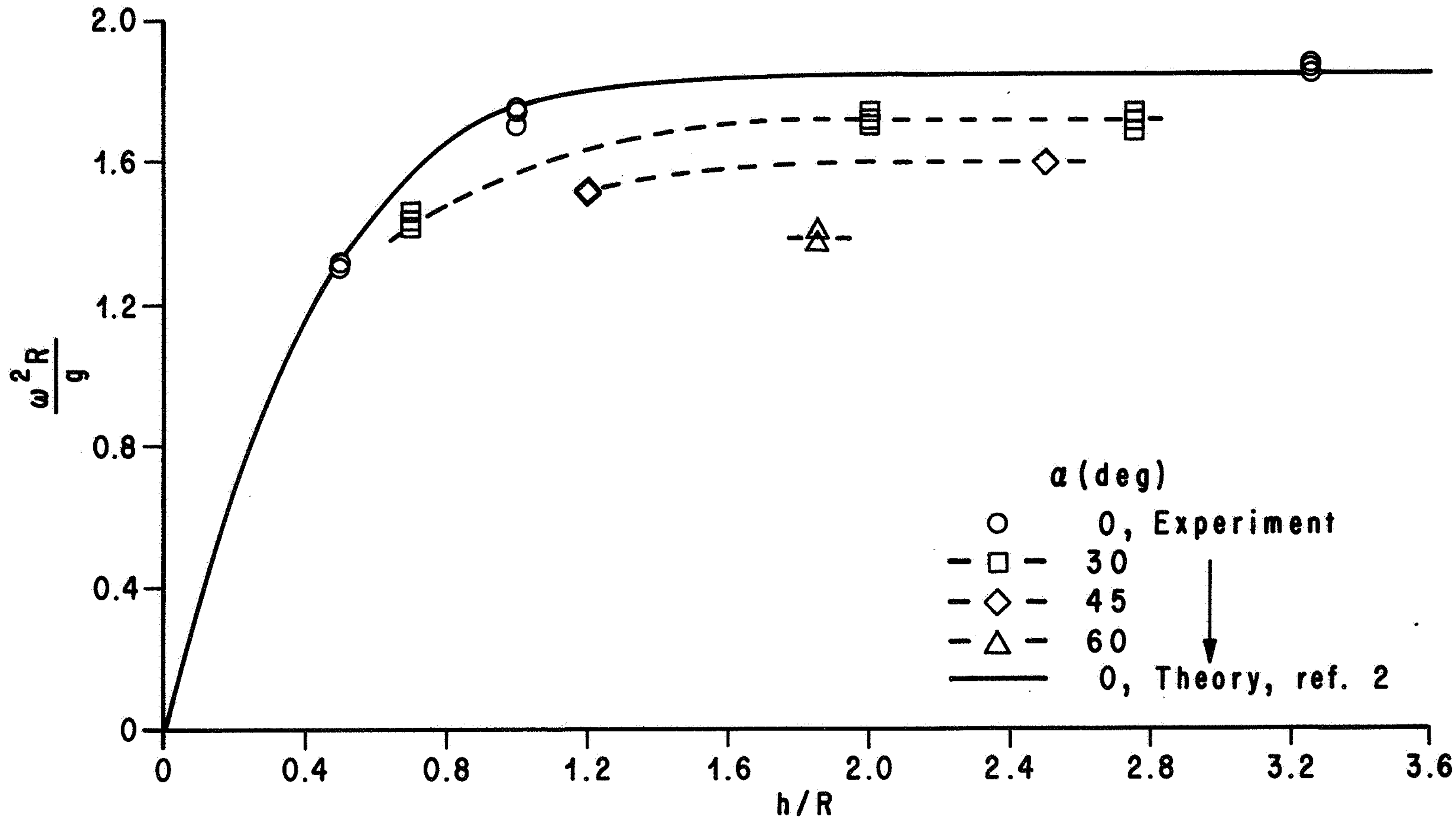


FIG. 3. EFFECT OF LIQUID DEPTH AND TILT ANGLE ON LATERAL FREQUENCY

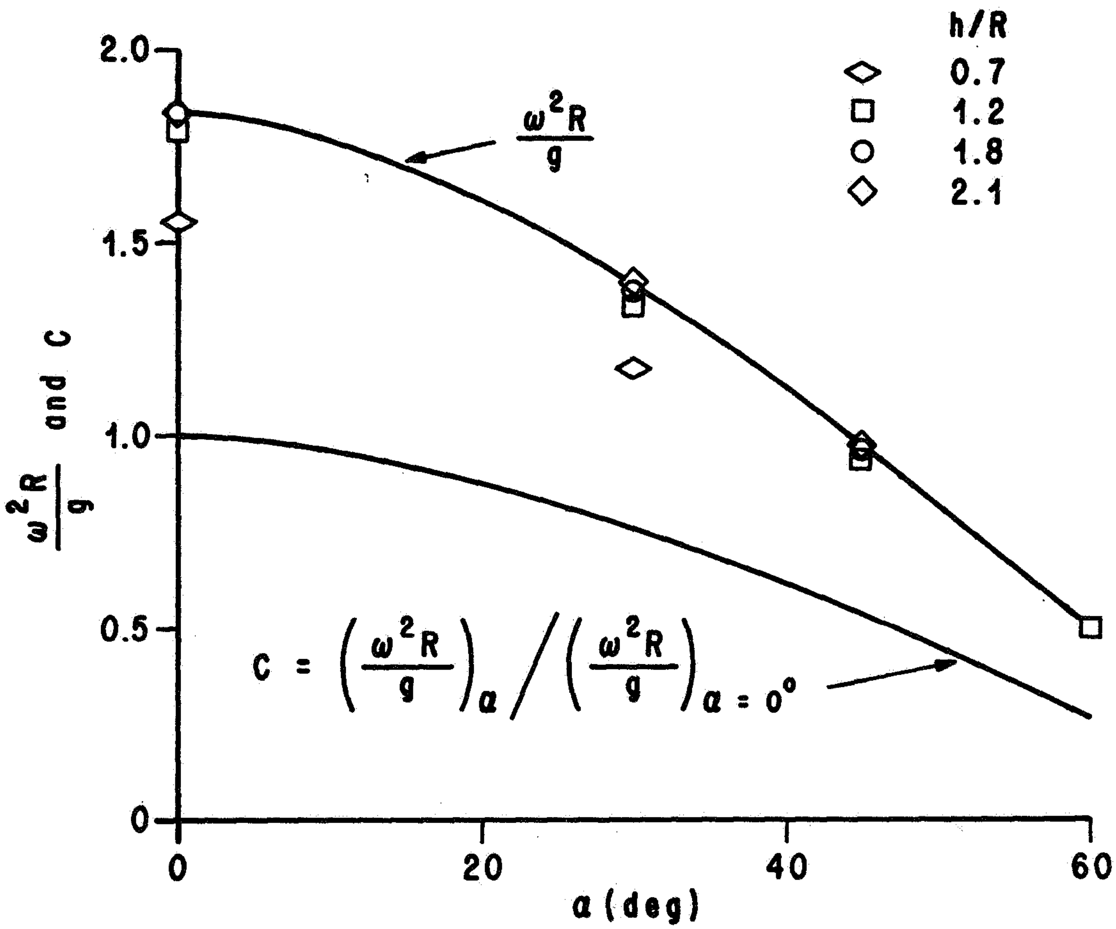


FIG. 4. EFFECT OF TILT ANGLE AT SPECIFIC LIQUID DEPTHS (LONGITUDINAL MODE)

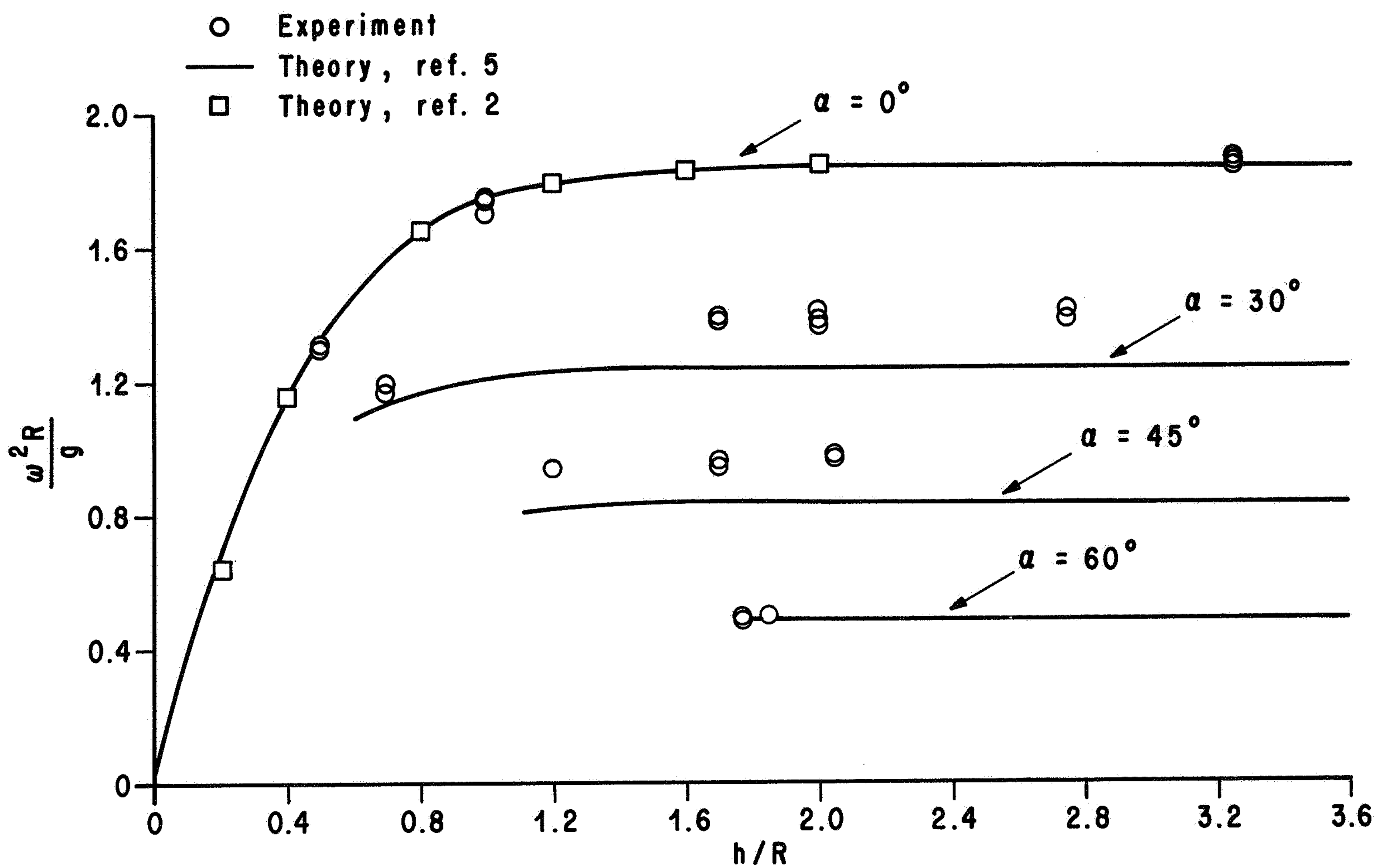


FIG. 5. COMPARISON WITH THEORY

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APPROVAL

EXPERIMENTAL DETERMINATION OF LIQUID OSCILLATION FREQUENCY IN AN INCLINED RIGHT CIRCULAR CYLINDER

by Frank Bugg

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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