CR 92082

23 MAY 1967

LMSC-A874729
CODE Y-87-67-1

A Study of LIQUID PROPELLANT BEHAVIOR DURING PERIODS OF VARYING ACCELERATIONS

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

SUMMARY REPORT

PREPARED UNDER CONTRACT NO. NAS 9-5174

For The
NATIONAL
AERONAUTICS
AND SPACE
ADMINISTRATION
MANNED SPACEFLIGHT CENTER
HOUSTON, TEXAS

LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SUNNYVALE, CALIFORNIA

INTRODUCTION

The static and dynamic behavior of liquid propellants in rocket tanks continues to be a subject of much concern to the propulsion system designer. Because of the increased sophistication of space vehicles, however, emphasis has shifted to the study of liquid behavior in tanks under conditions where the net body force per unit mass is very low compared to those encountered in the normal earth-bound state. Such circumstances have been called low-g conditions.

Over the past several years, a number of investigators in this country have worked to determine the nature of liquid behavior under low-g conditions. The problems solved have become increasingly more difficult and the results correspondingly more useful. The single characteristic which puts the behavior of liquid propellants in tanks in a special class is that a liquid propellant in its tank usually has a free surface. Further, the phenomena of interest is often transient or cyclic in nature. Such problems have proven to be very difficult from an analytical, as well as an experimental viewpoint.

STUDY OBJECTIVE

The purposes of the present study, carried out under NASA Contract No. NAS 9-5174, have been 1) to determine analytically the important aspects of liquid behavior affecting the performance of liquid rocket propelled spacecraft with special emphasis on liquid behavior in low-g and transient situations, and 2) to obtain experimental verification and,where possible, extension of the results of analysis. The work carried out in this study has been primarily influenced by the problems to be met in the use of so-called space storable propellants. The additional complications encountered in the use of cryogenic propellants were not considered.

RELATIONSHIP TO OTHER NASA EFFORTS

The motivation for performing this type of investigation has been the application of the results to problems to be met in the design and design review phases of vehicles of the Apollo Program and Post Apollo Programs. Just as earlier work in this field has been brought to bear on current vehicle designs, the work carried out in this study will be usefull in solution and review of liquid handling problems in future space vehicles. Even where cryogenic propellants are concerned, the information developed in the present study can be applied so long as the liquid can be considered to be subcooled.

The designs of other components of a space vehicle are affected by the solution to various liquid handling problems. In these cases, too, the results of the study can be applied as long as the liquid is subcooled and, in fact, should be applied wherever liquids are stored such that a liquid free-surface exists. A typical example of an additional application is the storage of liquid reactants in fuel-cell tanks in which bladders, diaphragms, etc., are not used for liquid positioning and expulsion.

Many other Government contract studies are related to this work directly or can make use of the results of this study. Examples include:

Contract Number	Title	Agency
NAS 3-7119	An Analytic Study of Interface Dynamics	LeRC
NAS 8-11525	Zero-g Heat Transfer Modes Boundary Layer Breakthrough	MSFC
NAS 3-7942	Liquid Propellant Thermal Conditioning System	LeRC
NAS 8-20553	Research and Design of a Practical and Economical Dielectrophoretic System for Control of Liquid Fuels Under Low-Gravity Environmental Conditions	LeRC
AF04(611)-11403	In-Space Propellant Orientation and Venting	AFRPL
NAS 10-4606	Orbital Refueling and Checkout Study	KSC

METHOD OF APPROACH

The approach called for in the study was to investigate analytically all of the liquid behavior phenomena expected in the course of space vehicle operations and to provide verification and extension where possible by means of scaled experiments. The range of liquid behavior situations considered important to spacecraft tankage design was divided into two main categories, characterized by lateral and axial motions, respectively.

Asymmetric liquid motions were the subject of seven distinct investigations performed in the course of the study:

a) Small amplitude lateral sloshing – the quasi-steady state analytical treatment of sloshing.

b) Large amplitude lateral motions – an analysis of such motions as an boundary initial value problem.

c) Transient lateral motions following engine shutdown – an analysis related to the one just preceding.

d) Damping provided by ring and screen type baffles – an analysis to extend the results of earlier work to tank geometries of practical interest.

e) An experiment to verify sloshing frequencies for small amounts of liquid in a hemispherically bottomed cylindrical tank and to verify calculated response to impulsive perturbations.

f) An experiment to determine the response of laterally sloshing liquid to the sudden reduction in body forces as when engine cutoff occurs.

g) An experiment to determine the effect of interface curvature (as when the axial Bond number is low) on the damping afforded by ring baffles.

Axisymmetric Motions – Axisymmetric liquid motions and related liquid behavior in spacecraft propellant tanks were the subject of five investigations, as follows:

a) Large amplitude axisymmetric slosh and analysis of liquid motions in response to axial accelerations.

b) An analysis of the liquid response to axisymmetric structural vibrations of a propellant tank.

c) An experimental investigation of the reorientation flow or response to an axial acceleration in clean tanks and in a baffled tank. This investigation also included an examination of the effect of an impulsive acceleration.

d) An experiment to examine the geysering or rebound that results from a reorientation flow.

e) An experimental investigation of ullage gas entrainment resulting from a reorientation flow.

An additional experimental study of gas bubble ingestion in the Lunar Module Reaction Control System is of particular interest, because it reveals a potential problem area of importance. Table I presents the various liquid behavior situations examined, together with brief outlines of the analyses and/or experiments performed for each.

In addition to the basic investigations required by the Study, the material developed as well as other available material was applied to the prediction of liquid behavior in:

a) The Apollo Service Propulsion System (SPS)

b) The Lunar Module Ascent and Descent Propulsion Systems

c) The SPS passive liquid retention system during an earth orbital mission in which the SPS is propelled backwards by the Lunar Module

Two special reports have also been prepared. An Engineering Handbook on Low Gravity Fluid Mechanics has been prepared as a part of this work. The purpose of the Handbook is to provide practical engineering guidance in applying available information to solution

Table I LIQUID BEHAVIOR SUBSTUDIES

LIQUID BEHAVIOR SITUATION	Analysis	Experiment
Axial Motions		
1. Large amplitude motions as in liquid settling maneuvers.	Treatment as a boundary/initial value problem. The velocity potential for inviscid, incompressible irrotational liquid motion was expanded in a Fourier series. Tank walls were considered rigid.	Drop tower test. Small scale models were employed to study early portions of the liquid reorientation phenomenon with tank diameter, fill level and g-level imposed by a pneumatic rocket varied to simulate various reorientation conditions. Baffles were installed in some models and in other cases, the reorienting acceleration on the model was terminated before the test. Later portions of the reorientation phenomenon were treated in a larger scale, 1-g, test in which the liquid was dropped in a sheet flow down the tank wall into the tank bottom. The effect of baffles was studied in selected runs. Ullage gas entrainment was studied in a steady-state experiment performed under 1-g conditions.
2. Effect of baffles on liquid reorientation motions.	A steady-state analysis employing global energy, mass, and momentum balances was employed to size the basic features expected in the flow.	
3. Motions induced by relaxation of tank structural strain energy upon thrust cutoff.	Treated as boundary/initial value problem in the same fashion as above. Here tank walls were not considered rigid. Wall motion was programmed in accordance with separate analysis performed in this task.	Not considered necessary.
Lateral Motions		
4. Large amplitude motions.	Treated as a boundary/initial value problem. Initial free surface shape or velocity may be specified. Assumptions used are similar to those used in Situation 1.	Drop tower test. Small scale models were used to study transient large amplitude sloshing motions occurring as high energy waves suddenly enter a reduced g environment. Liquid carry over in a model Apollo SPS tank was observed in several runs. Liquid forces on the tank was estimated from motion of the interface.
5. Small amplitude impulsive sloshing.	None carried out as a part of this contract.	Drop tower test. Small scale models were used to determine natural sloshing frequencies of small quantities of liquids in a hemispherically bottomed cylindrical tank. The response to laterally pulsed accelerations was also measured.
6. Damping in baffles under low-g conditions.	Liquid velocities predicted from potential flow (as if with no baffles) were used to predict the drag force on various baffle configurations. This is used to compute the rate of energy dissipation and thence the damping ratio. A method of computing damping factors for several baffles in hemispherically bottomed cylindrical tanks was developed.	Liquid-liquid analog experiments in a small model were used to assess the effect of free-surface curvature occurring in a zero g conditions.
Miscellaneous Studies		
7. Passive propellant retention system study.	Results of previous work were drawn together to assist with the design and evaluation of this type of device.	
8. Lunar Module Reaction Control bubble ingestion study.		A specific test employing Froude and Reynolds number scaling was performed to establish the likelihood of bubble ingestion by the LM RCS system.

of problems posed by low-g liquid propellant behavior; it is not intended to supplant conventional fluid mechanics texts. A complete annotated bibliography of the low-gravity fluid mechanics literature was also prepared.

RESULTS OF THE STUDY

The following is a list of findings of the basic investigations undertaken in the study. In some cases, specific examples are singled out for more detailed description. The size of the study precludes including detail in this report.

Axial Liquid Motions: Considerable improvement was gained in solution of large amplitude liquid behavior problems as initial value problems. The major analytic result of this work is that reorienting liquid accelerates down the tank wall at the value of the local acceleration level and not at a lesser rate as indicated by small scale experiments. Numerical problems still plague this work and much more effort is required to achieve complete simulation. Nevertheless, fairly good agreement is possible, as shown in Figure 1. Results of drop tower tests are compared here to analytical predictions. Although the tank bottom geometries differ, this difference is not significant for the early portions of the reorientation flow.

A criterion was developed for the minimum impulse required to reorient a portion of the liquid in a tank from one end to the other. The criterion resulting in no permanent displacement of liquid is stated in terms of a critical Weber number

$$We = \frac{\rho R (\Delta V)^2}{\sigma} < 4$$

where

R = tank radius

ΔV = tank axial velocity increment resulting from axial acceleration

σ/ρ = propellant surface tension over density ratio

The minimum conditions required to cause ullage bubble entrainment in the collecting pool of liquid during settling maneuvers were defined, and expected bubble sizes and the volume rate of gas entrainment were determined. These are:

Minimum entrainment condition;

$$We_i = \frac{U_i t_l \rho}{\sigma} = 0.5 \frac{U_l t_l \rho}{\mu} = 0.5 \text{ Re}$$

Minimum bubble diameter;

$$\frac{D_{min} U_l^2}{\sigma/\rho} = 15.9 \ \frac{\rho}{\rho'}^{\,1/3}$$

Maximum bubble diameter;

$$\frac{D_{max} U_l^2}{\sigma/\rho} = 15.9 \ \frac{\rho}{\rho'}^{\,1/3}$$

Entrained gas volume;

$$\frac{P'}{Q'} = 0.0009 \ Fr = 0.0009 \ \frac{(U_l - U_i)^2}{2 g t_l}$$

where $U_i, U_l, t_l, \rho, \sigma, \mu, \rho'$ are minimum entrainment wall sheet velocity, liquid density, surface tension, and viscosity, and ullage gas density.

The liquid jet rebounding toward the opposite end of the tank was determined to travel 60-80% of the available distance when the reorientation Bond number $B_R \sim 3000$. The diameter of this jet was determined to be 0.3 to 0.4 times the tank diameter.

Reorientation patterns to be expected in baffled tanks during liquid settling maneuvers were established. It is shown that the flow pattern depends heavily on baffle configuration; baffles, under certain circumstances, will cause the flow to pulsate during early stages.

The relaxation of tank structural strain energy following thrust cutoff was found not to cause large free-surface displacements. This result stems from the relatively long thrust decay transient normally experienced compared to the normally high tank wall oscillation frequencies, even when loaded with liquids.

Lateral Liquid Motions: Valuable analytical background was gained in treating this situation as an initial value problem. Qualitative agreement with experiments was obtained. A means for predicting tank-liquid force interaction was found based on experimental measurements of large amplitude liquid motions.

Other analyses of the first normal modes sloshing frequency of a liquid were verified to a reasonable extent by experiment. A comparison of drop tower test results and theoretical predictions is shown in Figure 2. The agreement between theory and experimental results is adequate. Differences are explained by the reduction of effective tank radius resulting from a viscous boundary layer on the tank wall and the further effect of viscosity in producing an effect resembling dynamic contact angle "hysteresis" which is known to increase natural frequencies. The damping afforded by baffles under low-g conditions was determined by analysis. Separate experiments to assess the importance of liquid free-surface curvature were performed. Major findings include the facts that the damping ratio of a given baffle is not materially changed by operation in low-g. The time to damp is very long and is only slightly reduced by a side effect of the baffle which actually results in an increase in sloshing frequency and thus shorter damping times, but still long compared to high-g damping times.

The study in drop tower experiments of large amplitude asymmetric motions indicates that the height of the wall wave after engine shutdown (if this occurs when the liquid has maximum kinetic energy) may be adequately expressed by

$$\frac{h_{\text{max after}}}{h_{\text{max before}}} = \sqrt{\frac{g_{\text{after}}}{g_{\text{before}}}}$$

where "after" and "before" refer to pre and post thrust reduction conditions. The force imposed by a high energy wave moving up the side of a tank of infinite length after thrust cutoff was estimated to be

$$F_{x_{\text{max}}} = \frac{4M\dot{x}_o^2}{2eR}$$

where m, $\dot{x}_o$, R, and e are the total mass of the liquid, the lateral velocity of liquid center of mass, the tank radius, and the transcendental number (e).

Miscellaneous Studies: The design procedures for passive liquid retention devices were collected after extensive review. The results of another experiment show that a high probability exists of ingesting ullage gas in LM RCS feedlines should the Ascent Propulsion System feed lines contain gas.

APPLICATION OF STUDY RESULTS TO THE APOLLO MISSION

A complete analysis of typical Apollo mission maneuver requirements was made for the Spacecraft Propulsion System, the Lunar Module Descent System, and the LM Ascent System. In addition, all possible failure modes of the SPS propellant retention system were investigated in the light of study results, with special emphasis on the AS503A earth orbital mission, in which the Service Propulsion System is accelerated backwards by the LM.

Except when the SPS is driven backwards no serious problems are apparent. In this case, the present retention system will not contain against the high resulting acceleration and a portion of its contents will be emptied. Prolonged SPS engine operation would be required to refill the system; thus gas ingestion into the engine can occur. Slosh wave response and lateral forces occurring during SPS firing were not computed since they obviously should ordinarily be within the capability of the spacecraft control system.

When considering sloshing with main engine firing for both the LM/DPS and LM/APS, slosh amplitudes less than 0.1 of the tank radius can be expected from the roll, pitch, and yaw perturbations programmed into the flight. For ring baffled tanks, this sloshing will be well damped as the liquid level approaches a baffle. If the tanks are not baffled, then a sloshing mode will persist for minutes of time, and will only be slowly damped due to viscous and geometry interactions with the tank walls. The period of sloshing in the LM tanks range from 1.3 to 6.5 seconds during main engine thrust in this study.

The amplitude of sloshing expected (0.1 tank radius) while searching for a lunar landing spot should cause no problems because of the large expected minimum fill level of 0.4 tank radius. Thus no gas injection during pre-touchdown hovering should occur.

Estimates of propellant reorientation and oscillation times were made for the propellants after main engine shutdown in a low Bond number, near zero gravity environment. Also, during the LM/CSM docking, a rough estimate of the forces induced by the propellants on the tops of the LM ascent tanks was made. These forces are estimated to be as high as 60 pounds for the oxidizer tank.

STUDY LIMITATIONS

Two major limitations became more apparent. First, analytical techniques for more extensive liquid behavior simulation require additional development. Sophisticated numerical techniques provide valuable information, but the methods presently available lead to early numerical instabilities and abbreviated simulations. Second, experimental techniques and facilities (even those now in construction or projected) cannot provide adequate experiment time for careful study of any but relatively simple liquid behavior phenomena.

Also, the late development of general information from the study delayed its application to prediction of liquid propellant behavior during typical Apollo Missions. This necessary, but unfortunate, scheduling difficulty prevented truly extensive application of the basic study results.

IMPLICATIONS FOR RESEARCH

A common finding of several investigations in this study is evident; viscosity affects liquid behavior in unexpected ways. An example of this is the apparent dynamic contact angle hysteresis effect discussed on Page 7. Greater emphasis must be placed on the investigation of the importance of viscous boundary layers to liquid behavior.

SUGGESTED ADDITIONAL EFFORT

Need for additional work in the following specific areas is apparent at the close of the present study.

- Numerical techniques for extensive simulation of liquid behavior as initial value problems still require considerable effort.
- Those best qualified for this type of analytical work should be encouraged to continue. The continued lack of truly adequate low-g experimental facilities increases the importance of analysis and the present need for its improvement.
- Additional time specifically for the analysis of liquid propellant behavior during Apollo mission should be allotted. This would make possible more effective use of general results of this study than was even possible within the framework of the present study.

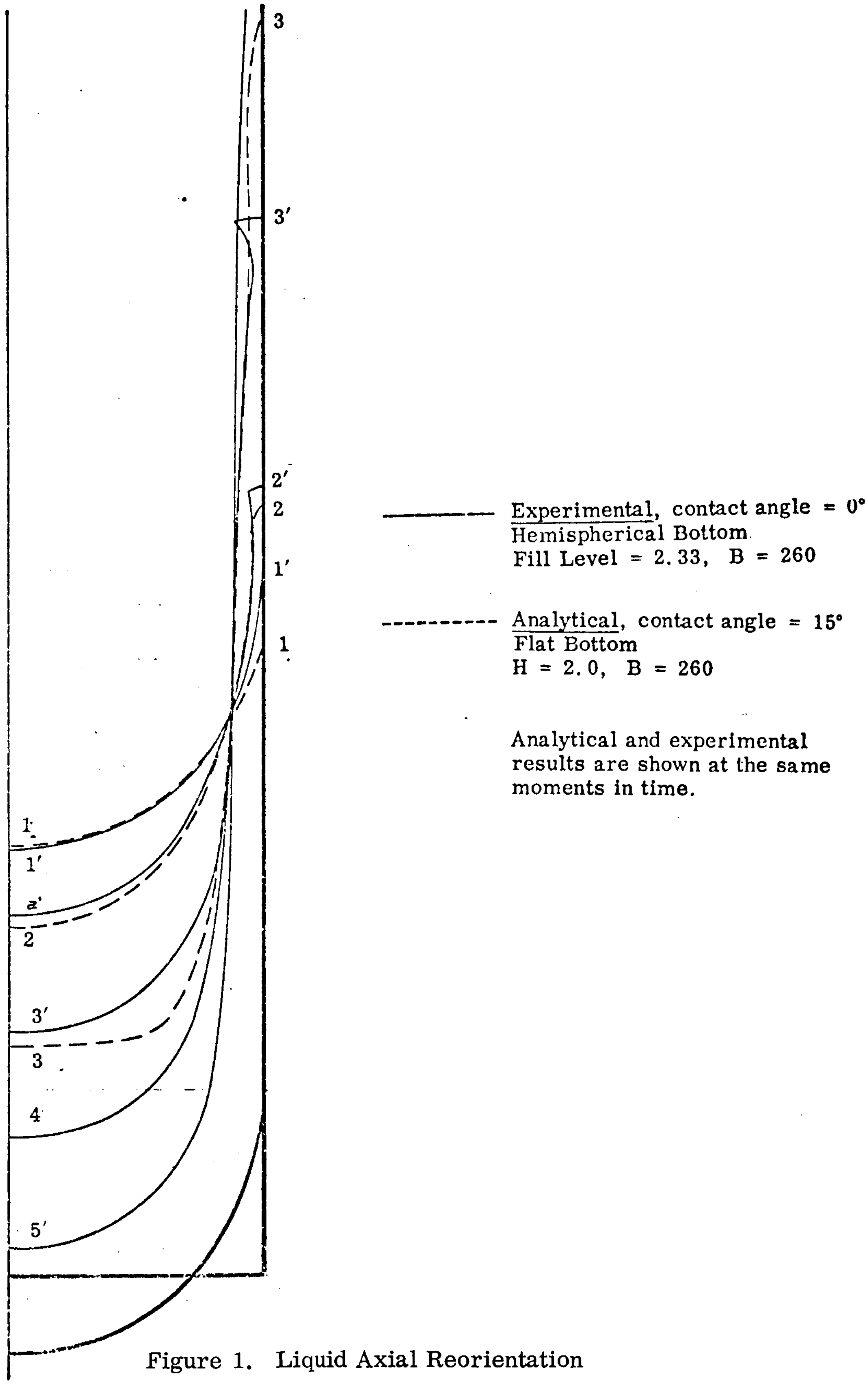

Figure 1. Liquid Axial Reorientation

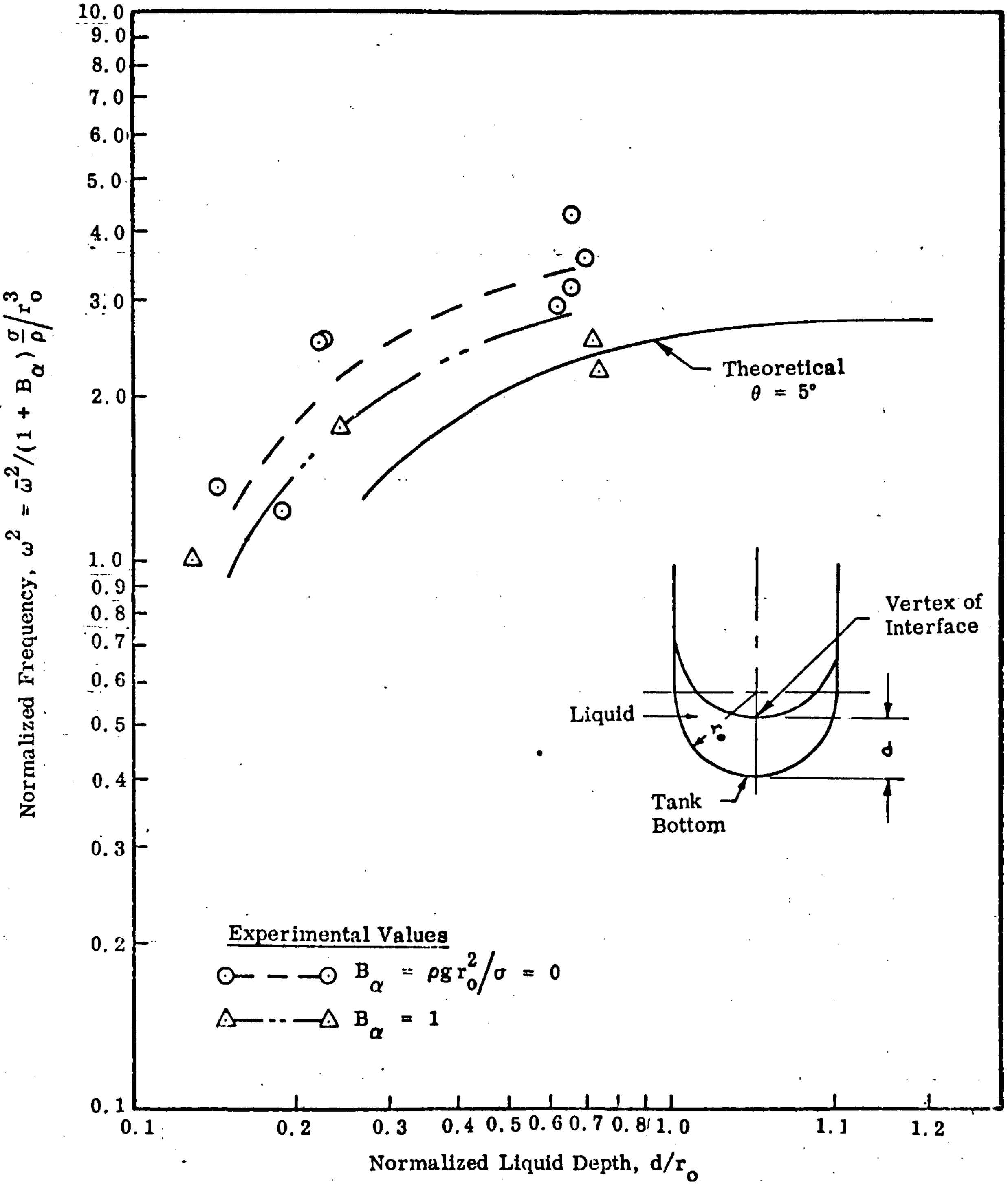

Figure 2. Comparison — Experimental and Theoretical Frequencies