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THE COUPLED DYNAMICS OF FLUIDS AND SPACECRAFT IN LOW GRAVITY

AND

LOW GRAVITY FLUID MEASUREMENT

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The very large mass fraction of liquids stored on board current and future generation spacecraft has made critical the technologies of describing the fluid–spacecraft dynamics and measuring or gauging the fluid. Combined efforts in these areas are described, and preliminary results are presented.

The coupled dynamics of fluids and spacecraft in low gravity study is characterizing the parametric behavior of fluid–spacecraft systems in which interaction between the fluid and spacecraft dynamics is encountered. Particular emphasis is given to the importance of nonlinear fluid free surface phenomena to the coupled dynamics.

An experimental apparatus has been developed for demonstrating a coupled fluid–spacecraft system. In these experiments, slosh force signals are fed back to a model tank actuator through a tunable analog second order integration circuit. In this manner, the tank motion is coupled to the resulting slosh force. Results are being obtained in 1-g and in low–g (on the NASA KC–135) using dynamic systems nondimensionally identical except for the Bond numbers.

The low gravity fluid measurement study is developing a radio frequency measurement technique, an inductive gauging technique, and an ultrasonic point measurement method. The radio frequency gauging technique measures the total fluid volume inside a tank by measuring the dissipation of electromagnetic waves within the fluid. The inductive gauging technique measures the total inductance of the fluid inside the tank which depends only on the volume of fluid contained. The ultrasonic point measurement technique measures total local fluid free surface height through the return time of a reflected ultrasonic wave.

INTRODUCTION

Many current and future spacecraft designs require that large volumes of fluids be carried for long periods in low gravity for

- Propellant resupply
- Spacecraft attitude control
- Orbital maneuvers

Two critical technologies being studied include

- The interactive or coupled dynamics between the stored fluid and the spacecraft motion
- High accuracy measurement and gauging techniques for observing the amount, orientation, and quality of the fluid

The research effort includes complimentary experimental and analytical programs consisting of

- An apparatus for studying a couple fluid–spacecraft dynamic system
- Unique measurement and gauging hardware

COUPLED DYNAMICS OF FLUIDS AND SPACECRAFT

Problem Motivation

- Large mass fractions of stored liquids on board spacecraft in low gravity (>50% liquid)
- Controller bandwidths which include many fluid slosh modes
- Low frequency spacecraft modes such as flexible and libration modes

Research Features

- Provides experimental investigation of fluid–spacecraft coupling
- Imposes a coupled system by matching masses and frequencies
- Uses a generic model tank and a simple type of spacecraft motion (cylinder and 1–DOF lateral spacecraft mode)
- Studies large amplitude responses
- Includes a broad parametric space
- Studies Bond number, viscosity scaling and contact angle hysteresis effects

Problem of Interest

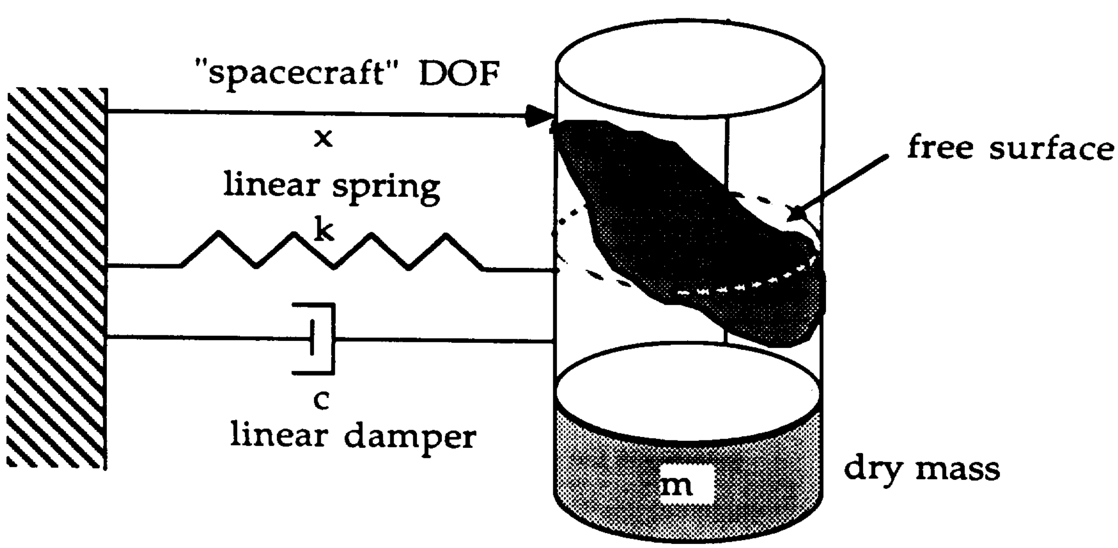


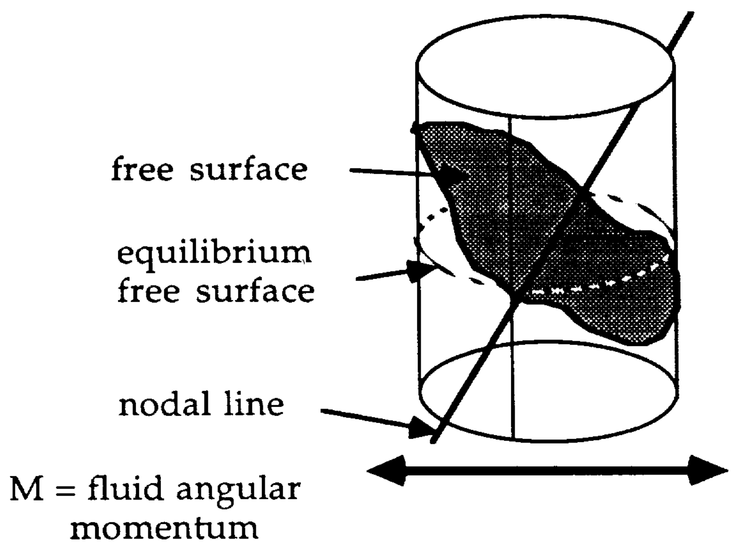
Figure 1

Nonlinear Effects in Fluid Slosh

An interactive or coupled system can result in large amplitude fluid slosh motion. Even small amplitudes of excitation near a slosh resonance can lead to nonlinear fluid slosh effects.

Nonlinear fluid slosh can lead to nonlinear effects in the spacecraft dynamics. Understanding these effects is important in determining the actual motion of the coupled system.

Four Possible Nonlinear Fluid Slosh Modes



M=0	1. planar harmonic (stationary nodal line)
M>0	2. nonplanar harmonic (rotating nodal line)
	3. limit cycle (swirl)
	4. chaotic (deterministic nonperiodic motion)

Which motion is excited depends upon the frequency of the excitation, the amplitude of the excitation, the amount of damping, and the initial conditions.

Figure 2

Overview of Experimental Effort

An apparatus has been developed which imposes in a controlled fashion coupling between the slosh with a model tank and a lateral spacecraft mode.

- Lateral slosh forces measured by a sensitive reaction balance
- Tank moved laterally by an electromagnetic shaker/servo
- Slosh force signal fed back to the shaker through a second order analog spacecraft mode circuit, thus coupling the slosh to the motion of the tank

The spacecraft mode circuit can be tuned to simulate a wide range of coupled systems. Spacecraft modal mass, frequency, and damping can be adjusted independently.

Block Diagram of the Closed Loop Slosh Coupling System

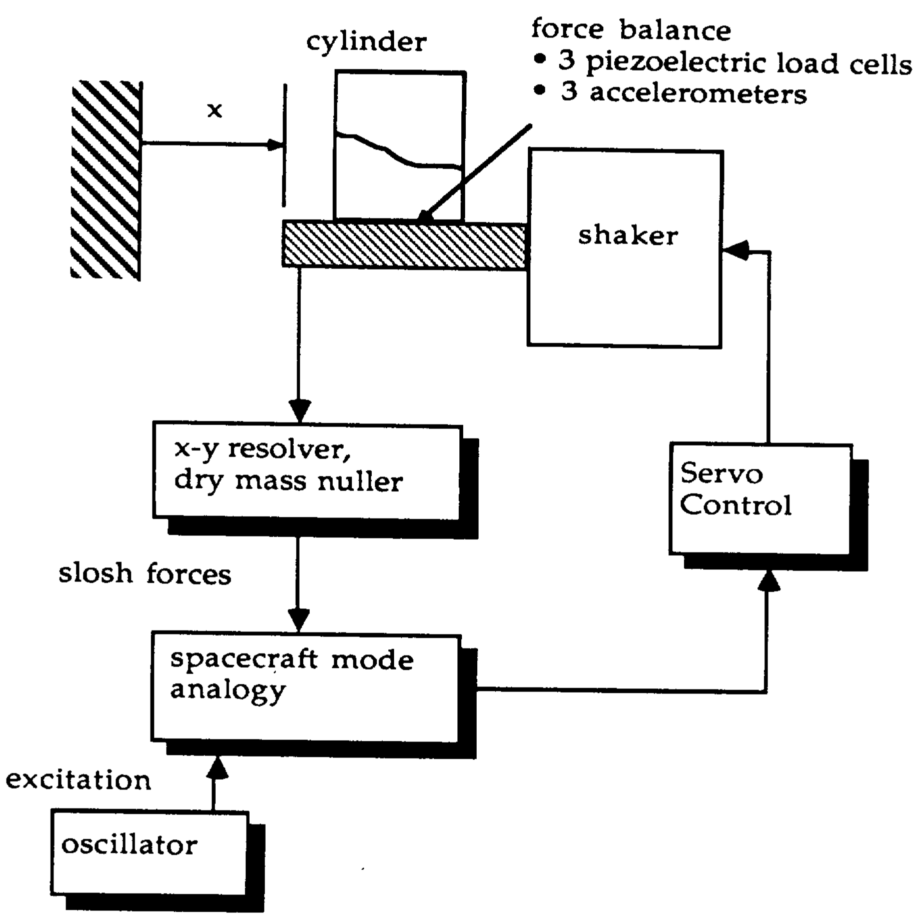


Figure 3

The response of the system is measured by the following quantities

- Slosh force
- Free surface motion
- Spacecraft mode amplitude (tank displacement)

The experiment varies the following nondimensional variables

- Bond number
- Mass ratio (fluid mass / spacecraft mass)
- Natural frequency ratio (fundamental slosh frequency / spacecraft modal frequency)
- Spacecraft modal damping rate

The Bond number is changed keeping the viscous scaling parameters constant by using the same diameter tank in

- 1–g capillary scaled experiments
- 0–g KC-135 experiments

In both cases, the large amplitude slosh of the fluid when not coupled to the spacecraft mode is also examined.

1-g Test Results

For the 1-g laboratory tests, a coupled system is studied using a steady harmonic excitation.

- Excitation frequency varied from below the fluid resonance to above the spacecraft mode resonance
- Excitation amplitude varied by a factor of 1 through 10 and the frequency sweep is repeated
- The response at resonance is plotted as a function of excitation amplitude
- Nonlinear effects are observed, as shown in Figure 4

Typical 1-g Results: Amplitude at Resonance as a Function of Input Amplitude

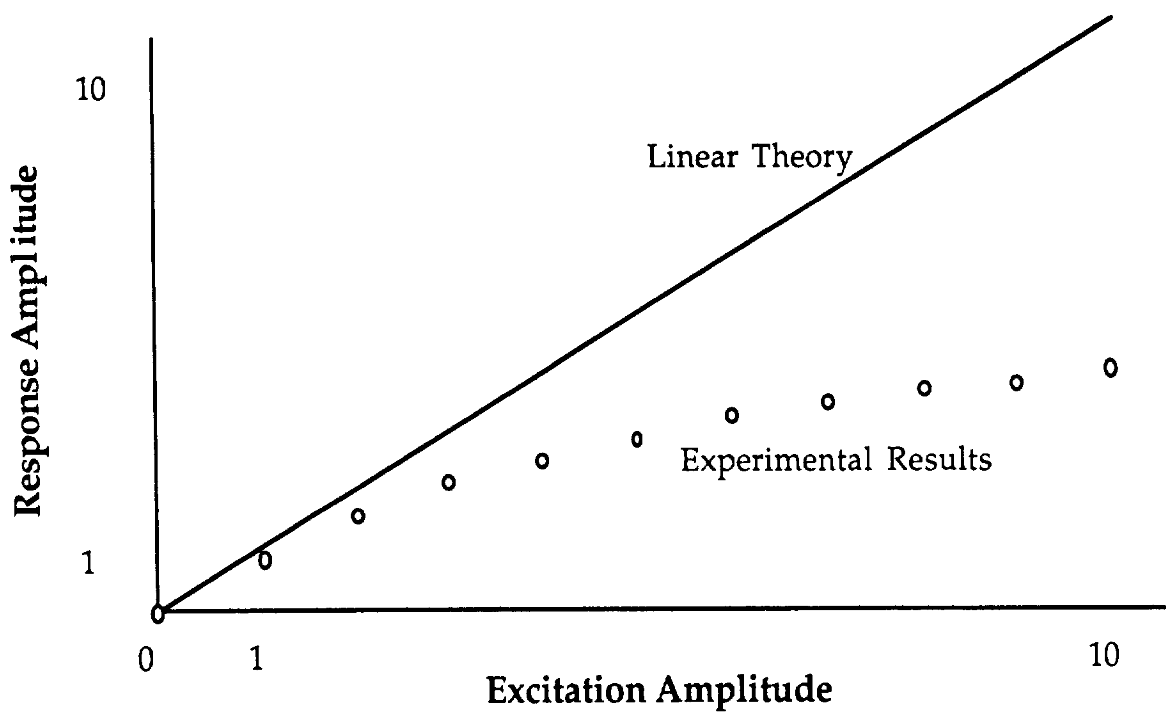


Figure 4

0–g KC–135 Tests

- Flown over 200 parabolas
- Use same diameter tank as in 1–g tests
- Isolates gravity effects

Issues

- Critical Bond number free surface instabilities
- Effects of small g level perturbations (0.03 gees rms typical)
- Data collected per parabola

Approach #1: Frequency Sweeps as in 1-g Tests

- Long time constant g level variations affect FFT output due to slosh natural frequency variation with g level
- Observe much higher fluid slosh damping than in 1–g

Approach #2: Pulse Ringdowns

- Pulse at various amplitudes and observe free decay
- Pulse 3 times per parabola and 1 time during 1.7 gee pullup
- Repeat tests for 2 parabolas to test repeatability
- Post flight data processing involves sophisticated ringdown system identification algorithms

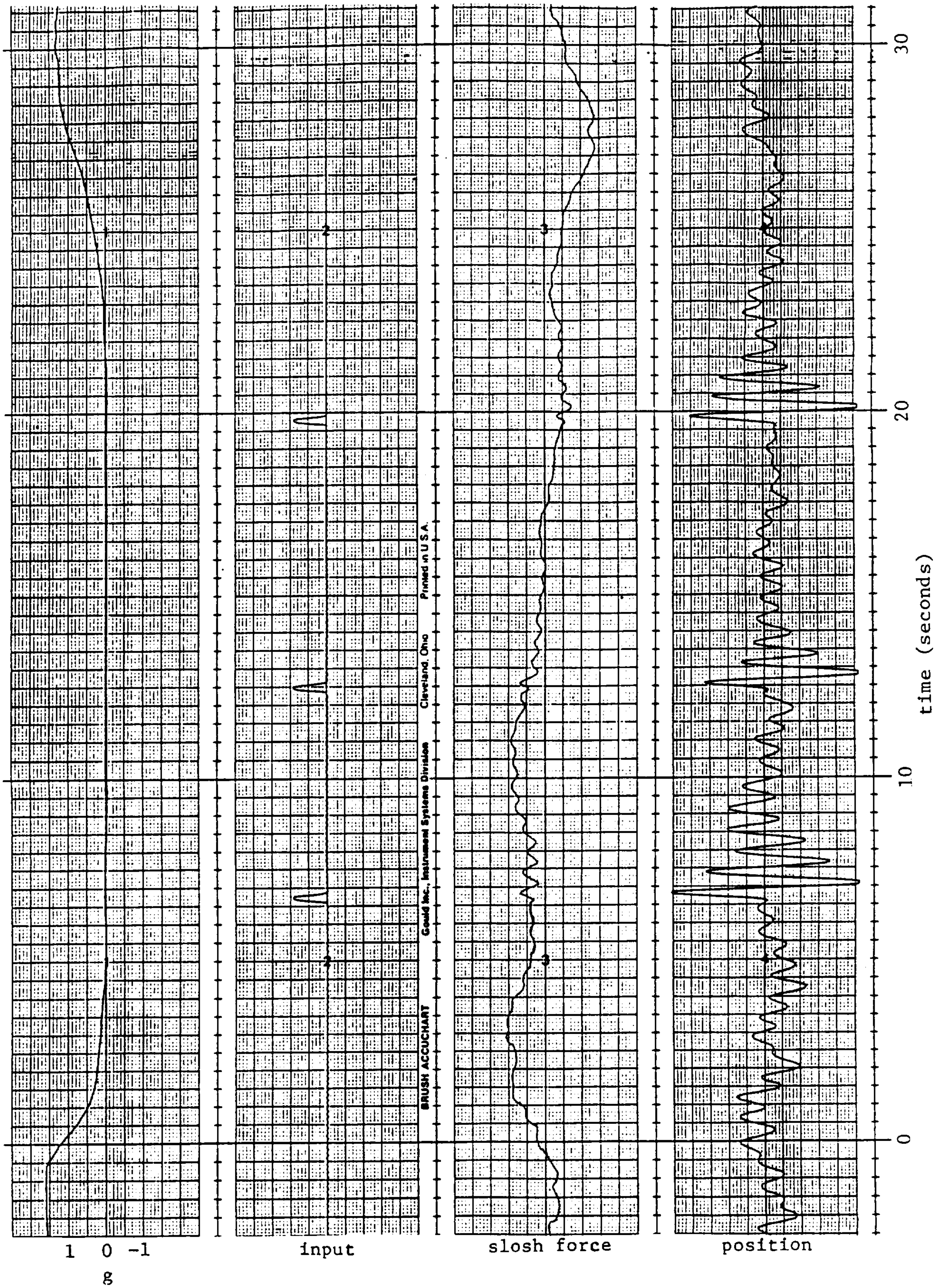


Figure 5 Typical Parabolic Flight Data

Preliminary Comparison of 1-g and 0-g Results

Uncoupled Large Amplitude Slosh Results

- Changing the Bond number to near 0 greatly increases fluid damping
- Moderate Bond number (1-g): See many nonlinear effects
  - Bi-stable modes
  - Periodically modulated slosh
  - Rotary slosh
  - Chaos
- Low Bond number (0-g): See fewer nonlinear effects due to increased damping
  - Increasing equivalent damping with excitation amplitude
  - Other effects suppressed

Coupled System Test Results

- Moderate Bond number (1-g)
  - Good degree of coupling
  - Amplitude dependence
  - Higher harmonics
  - Rotary slosh suppressed due to coupling
- Low Bond number (0-g)
  - Fluid is well behaved and is an efficient damper
  - Less coupling (due to less slosh mass?)
  - More mass ratio dependent than frequency ratio dependent in the ranges investigated so far
  - See simple nonlinear behavior

LOW GRAVITY FLUID MEASUREMENT

Measure

- Quantity
- Flow
- Position
- Quality

Fluids

- Storable propellants
- Cryogenics (O_2, H_2, He)
- Water
- Coolant
- Solar dynamic working fluids

Gauging Approaches under Development

- Radio frequency absorption
- Ultrasonic point measurement
- Inductive

Low Gravity Fluid Measurement Considerations

Low-g

- Ambiguous orientation
- Ambiguous density (trapped bubbles)
- Capillary effects

Cryogenics

- Low temp operation
- Phase change

Environment

- Radiation
- Vacuum
- Vibration/acceleration
- Chemical

Operational Constraints

- Safety
- Weight
- Size
- Size
- Complexity/Reliability
- Cost

Radio Frequency Gauging

Fluid quantity is measured by the dissipation of electromagnetic waves inside of the tank due to absorption by the fluid

- $Q = \dfrac{\text{Energy Stored in Tank}}{\text{Power Dissipated in Tank}}$

- Q can be related to fluid quantity

- $Q = \dfrac{\text{Resonant Frequency}}{\text{Full Width at Half Maximum of Resonance}}$

- Q can be measured by resonance width techniques

- If the electric field strength is uniform within the cavity (TEM modes) then the measurement is insensitive to fluid orientation

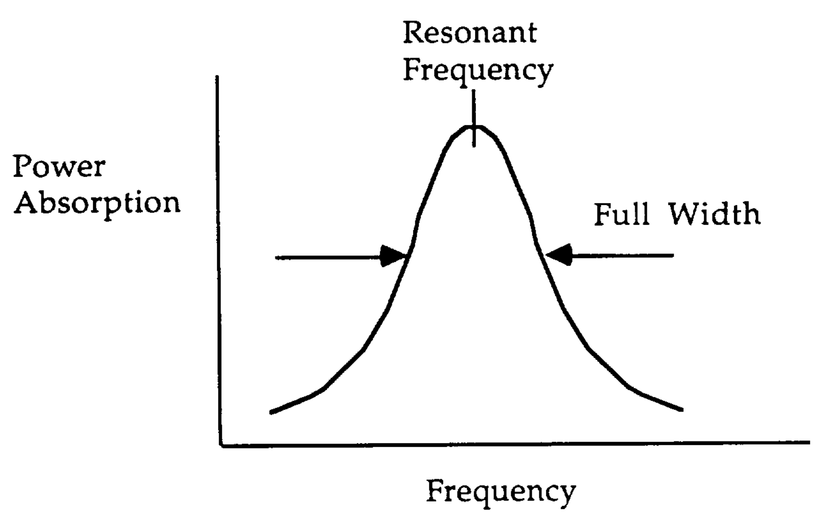


Figure 6

Schematic of Typical Resonance Width Gauging Set Up

Power is transmitted from an oscillator into the tank at various frequencies. On resonance, the power passes into the tank. Off resonance, the power passes back towards the oscillator. By monitoring the reflected power (voltage standing wave ratio) as a function of frequency, the quality factor Q may be inferred. Q can be related to the fluid quantity.

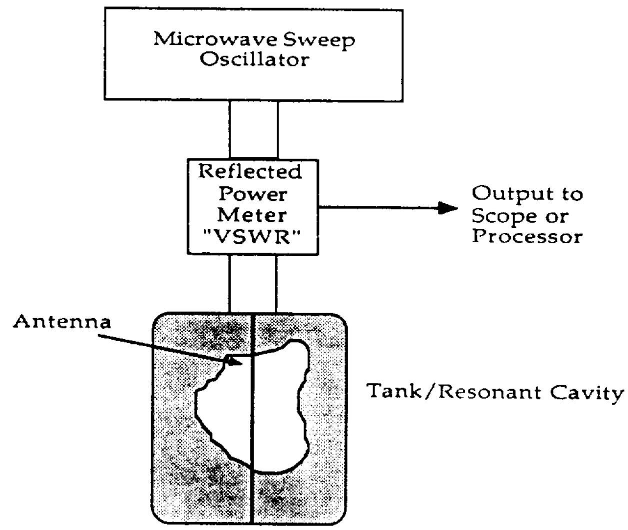


Figure 7

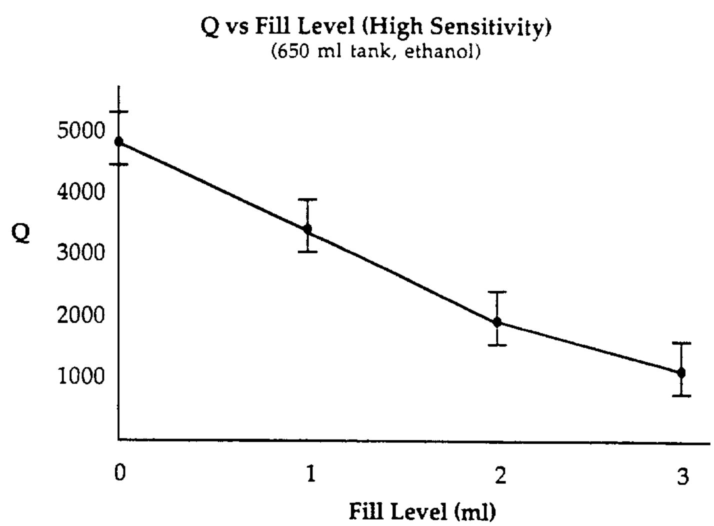


Figure 8

Q vs Fill Level (Low Sensitivity)
(650 ml tank, ethanol)

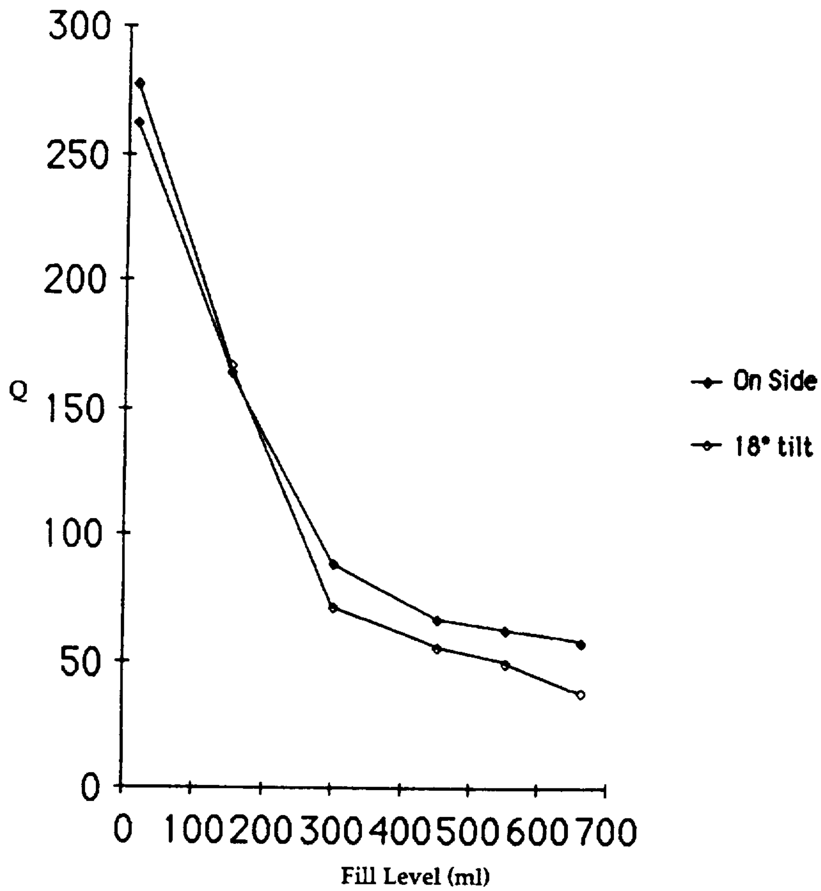


Figure 9

Ultrasonic Point Measurement

- Individual transducers measure thickness of fluid at specific points by line of sight techniques
- Transducers may be external to tank
- Requires "benign" fluid orientation for quantity gauging
- Potential applications

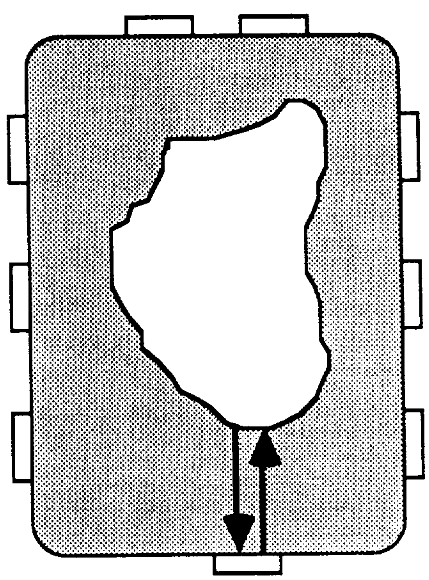
    Intermediate Bond numbers

    Specific geometries (eg. screen wall gap)

    Quality monitoring in pipes

    Slosh frequency identification

- Has been demonstrated in KC–135 tests by MIT and by MacDonald–Douglas



Ultrasonic Transducer

Figure 10

Free Surface Slosh Behavior of a Cylindrical Tank as Measured by the Ultrasonic Ranging Technique

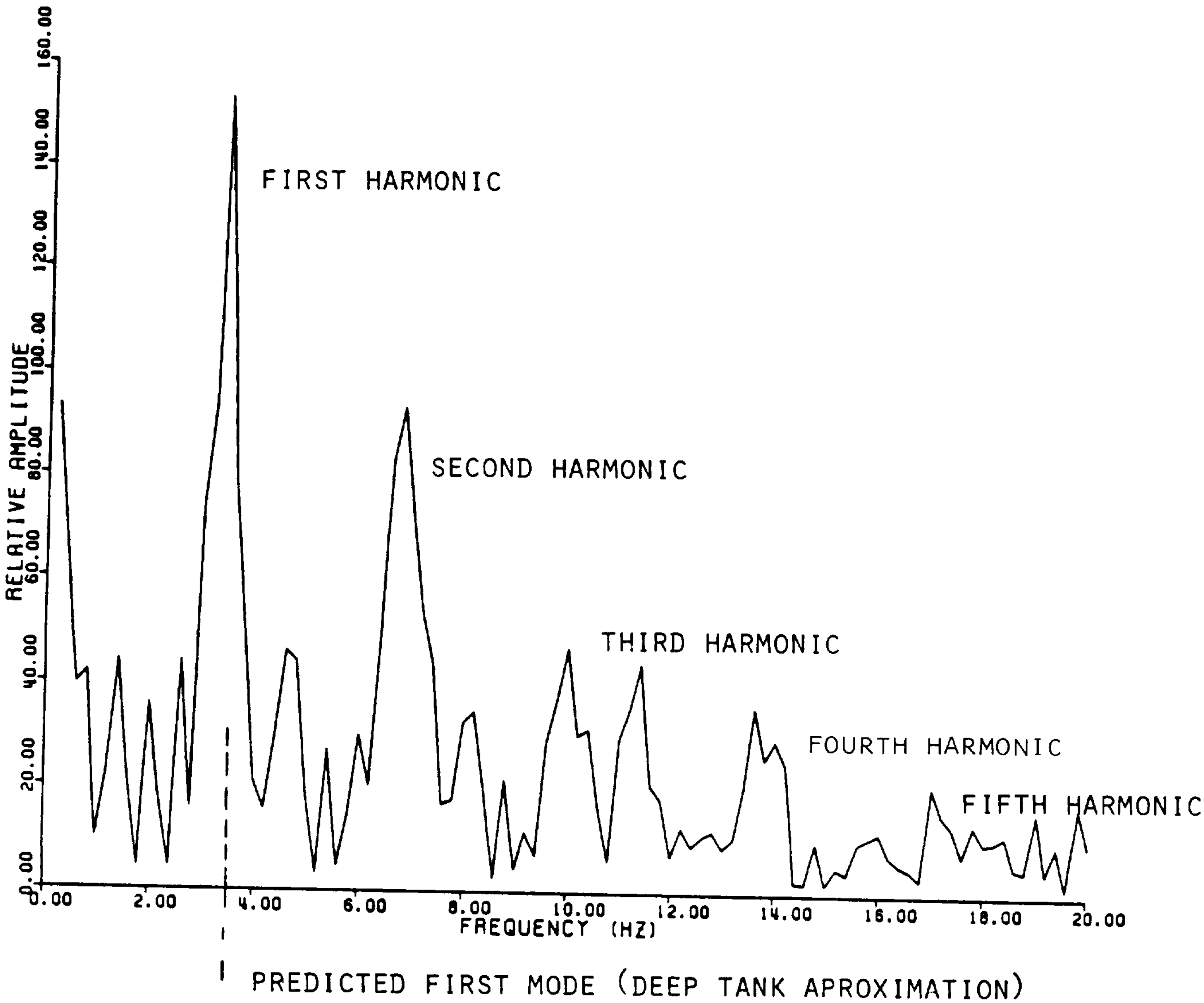


Figure 11

Inductive Gauging

- The magnetic inductance of a partially filled tank will depend on the quantity of high magnetic susceptibility fluid within the tank
- Liquid Oxygen has a high magnetic susceptibility
- The inductance can be measured by a coil which is external to the tank and can integrate over the entire tank volume
- Inductance and accuracy will increase with tank size
- In simple geometries the method is analytically <u>insensitive to fluid orientation</u>
- Preliminary experimental evaluation is underway

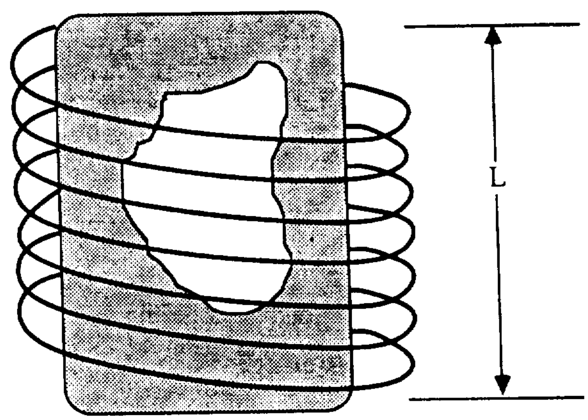


Figure 12

SUMMARY

Studying two critical technologies to large volume fluid management

- The interactive or coupled dynamics between the stored fluid and the spacecraft motion
- High accuracy measurement and gauging techniques for observing the amount, orientation, and quality of the fluid

Have developed

- An apparatus for studying a coupled fluid–spacecraft dynamic system
- Unique measurement and gauging hardware