MIT
Space
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Center

MIDDECK 0-GRAVITY DYNAMICS EXPERIMENT (MODE)

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MIT Space Engineering Research Center
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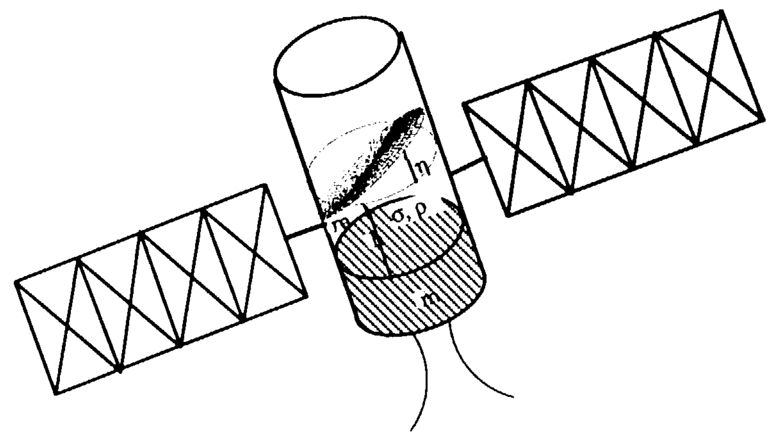

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OUTLINE

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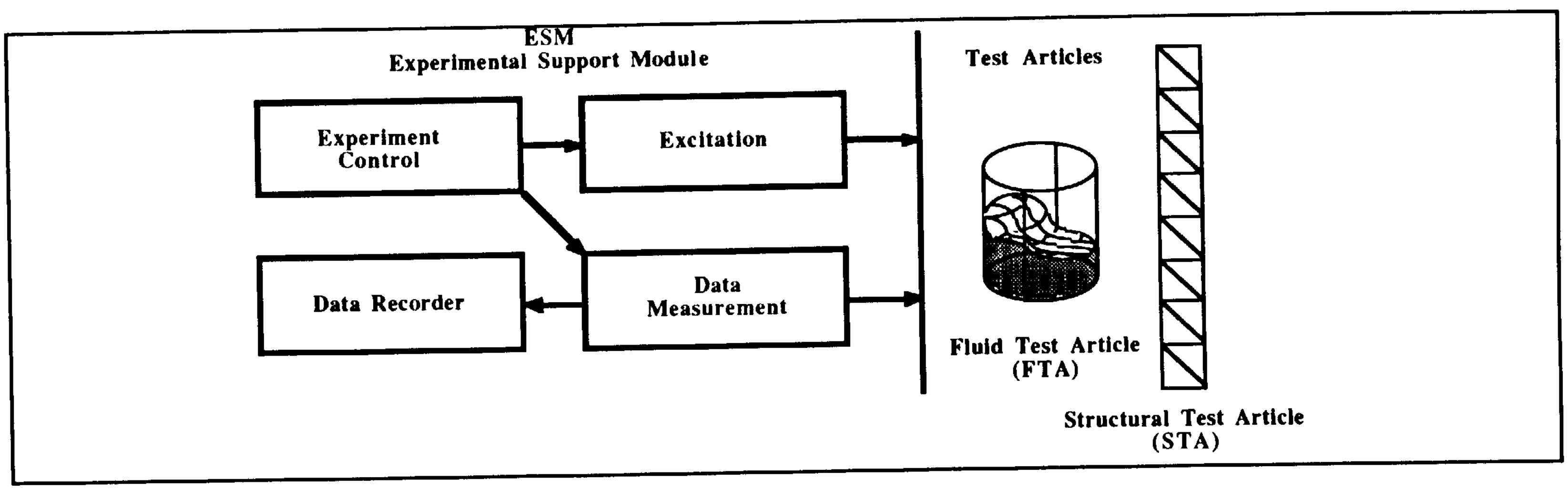
- Program Objectives
- Science Overview
  - Truss structures
  - Contained fluids
- Experimental Design
  - Structures
  - Contained Fluids
- Progress to date
  - Component Tester
  - ESM, STA and FTA
  - Schedule

MODE and its Rationale

- An experiment that investigates the nonlinear characteristics of two important components of spacecraft
  - Nonlinear dynamics of truss structures
  - Nonlinear dynamics of contained fluids



MODE

- Why investigating the dynamics of truss structures ?
    - Nonlinear dynamics of jointed space structures can alter the vibrational/acoustical characteristics of a space structure
    - This behavior is important for:
        - On-board micro-gravity experiments
        - Passive damping characteristics of “open-loop” structures
        - Closed-loop stability and performance of controlled structures
    - Little experimental data is available on how gravity effects the dynamic characteristics of jointed space structures and models are not verified

MODE and its Rationale (Continued)

- Why investigating the dynamics of contained fluids ?
  - Large fluid/spacecraft mass fractions are desirable
  - Dynamics of contained fluids in space are inherently different from their behavior in 1-g
  - The traditional "linearized or small amplitude" approach , cannot be used since

    The motion resulting from large amplitude vibrations significantly departs from the linear behavior

    Bifurcation instabilities and non-deterministic motion also exist

    Nonlinear fluid motion interacts with the spacecraft degrees-of-freedom to yield nonlinear spacecraft modal behavior
  - The existing linear/quasi-nonlinear models are inadequate and new nonlinear models are not validated for zero-gravity conditions. This leads to conservative attitude control designs for spacecraft's with on-board fluids to avoid instabilities

Program Objectives

- For space structures ?
  - To establish a database of the dynamic response behavior of structures with typical space structure-components
  - To develop a nonlinear model for the spacecraft's zero-gravity nonlinear structural resonant and transient response characteristics
  - To use the results/model to understand and model how the nonlinear characteristics will alter the spacecraft's vibration/acoustics characteristics
  - Identify the limitations of earth modal testing given the influence of gravity effects on the modal characteristics
  - Use the knowledge and models to design optimal structures and robust and optimal structural controllers.

Program Objectives (Continued)

- For the contained fluids ?
  - To obtain the “missing” data point. The measurement of the nonlinear dynamic characteristics of contained fluids in zero-gravity
  - To understand how the nonlinear fluid dynamics interact with the motion of the spacecraft
  - To use the experimental results to verify the nonlinear model developed at MIT
  - To establish a design tool with which designers can with confidence design optimal and robust attitude controllers - even for spacecraft with high fluid/spacecraft mass fractions

Science Overview (Truss Structures)

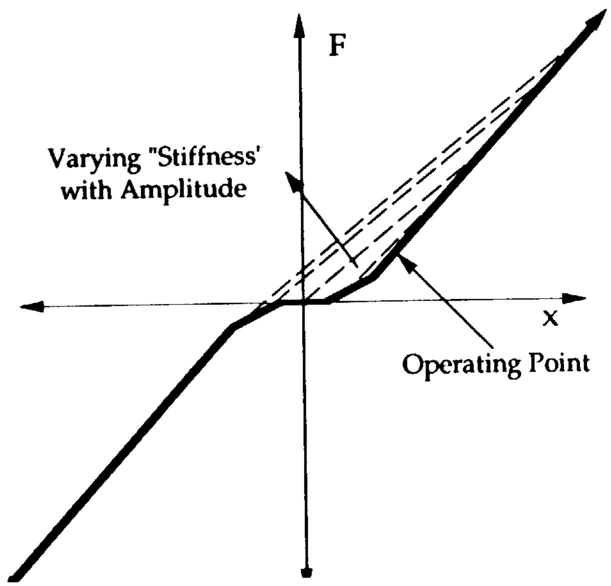
Gravity effects that alter the modal characteristics of truss structures

- Gravity loading which scales with:

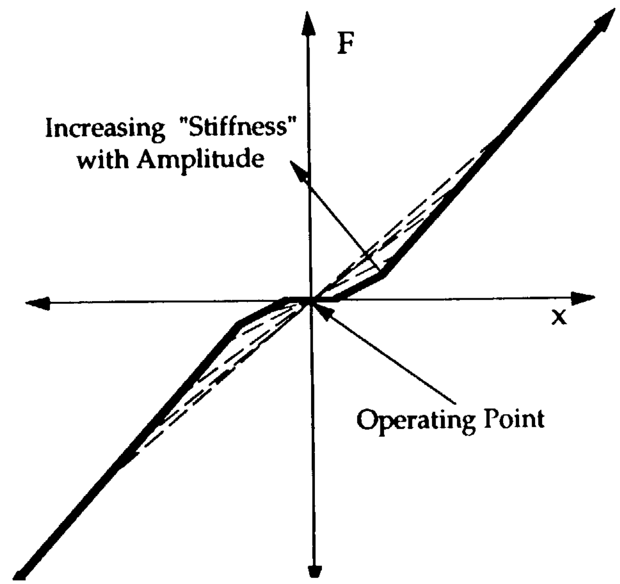
$$\frac{Gravity\,Load}{Pre-Load}$$

Nonlinear Joint

Earth



Space



Gravity alters the operating point and, therefore, the apparent stiffness and damping of joints and tensioning wire:

- Similar for tensioning wires

- Gravity field also alters the modal characteristics (frequency and mode shapes) of the structure. This effect scales with:

$$\frac{g / L_{Suspension}}{\omega^2} = \frac{\omega^2_{Pendulum}}{\omega^2_{1st}}$$

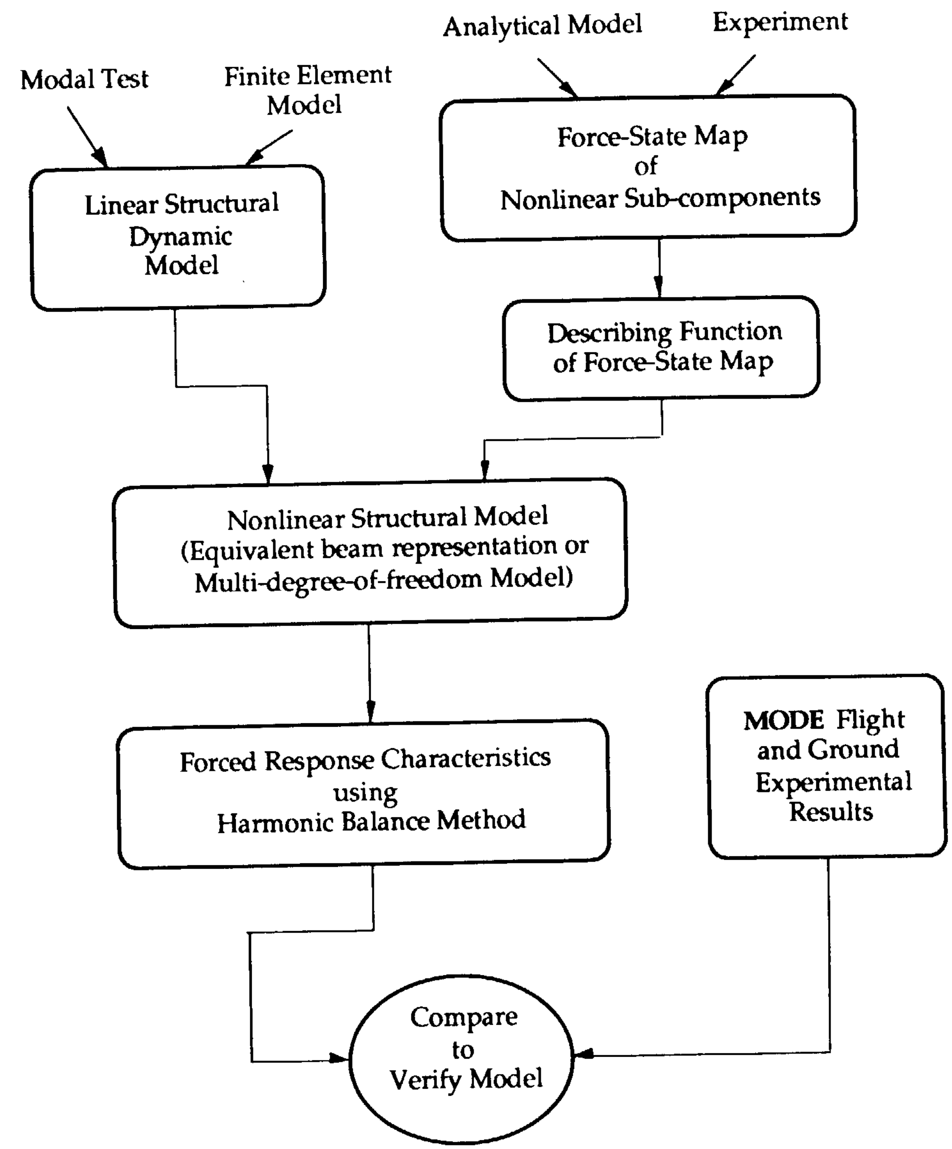
  where ω^2_{1st} is the 1 st modal frequency of interest.
  For example; significant changes in the modal characteristics are observed for a 6 foot long structure if the natural frequency is less than 1 Hz.

- Suspension of the structure changes the boundary conditions:
  - On earth, free-free boundary conditions are simulated by suspending the structure with a very flexible suspension system.
  - Effect scales with:

$$\frac{\omega_{Suspension}}{\omega_{1st}}$$

  - Need suspension frequency 1 order of magnitude lower than 1 st natural frequency of structure.
  - 0.1 Hz suspension frequency can be achieved with state-of-the-art suspension systems.

Modelling Approach

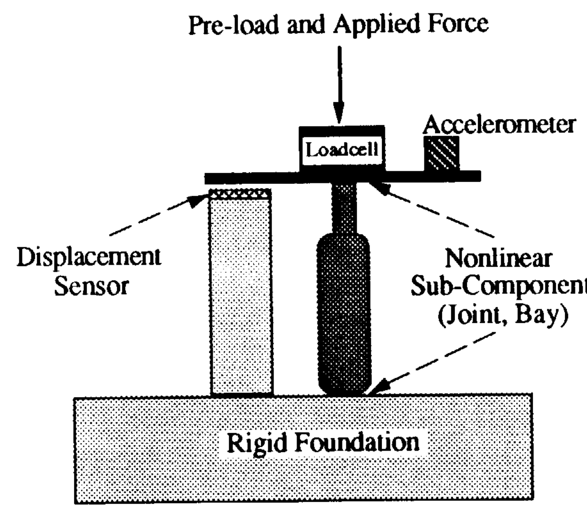


Characterization of the Nonlinear Components

- Force transmitted by a nonlinear structural component is:

$$F_t(x,\dot{x}) = F - M\ddot{x} = D(x,\dot{x})\dot{x} + K(x,\dot{x})x$$

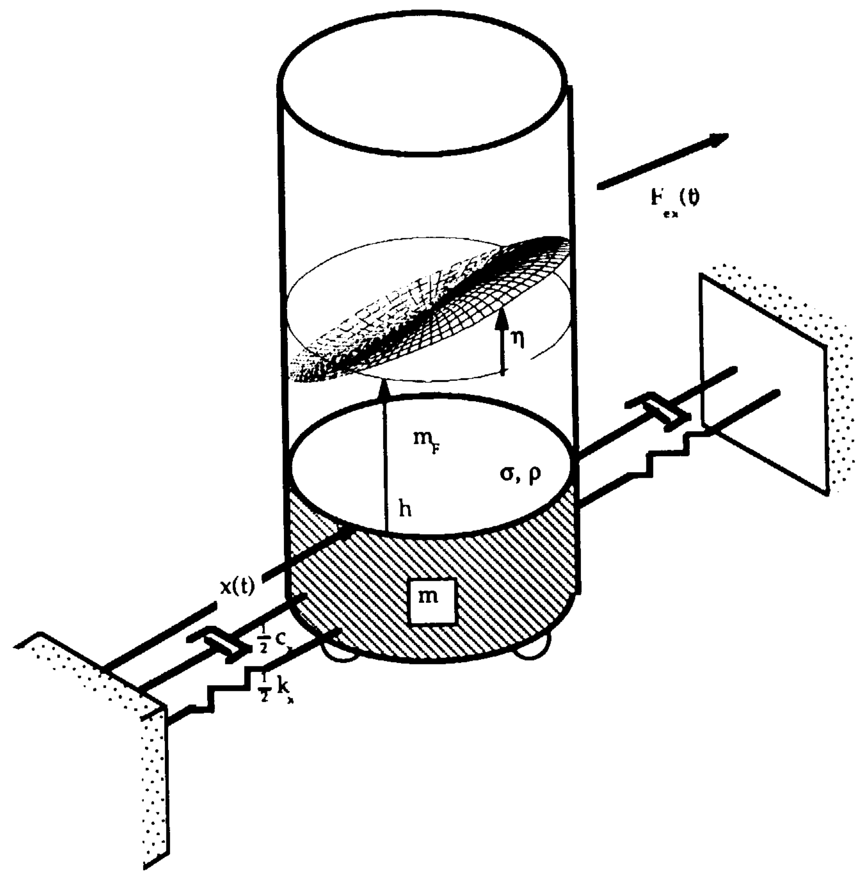
- Model requires a force-state map (Force transmitted as a function of the states of the component) of nonlinear sub-components
- Typical measurement of the force-state characteristics



Science Overview (Contained Fluids)

Major sources of nonlinearities in the dynamics of contained fluids

1 Potential energy stored in surface tension is a nonlinear function of the amplitude of motion



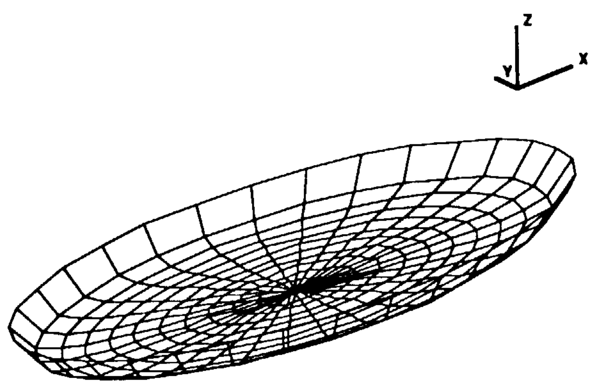
Simplified Nonplanar Model

Let $\eta(r,\theta,t) = f(r,\theta) + \eta_d(r,\theta,t)$

f is the function that describes the equilibrium free surface

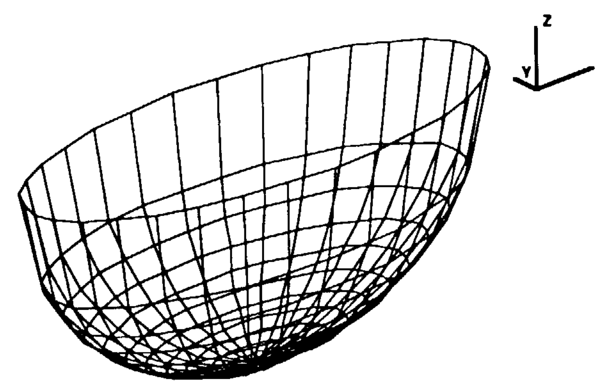
For example the equilibrium fluid shape of Silicone Oil in a 3.1 cm cylindrical tank

Silicon Oil: 1-Gravity (Earth)



Earth

Silicon Oil: 0-Gravity (Space)



Space

The surface tension potential energy is given by

$$U_\sigma = \sigma \iint_S \sqrt{1 + \nabla(f+\eta_d) \bullet \nabla(f+\eta_d)}\, dS$$

Effect scales with the Bond number $Bo = \dfrac{\rho g a^2}{\sigma}$

2 Convection forces at the free surface

$$\frac{\partial \eta}{\partial t} + \nabla\phi \bullet \nabla\eta\Big|_{z=\eta} = \frac{\partial \phi}{\partial z}\Big|_{z=\eta}$$

Dirichlet or Neumann time dependent boundary condition

"The internal fluid must follow the motion of the free surface"

- This boundary condition is also dependent on the equilibrium free surface

$$\frac{\partial \eta}{\partial t} = \frac{\partial \phi}{\partial z}\Big|_{z=\eta} - \nabla\phi \bullet \nabla(\eta_d + f)\Big|_{z=\eta}$$

- Even when linearized $\frac{\partial \eta}{\partial t} = \frac{\partial \phi}{\partial z} - \frac{\partial f}{\partial r}\frac{\partial \phi}{\partial r}$

Modelling Approach

Start out with Two Sets of Assumed Solutions:
One for Fluid Flow Potential and One for FreeSurface Motion

↓

Step 1: Use fluid boundary conditions expressed as a variational integral to obtain relationship between the two sets of generalized coordinates

↓

Step 2: Express Kinetic and Potential Energy in Terms of Generalized Coordinates

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Step 3: Formulate Coupled System Lagrangian

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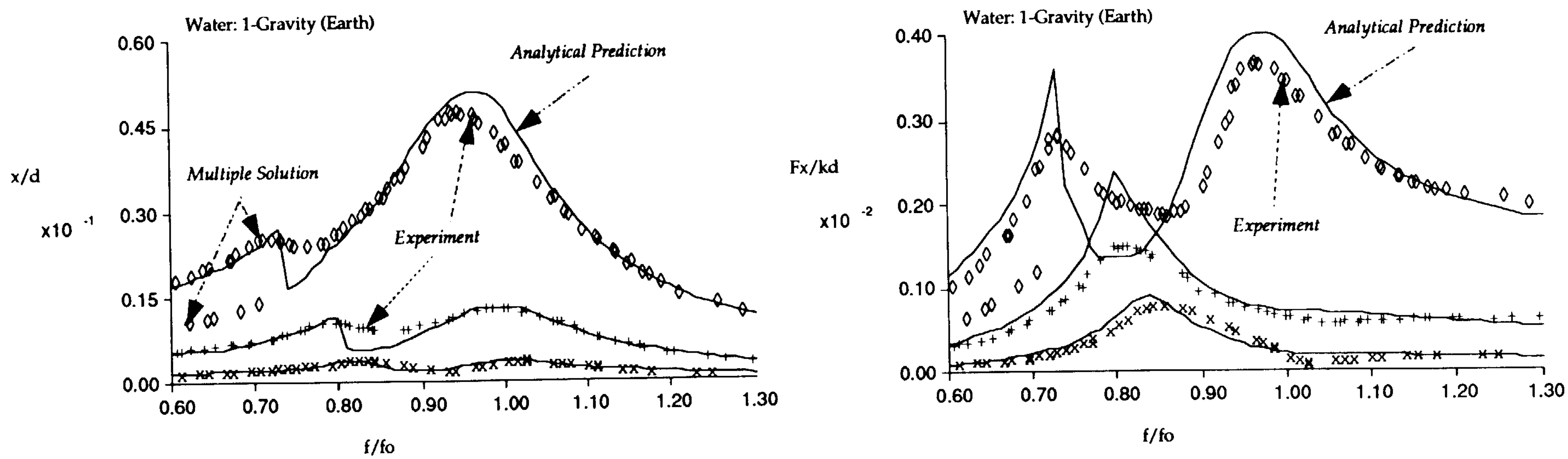
Step 4: Apply Lagrange's Principle to obtain the Governing Differential Equations

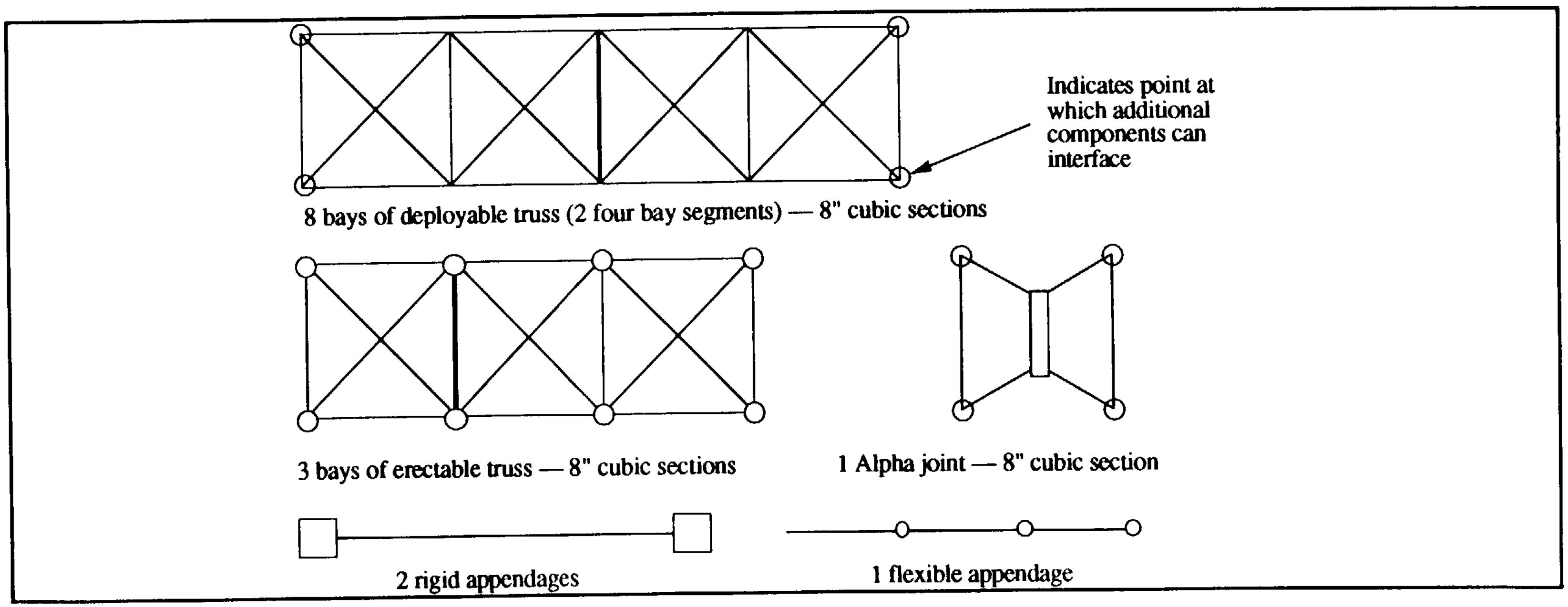
Typical Ground Test Experimental and Predicted Results

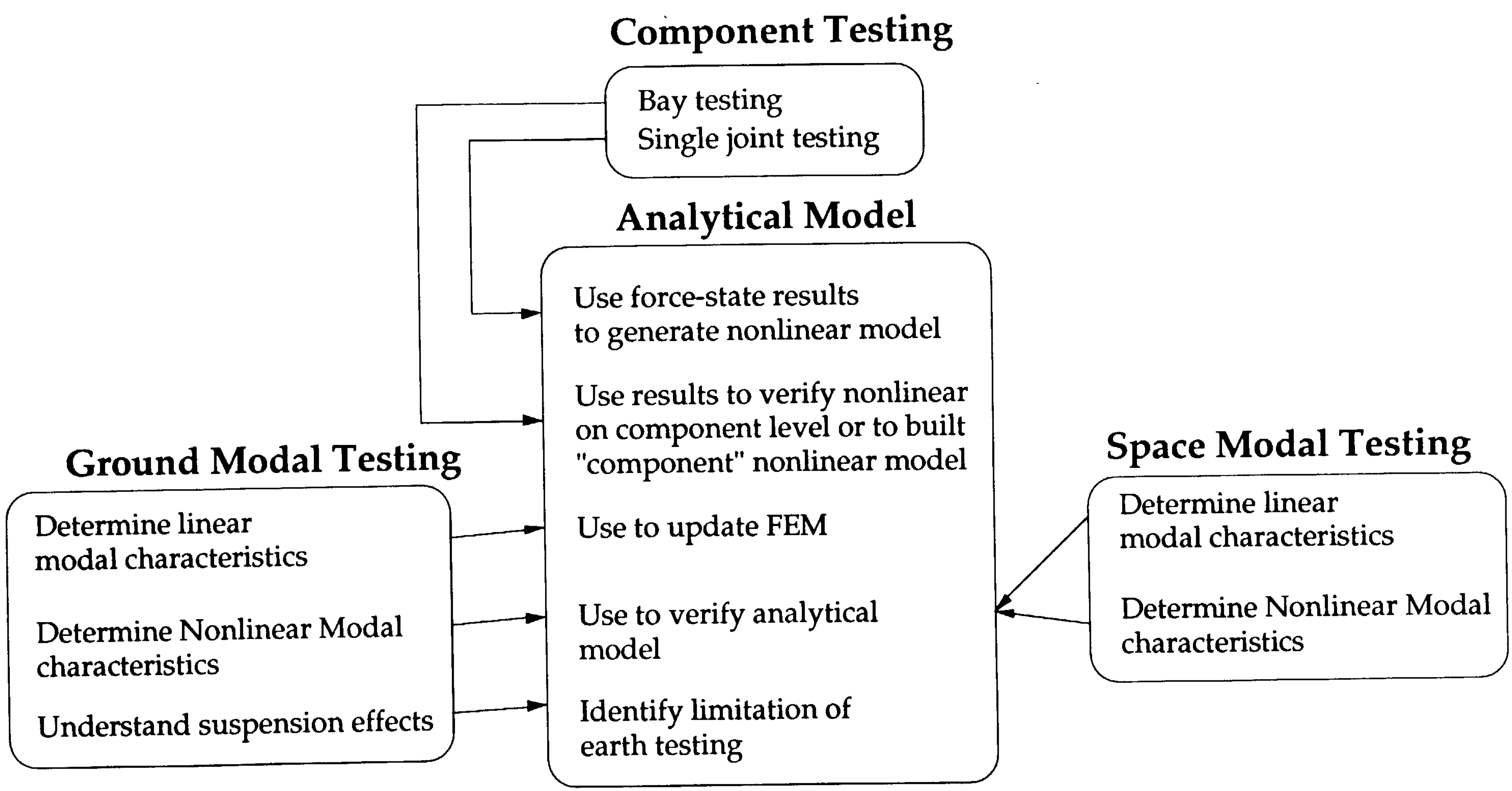


Measured and Predicted One-Gravity Results for a Cylindrical Tank with Water. Tank Diameter=3.1 cm. μ=0.16, ν=0.89, ζ=9.1%, Bo=33, fo = 7 Hz)

Experimental Design (Structures)

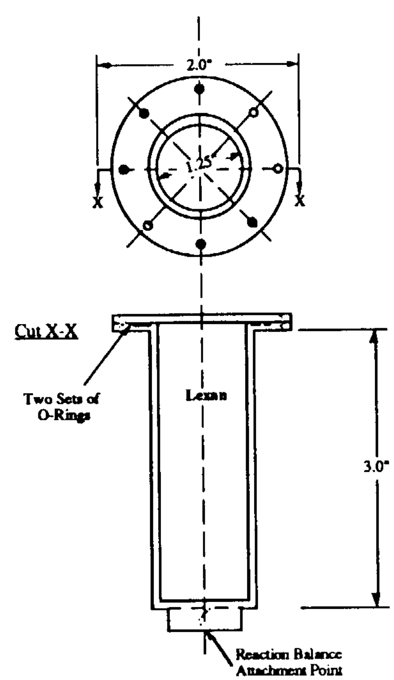
- Scaled models of prototypical space truss structures
  - Deployable bays with a bay with variable pre-tension and nonlinear joints
  - Erectable bays
  - Scaled Alpha (α) joint
  - Very flexible appendage (1 Hz)

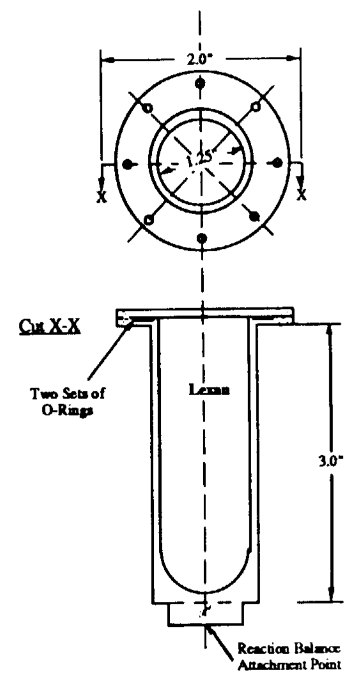



Component Testing
Bay testing
Single joint testing
Analytical Model
Use force-state results
to generate nonlinear model
Use results to verify nonlinear
on component level or to built
"component" nonlinear model
Use to update FEM
Use to verify analytical
model
Identify limitation of
earth testing
Ground Modal Testing
Determine linear
modal characteristics
Determine Nonlinear Modal
characteristics
Understand suspension effects
Space Modal Testing
Determine linear
modal characteristics
Determine Nonlinear Modal
characteristics

Experimental Design (Contained Fluids)

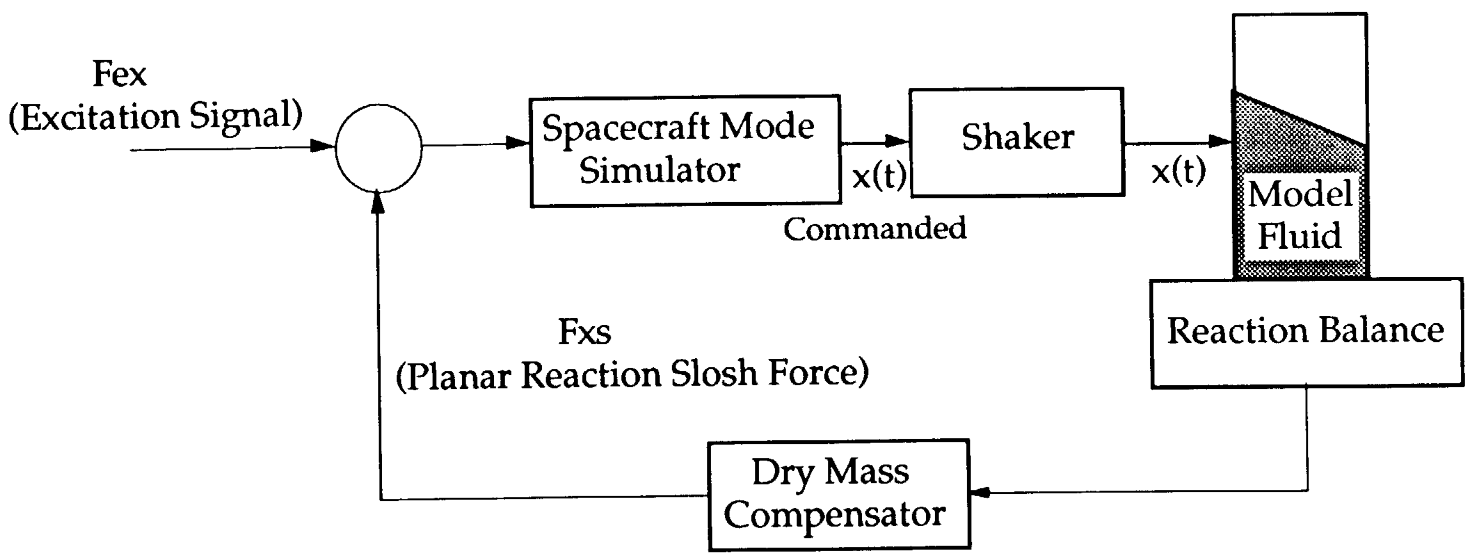
- Scaled tanks of prototypical spacecraft fluid containers
  - Cylindrical tank with a flat bottom
  - Cylindrical tank with a spherical bottom
- Fluids matching the properties of typical cryogenics
  - Silicone oil (Potential stability problem)
  - Water as a backup
  - Both are non-toxic and non-flammable

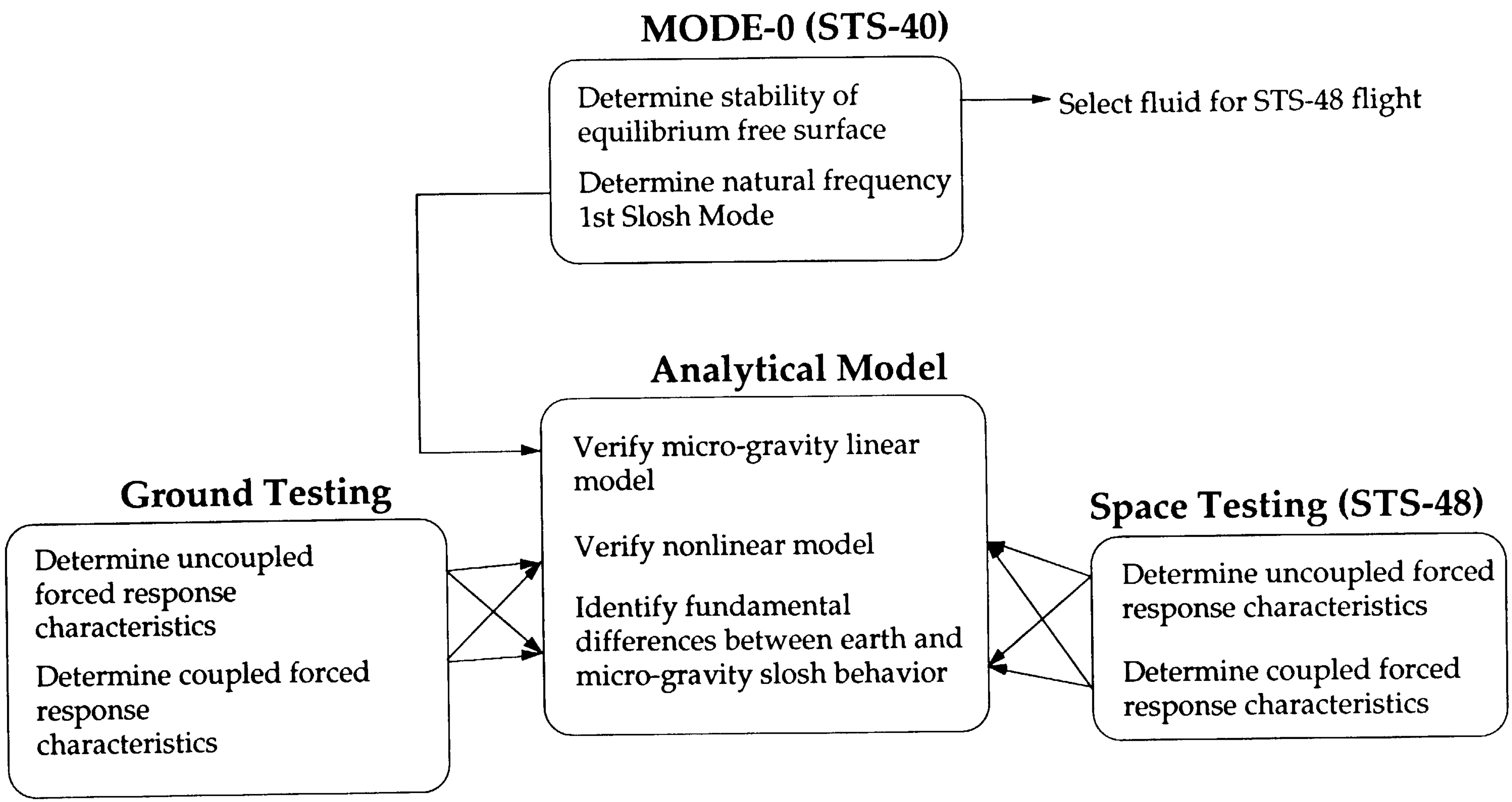




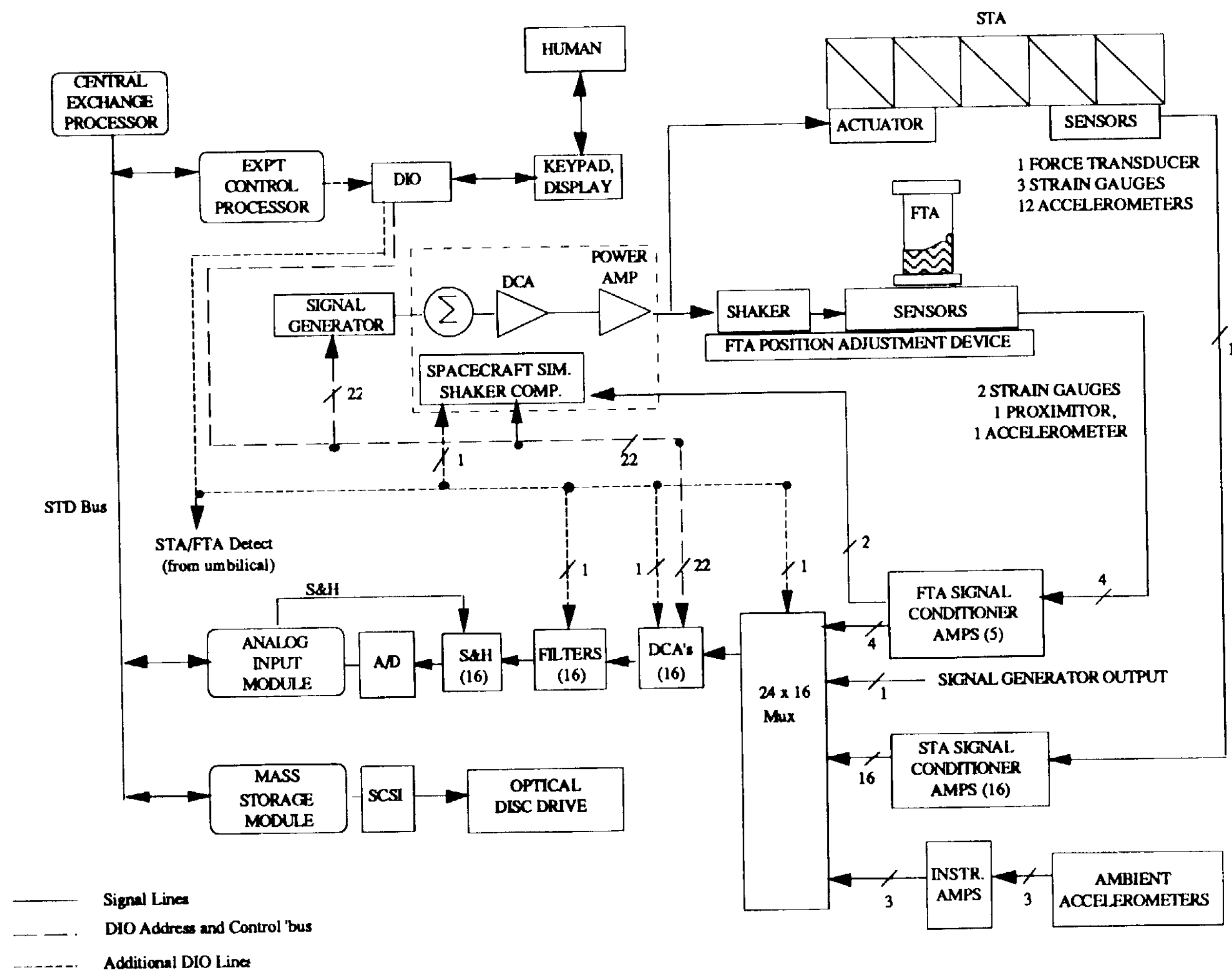
Experimental Design (Contained Fluids - Cont.)

- Fluid/Spacecraft interaction studied by including an analog simulation of a spacecraft's mode




MODE-0 (STS-40)
Determine stability of equilibrium free surface
Determine natural frequency 1st Slosh Mode
Select fluid for STS-48 flight
Analytical Model
Verify micro-gravity linear model
Verify nonlinear model
Identify fundamental differences between earth and micro-gravity slosh behavior
Ground Testing
Determine uncoupled forced response characteristics
Determine coupled forced response characteristics
Space Testing (STS-48)
Determine uncoupled forced response characteristics
Determine coupled forced response characteristics

Progress to Date



Progress to Date (Continued)

M.O.D.E. Component Tester