**Middeck 0-Gravity Dynamics Experiment (MODE)**

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**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
• 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:

\[
\frac{\text{Gravity Load}}{\text{Pre - Load}}
\]

Nonlinear Joint

Earth

Space

Gravity alters the operating point and, therefore, the apparent stiffness and damping of joints and tensioning wires.

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

\[
\frac{g}{L_{\text{Suspension}}} = \frac{\omega_{\text{Pendulum}}}{\omega_{1st}^2}
\]

where \( \omega_{1st}^2 \) is the 1st 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:

\[
\frac{\omega_{\text{Suspension}}}{\omega_{1st}}
\]

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

Modal Test → Finite Element Model → Linear Structural Dynamic Model → Analytical Model

Analytical Model → Force-State Map of Nonlinear Sub-components → Describing Function of Force-State Map

Describing Function of Force-State Map → Nonlinear Structural Model (Equivalent beam representation or Multi-degree-of-freedom Model)

Nonlinear Structural Model → Forced Response Characteristics using Harmonic Balance Method

Forced Response Characteristics using Harmonic Balance Method → Compare to Verify Model

Compare to Verify Model → Experiment

MODE Flight and Ground Experimental Results

Space Engineering Research Center
Characterization of the Nonlinear Components

- Force transmitted by a nonlinear structural component is:

\[ F_i(x, \dot{x}) = F - M\ddot{x} = D(x, \dot{x})\ddot{x} + K(x, \dot{x})x \]

- 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

Earth
The surface tension potential energy is given by

$$U_\sigma = \sigma \int \int_S \sqrt{1 + \nabla(f + \eta_d) \cdot \nabla(f + \eta_d)} \, dS$$

Effect scales with the Bond number $Bo = \frac{\rho g a^2}{\sigma}$
2 Convection forces at the free surface

\[ \frac{\partial \eta}{\partial t} + \nabla \phi \cdot \nabla \eta \bigg|_{z=\eta} = \frac{\partial \phi}{\partial z} \bigg|_{z=\eta} \]

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

\[ \frac{\partial \eta}{\partial t} = \left. \frac{\partial \phi}{\partial z} \right|_{z=\eta} - \nabla \phi \cdot \nabla (\eta_d + \phi) \bigg|_{z=\eta} \]

- 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

Step 3:
Formulate Coupled System Lagrangian

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. $\mu=0.16, \nu=0.89, \zeta=9.1\%, Bo=33, f_0 = 7$ 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

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
Use to update FEM
Use to verify analytical model
Identify limitation of earth testing
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 (Continued)

**M.O.D.E. Component Tester**