

*MIT  
Space  
Engineering  
Research  
Center*

# ***THE MODE FAMILY OF FACILITY CLASS EXPERIMENTS***

**Dr. David W. Miller**

**MIT**

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# ***THE MODE FAMILY OF EXPERIMENTS***

**Fluid Test Article  
(FTA)**

**Coupled Non-Linear  
Dynamics of Fluids and  
Structures in Zero  
Gravity**

**Structural Test Article  
(STA)**

**Non-Linear Dynamics of  
Jointed Truss Structures in  
Zero Gravity**

**MACE Test Article**

**Influence of Gravity on the  
Active Control of a  
Multibody Platform**

**Flight # 1:  
September 1991**

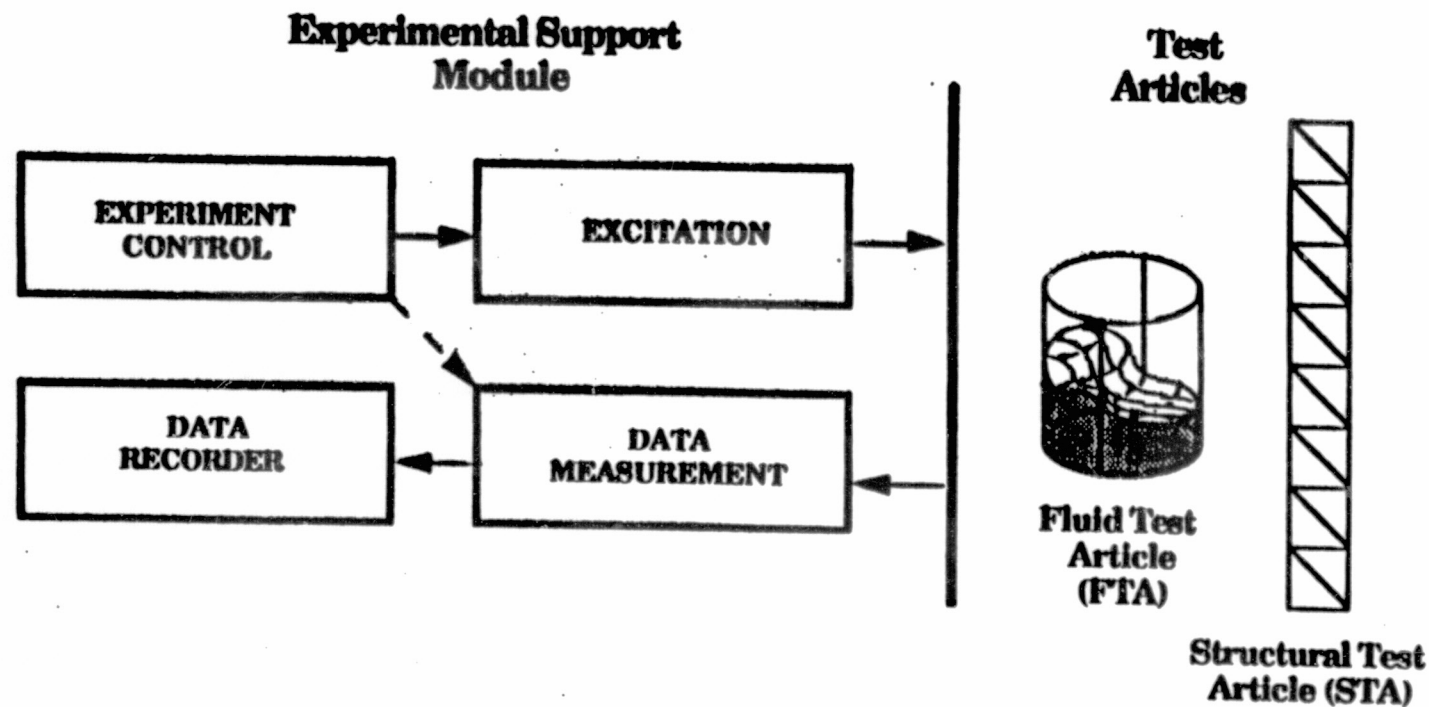
**Flight #2:  
June 1994**

**MACE is part of a logical sequence of cost-effective flight experiments designed to advance technology of interest to NASA in the area of controlled structures.**

# ***EXPERIMENTAL PHILOSOPHY***

- **Use the shuttle/station for engineering research (as opposed to demonstration or verification)**
- **Investigate (dynamics) phenomena which are influenced by gravity**
- **Use the Middeck ~~/~~ Laboratory Module as a shirt sleeve lab environment with heavy reliance on crew interaction**
- **Use scaling laws to build model which capture the essential physics of the problem and yield results of practical value, at modest size and cost**

# **THE MIDDECK 0-GRAVITY DYNAMICS EXPERIMENT (MODE)**



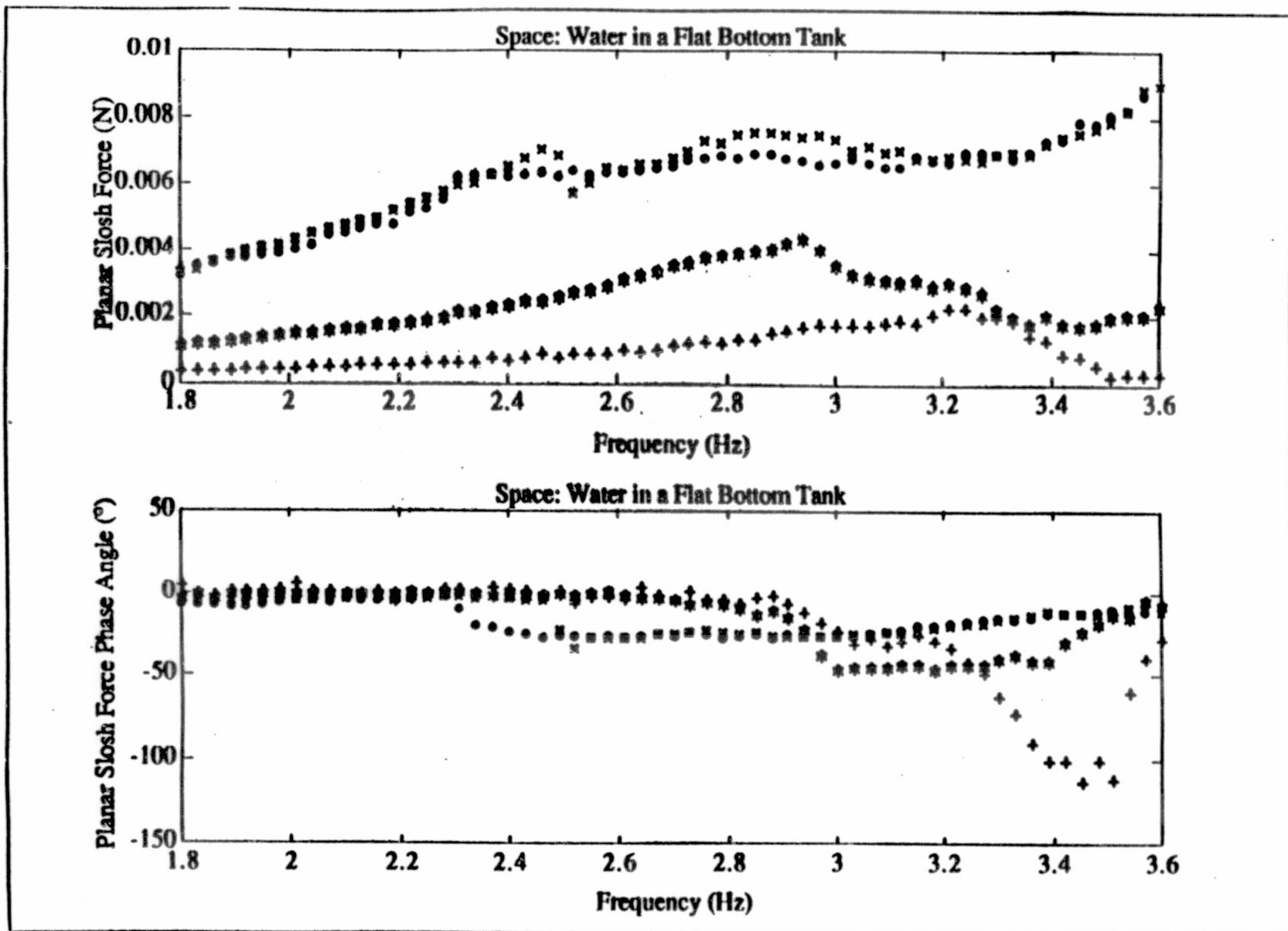
**MODE** provides a reusable dynamics test facility which will be used on the first flight to test two rather different types of test articles.



# **OBJECTIVES**

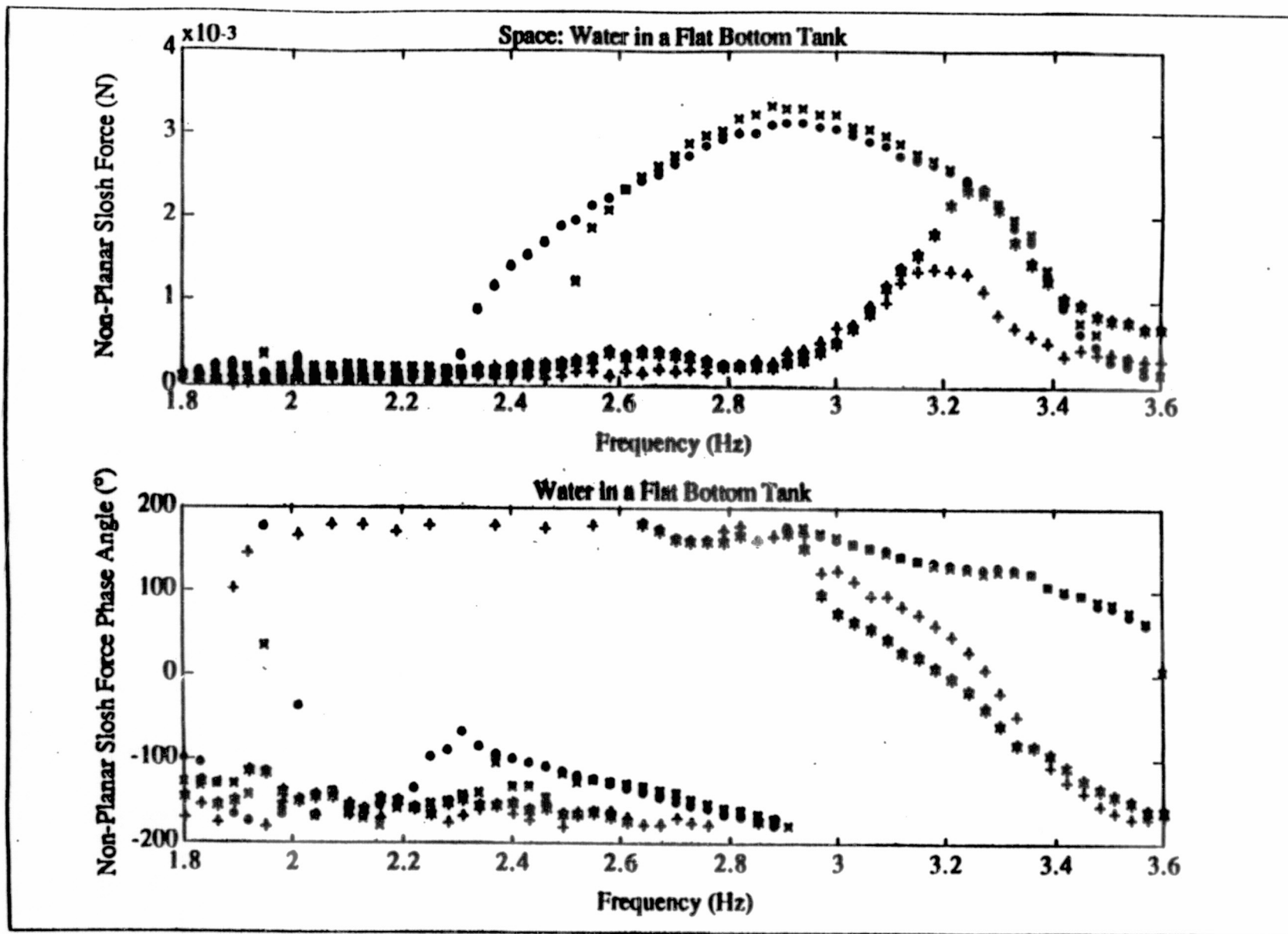
- **Engineering science objective is to characterize fundamental 0-g slosh behavior and obtain quantitative data on slosh force and spacecraft response for correlation of analytical model.**
- **Why:**
  - **Higher fluid mass fractions of on-board fluids.**
  - **Uncertainty in fuel behavior requires larger  $\Delta V$  margins.**
  - **Nonlinear dynamics significant alters spacecraft dynamics and fluid cannot considered to be isolated from the spacecraft dynamics.**
- **To:**
  - **Design more efficient spacecraft.**

# SPACE RESULTS



Uncoupled Test with Distilled Water as Test Fluid in a 3.1 cm Flat Bottom Cylindrical Tank .  
Planar Slosh Force.

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Uncoupled Test with Distilled Water as Test Fluid in a 3.1 cm Flat Bottom Cylindrical Tank .  
Non-planar Slosh Force.

# **SUMMARY AND CONCLUSIONS**

## **Space Experiments:**

- **More benign nonlinear behavior in space than observed on earth**
- **Modal damping ratios and frequencies significantly different from earth tests**
- **Demonstrated the ability to investigate fluid slosh in micro-gravity**

## **Analytical Model**

- **Model more accurate for one-gravity conditions**
- **Nonlinear solution required that can find "all" the solutions**
- **Accurate prediction of slosh damping ratios a pre-requisite for an accurate prediction**

## **Future**

- **Improve nonlinear solution technique**
- **More space experiments required to investigate effects of contact angle hysteresis, contact angles and dissipation rates.**

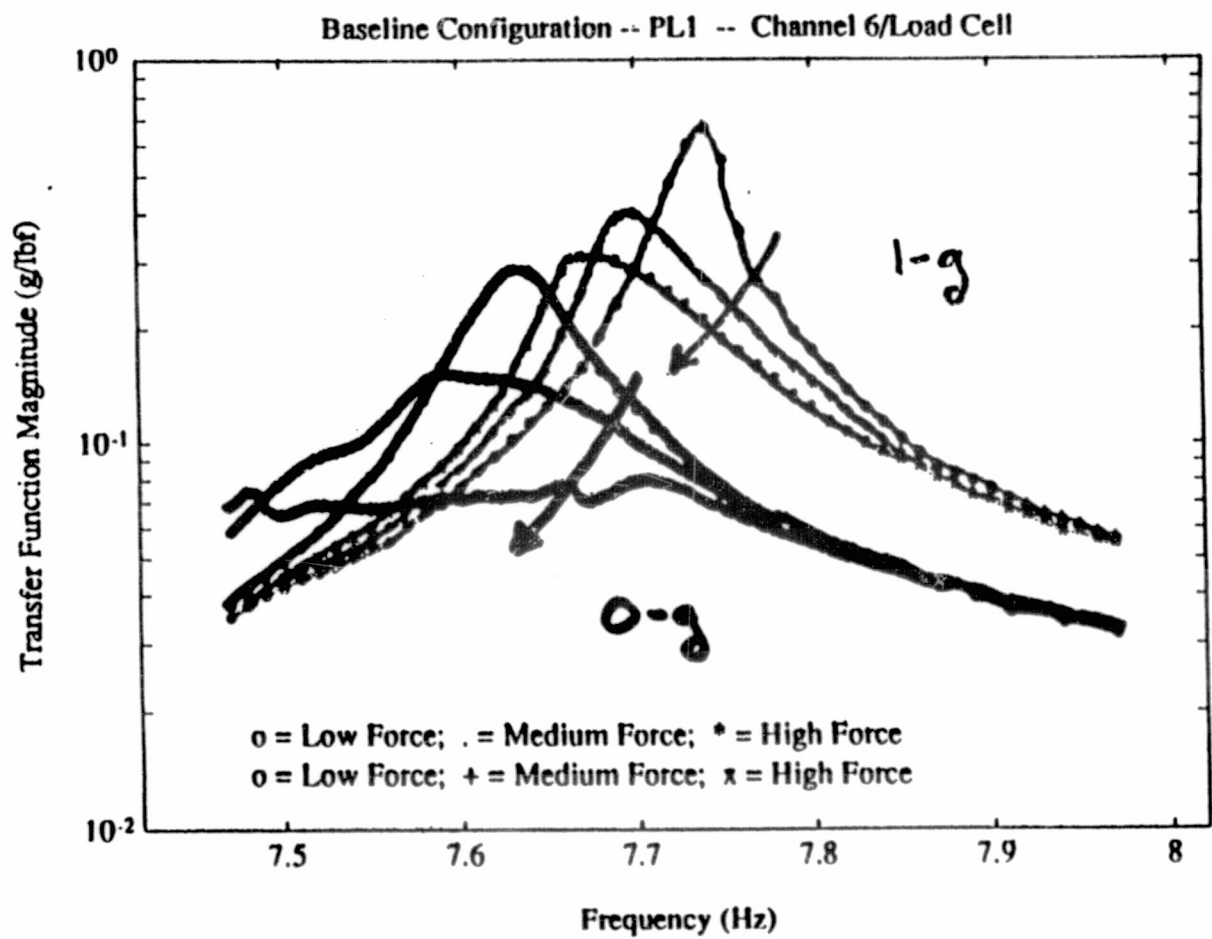
# **STA OBJECTIVES, REQUIREMENTS & APPROACH**

- **Engineering science objectives are to characterize the fundamental changes in dynamics in 0-g due to absence of gravity on joints, to quantify the changes due to the absence of suspension and gravity load on members, and to obtain quantitative data for correlation with numerical models.**
- **Requirements**
  - Truss structure containing elements of future space structures.**
  - Nonlinear joints with variable pre-load to test nonlinear behavior in several gravity/joint pre-load conditions.**
  - Reconfigurable truss with deployable and erectable bays.**
- **Modelling approach**
  - Develop global linear model using FEM and modal test data.**
  - Develop Force-State Map of non-linear sub-components.**
  - Develop describing functions from Force-State Map.**
  - Insert describing functions into global model and solve for forced response using Harmonic Balance Method.**
  - Verify predictions with MODE flight and ground test results.**





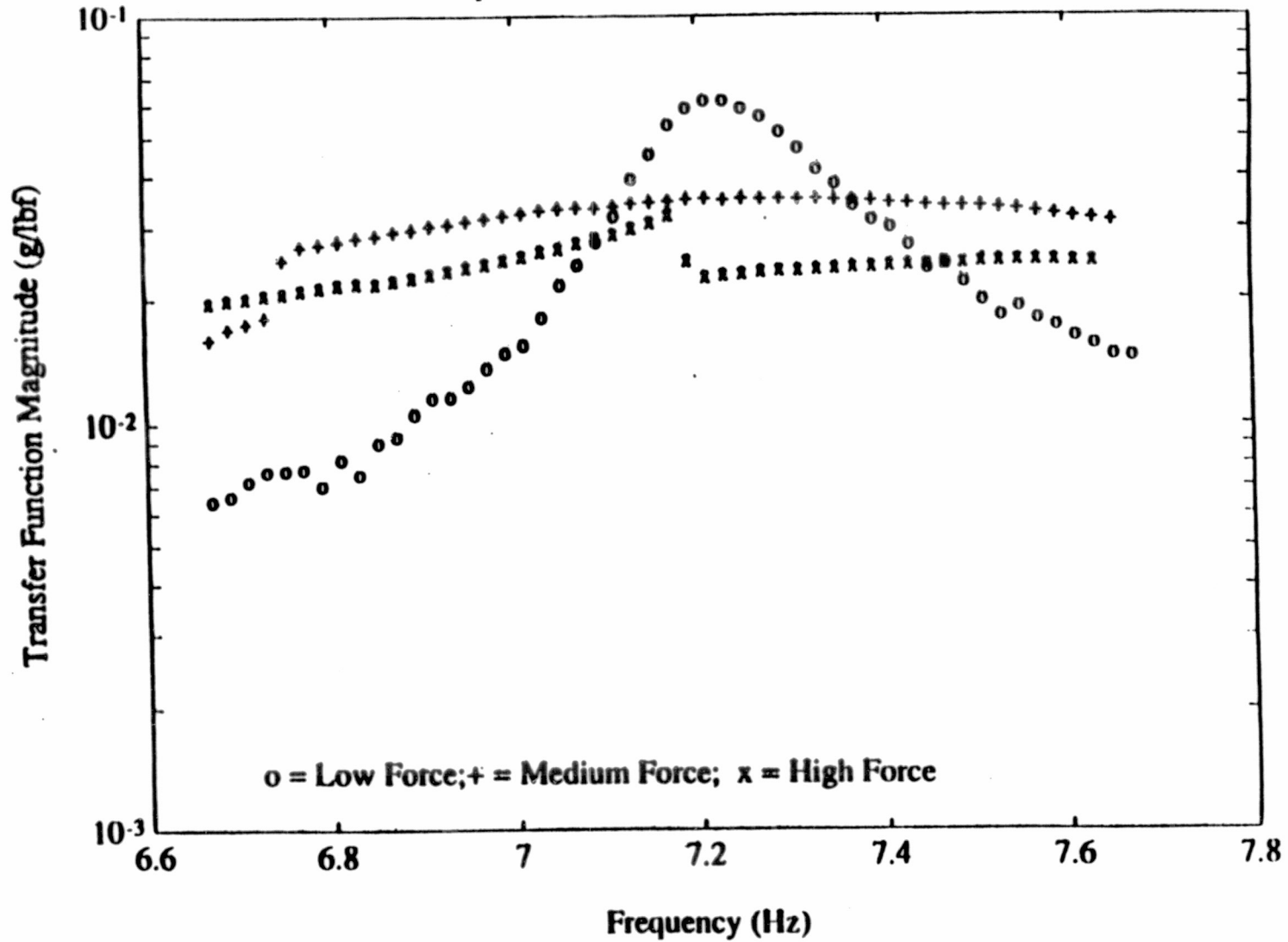
# COMPARISON OF GROUND TO ORBITAL DATA FOR THE BASELINE CONFIGURATION



NOTE: Torsion Mode Only. High Pre-Load.

# TORSION MODE ALPHA LOOSE

Space Data -- Channel 6/Load Cell

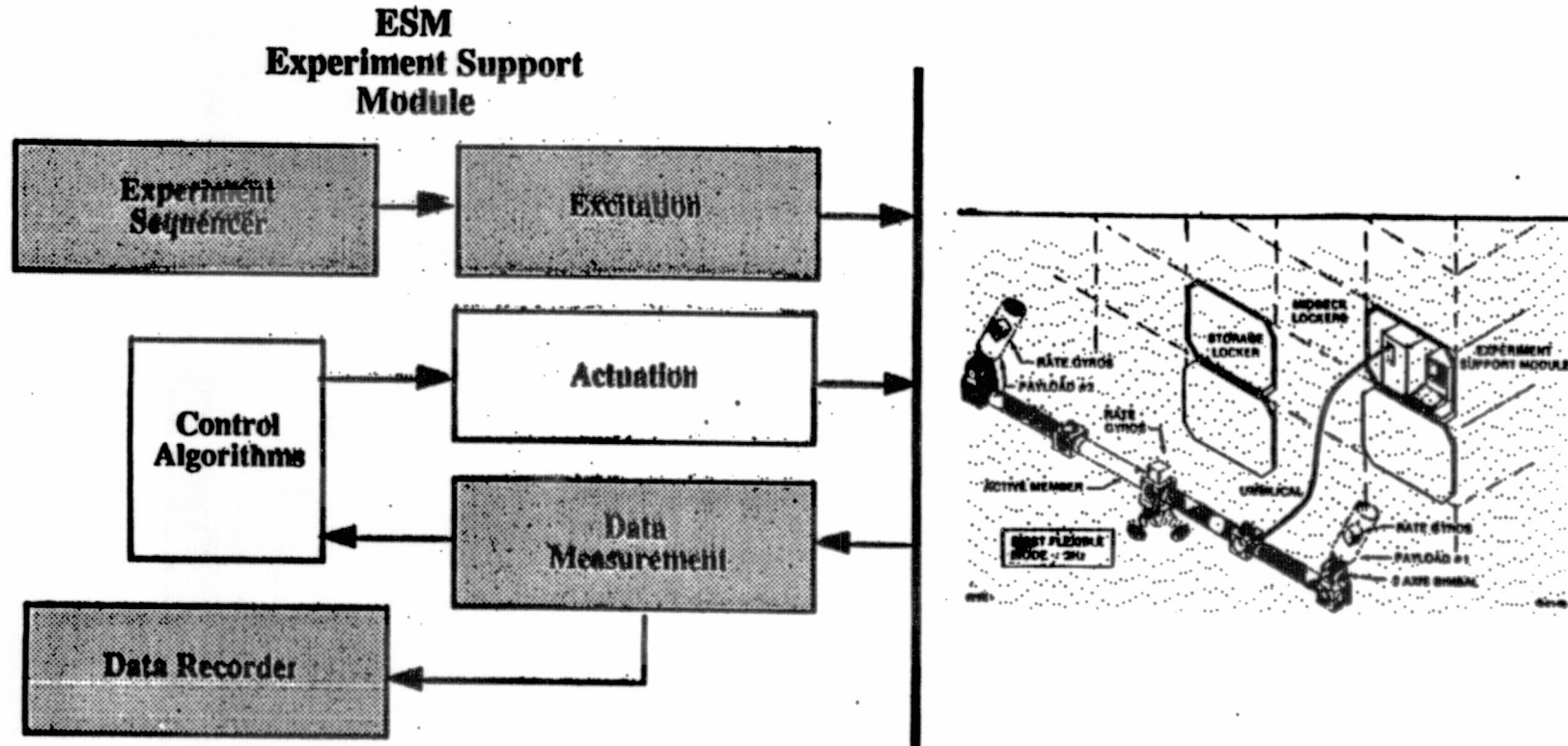




## **CONCLUSIONS OF ORBITAL TESTING**

- **Variation measured for erectable, deployable and articulated hardware as a function of force amplitude, joint preload and gravity loading**
- **Nonlinearities of the STA are more apparent in 0-gravity, especially the alpha loose, which loses resonant behavior**
- **Modes generally soften with increasing force, but increase in damping is significantly more pronounced**
- **Changes in frequency between earth and space are generally within the variance of ground testing for the baseline, but outside the variance for the alpha and L configurations.**
- **Changes in damping are well outside the variance of ground testing**

# FLIGHT EXPERIMENT RESOURCES

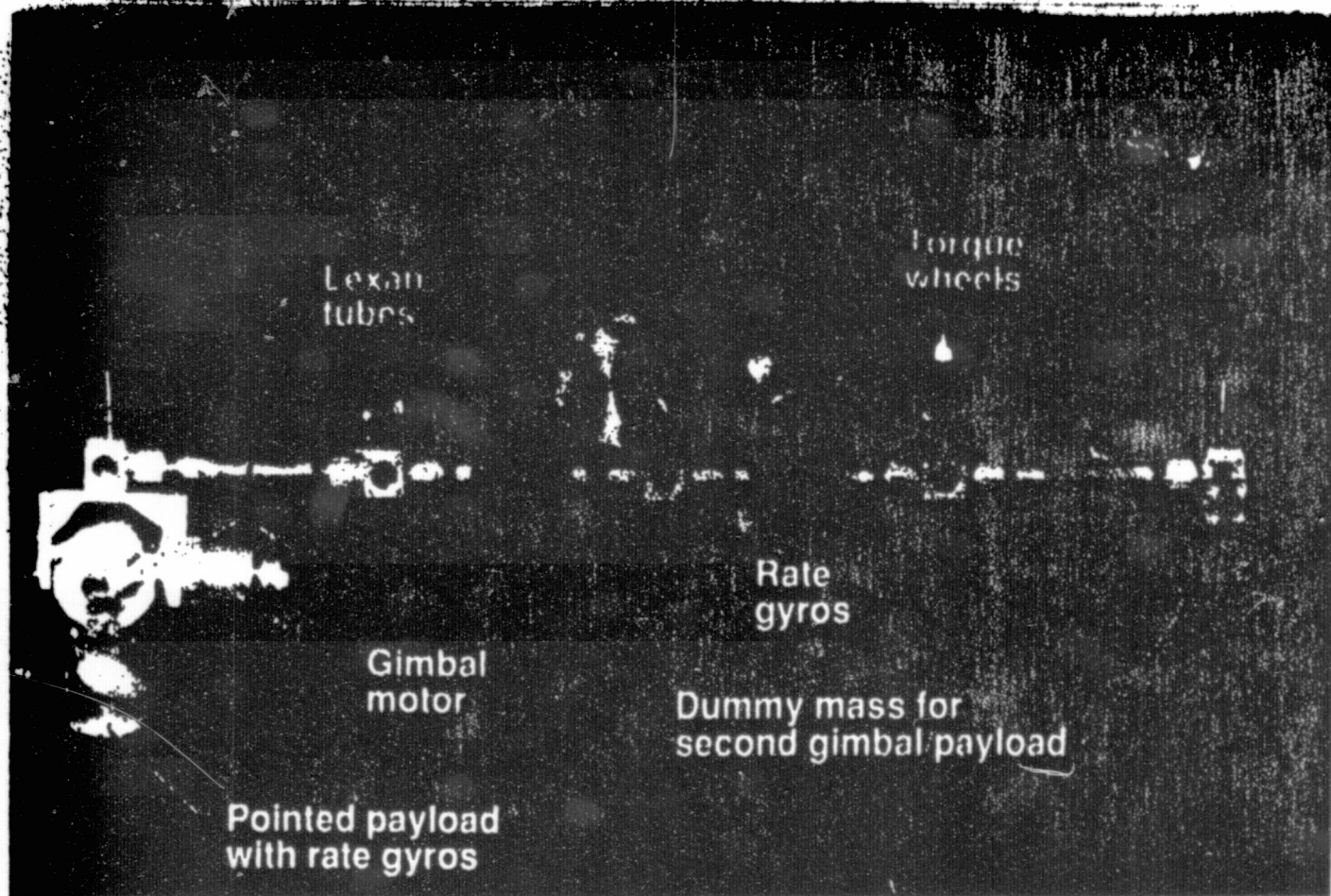


- Three eight hour days of one crew member.
- Test article and support equipment stored in 3 middeck lockers.
- ESM stored in a fourth middeck locker.
- Wiring is pre-integrated in the test article for ease of assembly.

# MIDDECK ACTIVE CONTROL EXPERIMENT (MACE)

## Development Model Lab Testing

(Flight unit will have smaller torque wheels and gimbal motors)



# ***PROGRAM OBJECTIVES***

- **Science Objective**

To develop a verified set of methods that will allow designers of CSI/CST spacecraft, which cannot be dynamically tested on the ground in a sufficiently realistic 0-g simulation, to have confidence in the eventual orbital performance of such spacecraft.

- **Implications**

Understand direct and indirect gravity effects and the relation between control authority and manifestation.

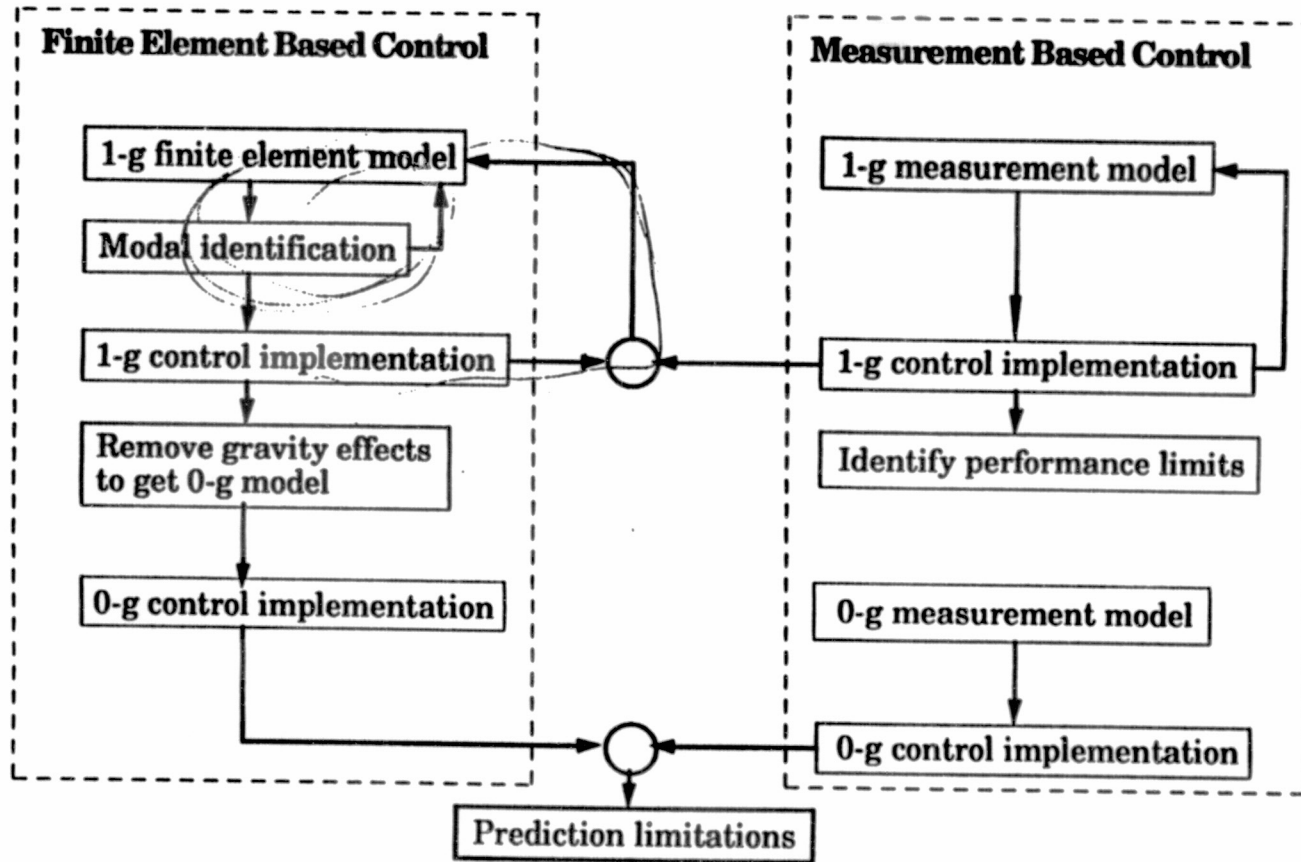
Develop procedures for predicting on-orbit performance.

Quantify prediction accuracy achievable through analysis and ground tests.

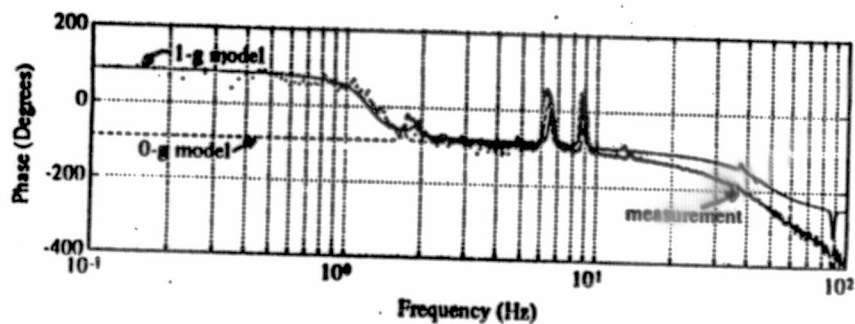
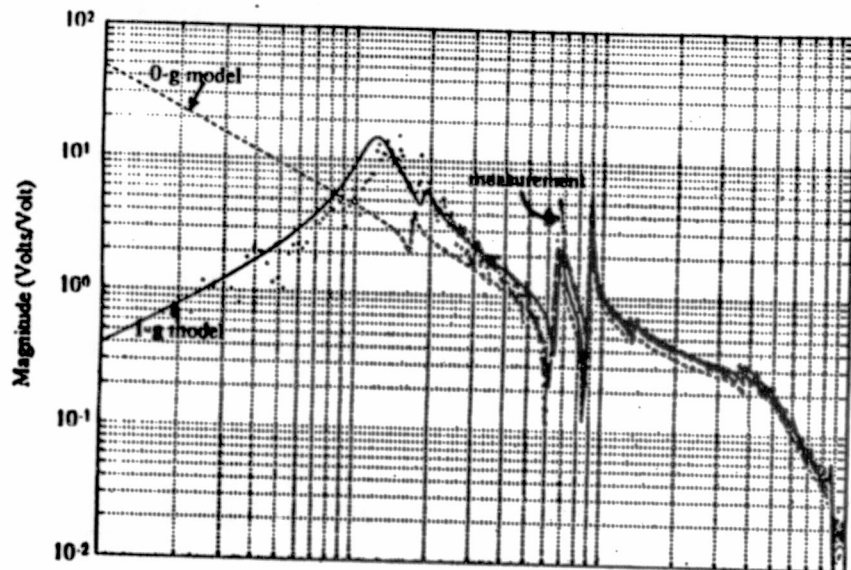
Develop techniques for on-orbit identification.

Quantify performance improvement through control redesign based upon on-orbit identification.

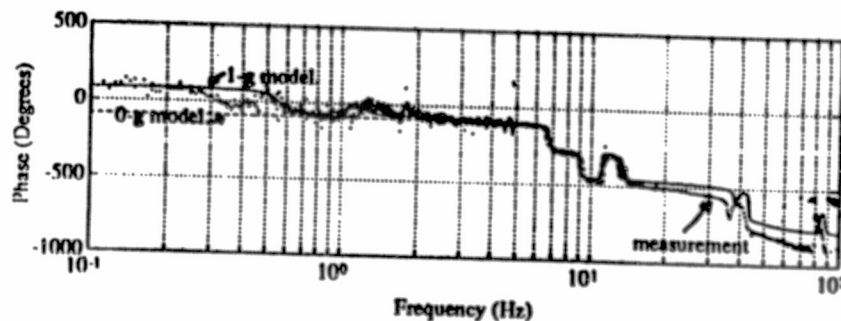
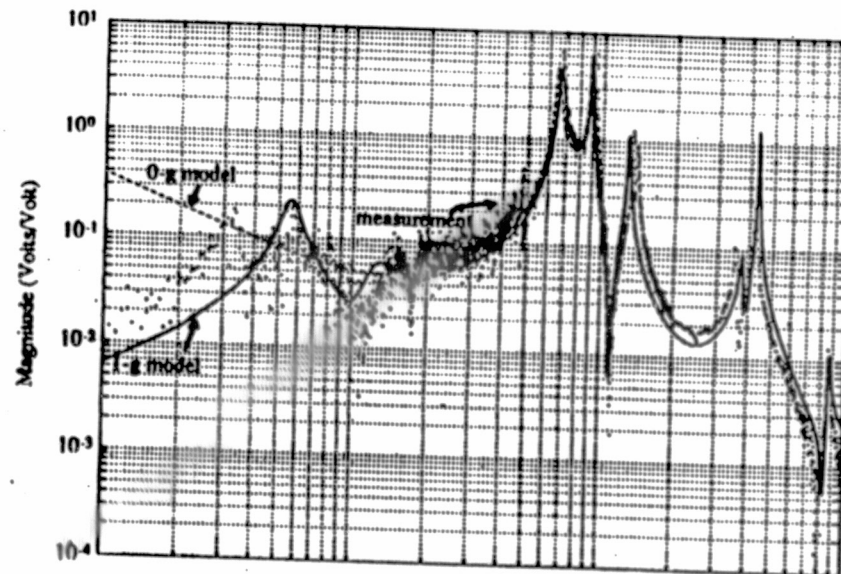
# SCIENCE APPROACH



# MACE 1-G AND 0-G MODELS



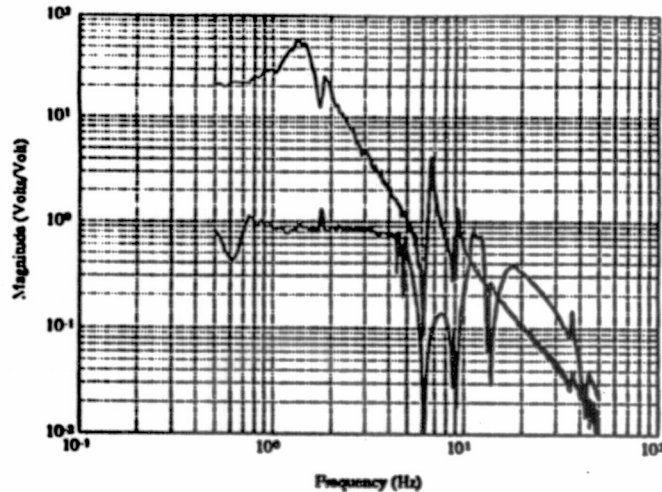
Transfer function from z-axis gimbal torque to z-axis payload inertial angular rate.



Transfer function from z-axis gimbal torque to z-axis bus inertial angular rate.

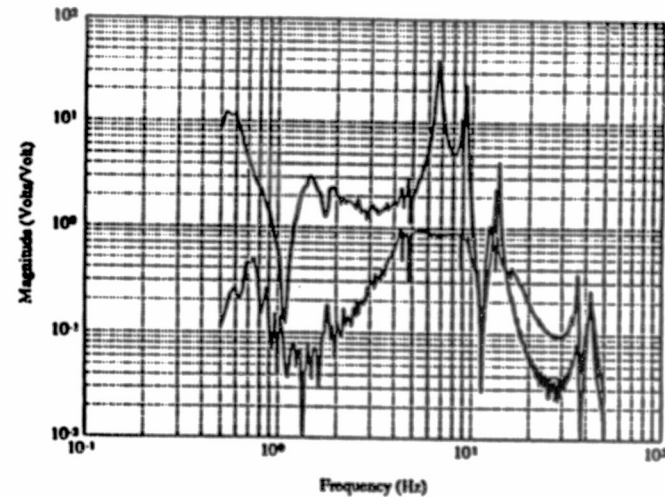


# SINGLE-INPUT, TWO-OUTPUT WITH PAYLOAD AND BUS PENALTY

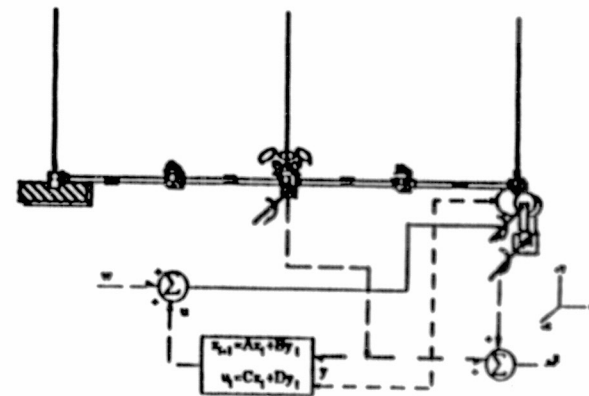


Transfer functions from gimbal to payload inertial angle

- Payload pendulum and first bending modes are suppressed
- In addition, higher frequency flexible modes are suppressed.
- An order of magnitude reduction in pointing error is achieved.



Transfer functions from gimbal to bus inertial angle



Control Topology #3

## ***FUTURE EFFORTS***

M.I.T. SERC is pursuing followon flight experiments which either reuse the MODE and MACE hardware or build upon the associated experience.

- **MODE Reflight in 1993**
  - Reflight of the Structural Test Article (STA) to investigate two unexpected physical phenomena which appeared during the on-orbit operation of MODE I.
  - Shifts in the modal frequencies in the most geometrically complex configuration were greater than expected and laid outside the preprogrammed test windows.
  - The alpha joint exhibited jump phenomena.
- **Fluid Advanced Dynamic Experiment (FADE)**

The MODE ESM with Fluid Test Article (FTA) Assembly is available to conduct on-orbit fluid dynamic research.
- **MODE on MIR**

M.I.T. SERC has received a written invitation to fly MODE hardware on the Russian Space Station (MIR) for acquisition of extended micro-gravity test data.



# ***SUMMARY***

- **The MODE family of flight experiments is designed to verify analytical tools developed to predict the gravity dependent behavior of proposed space structures.**
- **The MODE family of flight experiments uses reusable dynamic and control test facilities and exploits the shirt sleeve environment on the STS middeck.**
- **MACE investigates gravity dependent phenomena pertinent to the closed-loop dynamics of proposed space structures.**
- **Gravity and suspension effects perturb the MACE test article flexible modes when tested on the ground.**
- **Suspension mode stabilization can obscure important gravity influences on the flexible behavior during 1-g closed-loop testing.**
- **Measurement models have been used successfully to achieve over an order of magnitude improvement in pointing accuracy.**