NASA-CR-192687

MIT
Space
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Center

DYNAMICS AND CONTROL OF MULTIPAYLOAD PLATFORMS:

THE MIDDECK ACTIVE CONTROL EXPERIMENT (MACE)

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(NASA-CR-192687) DYNAMICS AND CONTROL OF MULTIPAYLOAD PLATFORMS: THE MIDDECK ACTIVE CONTROL EXPERIMENT (MACE) (MIT) 19 p

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Outline

Objectives and Rationale

Experimental Approach

- Capturing the Essential Physics
- Validation of the Analytical Framework

Pointing on a Flexible Structural Bus

- Control Design Issues for Multipayload Pointing
- Linear Typical Section Models
- Nonlinear Analysis

Effect of Gravity on the Structural Control Problem

Testbed Program

- Ground Based Engineering Model Testbed
- Flight Testbed

Summary

Objectives and Rationale

- Objective: to develop a well verified set of Controlled Structures Technology tools that will allow designers to either be able to predict on-orbit behavior or allow sufficient versatility in the design to allow identification and tuning of the structure on-orbit.
- Since the model fidelity required for stability and performance robustness is intimately related to the level of control authority, closed-loop testing is required.
- Vehicle qualification testing will most likely occur on the ground where suspension and direct gravity effects will cause the 1-g and 0-g dynamics to differ.
- While all known influences cause regular perturbations, even small perturbations can substantially alter closed-loop behavior.
- Differences between the ground and on-orbit environment cause perturbations which can substantially alter closed-loop behavior.
- Therefore it is essential to perform on-orbit closed-loop testing for comparison with ground testing and analytical predictions to develop these CST tools.

Capturing the Essential Physics: Test Article Requirements

The simulation of a vehicle with payloads and articulating appendages with pointing and positioning requirements, necessitates a test article with the following attributes:

- appropriately scaled to fit in the middeck while preserving the essential performance requirements.
- two gimballing payloads to enable implementation of multiple interacting control systems with independent objectives.
- two rigid payloads and a flexible appendage, representative of compact high mass fraction devices and a robotic servicer.
- flexible bus with resonances within the controller bandwidth and to exhibit suspension coupling, gravity stiffening and droop.
- sufficiently low structural damping representative of structures incorporating typical aerospace materials.
- sufficiently complex geometry such that the test article;e undergoes full 3-D kinematic and coupled flexible motion.

Capturing the Essential Physics: Test Objectives and Performance Metrics

Test Objectives:

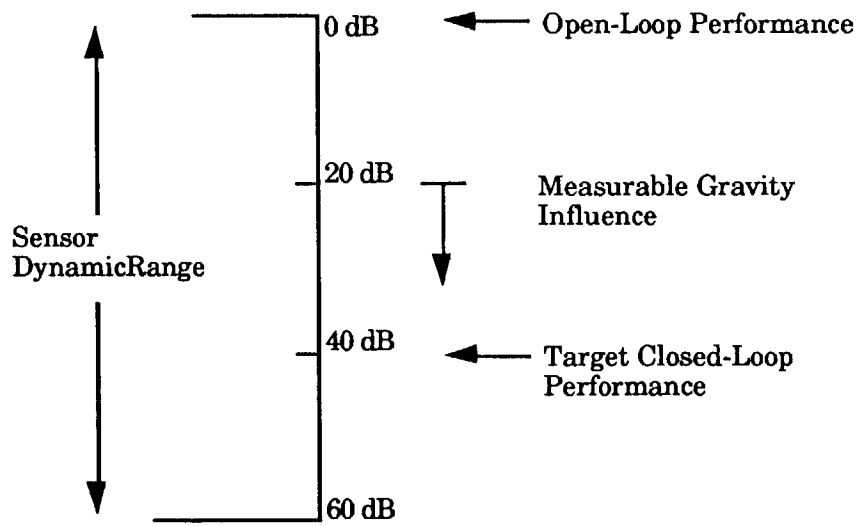
- **Pointing** performance of single and multiple payloads.
- **Tracking** performance of single and multiple payloads.

Performance Metrics:

- **Stability**--RMS 2-axis angular position about pointing line of sight or tracking reference profile.
- **Jitter**--RMS 2-axis angular rate about pointing line of sight or tracking reference profile.
- **Slew response time**--time required to complete maneuver.
- **Percent degradation**--reduction from single payload performance associated with addition of an interacting, controlled payload.

Validation of the Analytical Framework

- Ground testing will include suspension and gravity effects, typical of preflight qualification testing.
- Realistic goal is to improve pointing/tracking performance by 40 dB over open-loop value.



- Independent of absolute performance level, this demonstrates CST effectiveness.
- Sensor dynamic range of 60 dB is typical.

Pointing on a Flexible Structural Bus

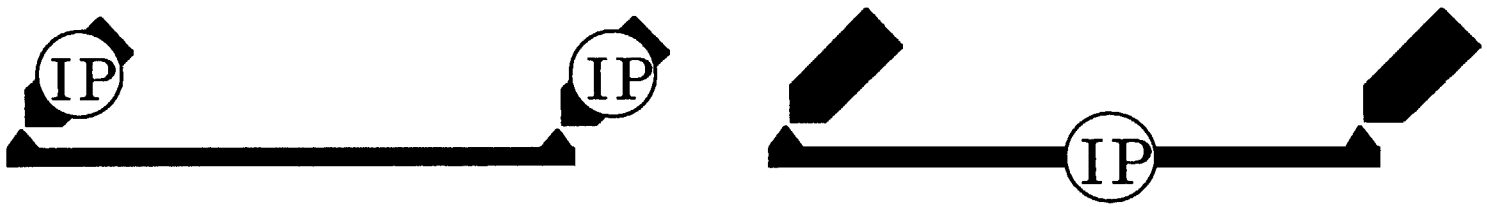
Two questions must be addressed:

1) How does unmodelled flexibility degrade payload pointing performance? and
2) How are controllers designed and implemented on a modelled flexible bus?

To answer these questions, the following tasks must be performed:

Task 1. Design a controller assuming the structural bus is rigid.
Task 2. Evaluate the performance of this controller on an evaluation model which incorporates flexibility in the structural bus.
Task 3. Use a flexible model to design the active controller using existing pointing and tracking hardware.
Task 4. Allow the flexible model controller to use additional sensors which measure flexible motion of the bus.
Task 5. Allow the flexible model controller to also use actuators to control this flexible motion.

Control Design Issues for Multipayload Pointing



Localized **Centralized**

- Two basic topologies exist for measuring inertial orientation: localized and centralized configurations.
- The localized configuration employs an inertial measurement platform (IP) at each payload.
- The centralized configuration employs a single IP on the structural bus and each payload estimates its inertial orientation with respect to this shared utility.
- The centralized configuration provides commonality of hardware while the localized configuration enables more independent payload control design.

Control Design Issues for Multipayload Pointing *(cont)*

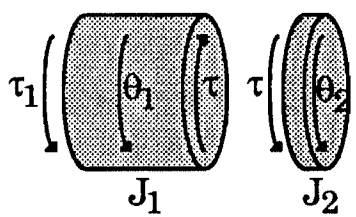
- Decoupling of payload control loops allows more independent design, simplified reconfiguration and payload replacement.
- Decoupling of payload loops is facilitated by:
  - small payload/bus inertia ratios,
  - rigid bus design,
  - CG-mounting,
  - low bandwidth control.
- Given that these options are not available, possible actions are:
  - stored angular momentum to increase apparent bus inertia,
  - design and place control hardware to minimize interaction between payload and bus (reactuators and localized inertial sensing),
  - active and passive structural damping to minimize disturbance response,
  - decoupling control architecture,
  - reference command prefiltering.

Control design objective is to minimize the conservativeness bounds in the design of the payload loops to allow for higher performance.

Linear Typical Section Models

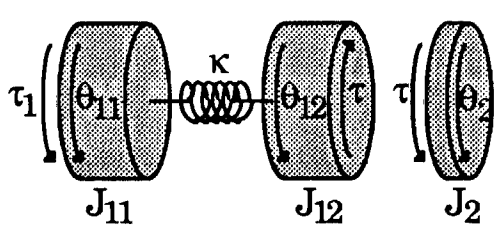
$$x=\begin{Bmatrix}\theta_1\\ \theta_2\\ \dot\theta_1\\ \dot\theta_2\end{Bmatrix},\ Q=\begin{bmatrix}0&0&0&0\\0&\nu&0&0\\0&0&0&0\\0&0&0&0\end{bmatrix},\ u=\begin{Bmatrix}\tau_1\\ \tau\end{Bmatrix}\text{ and } R=\begin{bmatrix}\alpha&0\\0&\beta\end{bmatrix}$$

$$\begin{Bmatrix}\tau_1\\ \tau\end{Bmatrix}=-\begin{bmatrix}0&0&0&0\\0&\sqrt{\frac{\nu}{\beta}}&0&\sqrt{2J_2}\sqrt[4]{\frac{\nu}{\beta}}\end{bmatrix}\begin{Bmatrix}\theta_1\\ \theta_2\\ \dot\theta_1\\ \dot\theta_2\end{Bmatrix}=-Gx$$



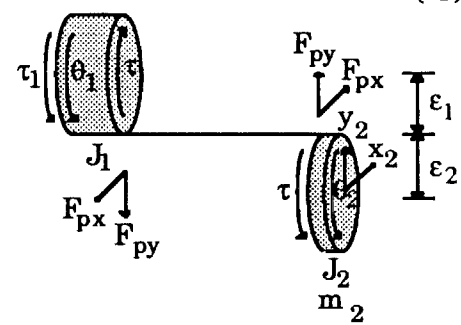
DESIGN MODEL FOR CG MOUNTED PAYLOAD

$$s=0,0,\frac{1}{\sqrt{2J_2}}\sqrt[4]{\frac{\nu}{\beta}}(-1\pm i)$$



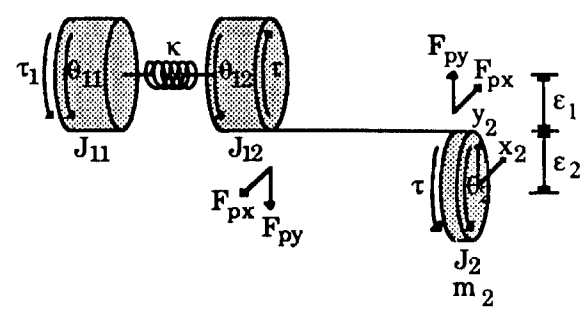
EVALUATION MODEL FOR CG MOUNTED PAYLOAD

$$\begin{Bmatrix}\tau_1\\ \tau\end{Bmatrix}=-\begin{bmatrix}0&\frac{1}{\alpha}b_{32}\sqrt{\frac{\nu}{\mu}}&0&b_{32}\sqrt{\frac{2}{\mu}}\sqrt[4]{\frac{\nu}{\mu}}\\0&\frac{1}{\beta}b_{33}\sqrt{\frac{\nu}{\mu}}&0&\frac{1}{\beta}b_{33}\sqrt{\frac{2}{\mu}}\sqrt[4]{\frac{\nu}{\mu}}\end{bmatrix}\begin{Bmatrix}\theta_1\\ \theta_2\\ \dot\theta_1\\ \dot\theta_2\end{Bmatrix}=-Gx$$



DESIGN MODEL FOR NON-CG MOUNTED PAYLOAD

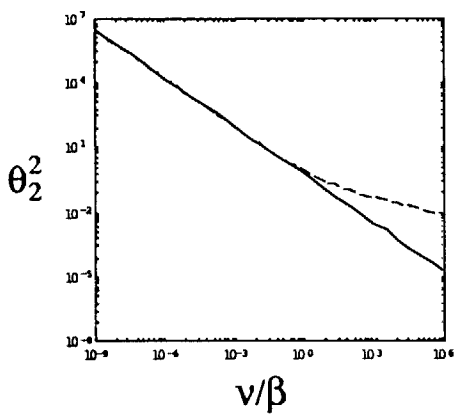
$$s=0,\ 0,\ \frac{1}{\sqrt{2}}\sqrt[4]{\nu\mu}(-1\pm i)$$



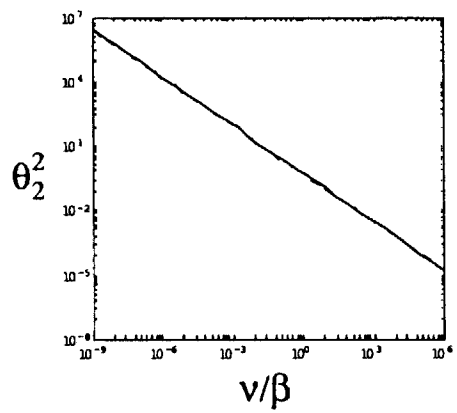
EVALUATION MODEL FOR NON-CG MOUNTED PAYLOAD

Linear Typical Section Models (cont'd)

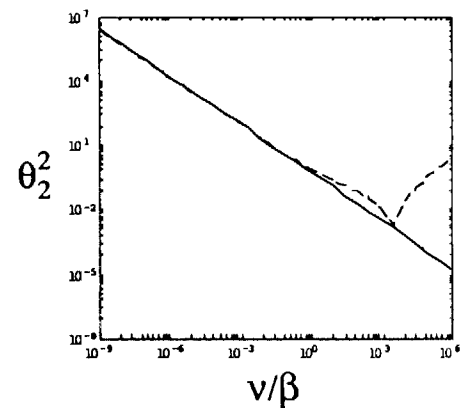
$$XA_{cl}^{T} + A_{cl}X = -V$$



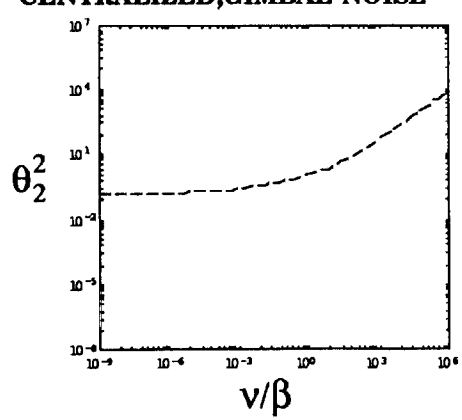
CENTRALIZED,GIMBAL NOISE



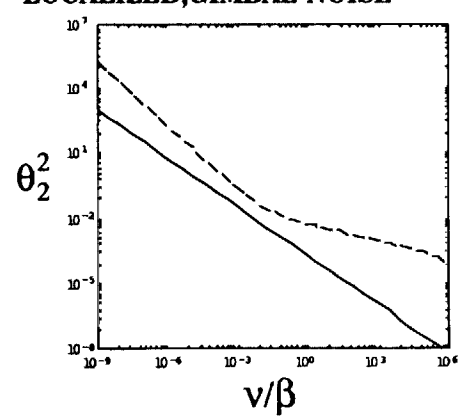
LOCALIZED,GIMBAL NOISE



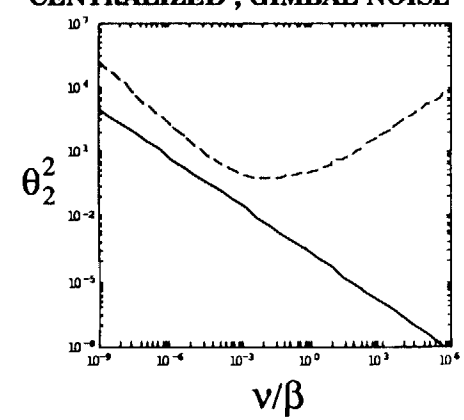
CENTRALIZED , GIMBAL NOISE



CENTRALIZED, ATTITUDE NOISE



LOCALIZED,ATTITUDE NOISE



CENTRALIZED , ATTITUDE NOISE

CG MOUNTED **NON-CG MOUNTED** **NON-CG MOUNTED**

Nonlinear Analysis

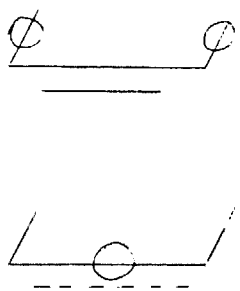
A NONLINEAR CONTROL EVALUATION MODEL WAS DEVELOPED FOR THE **MACE** TEST ARTICLE FOR THE FOLLOWING REASONS:

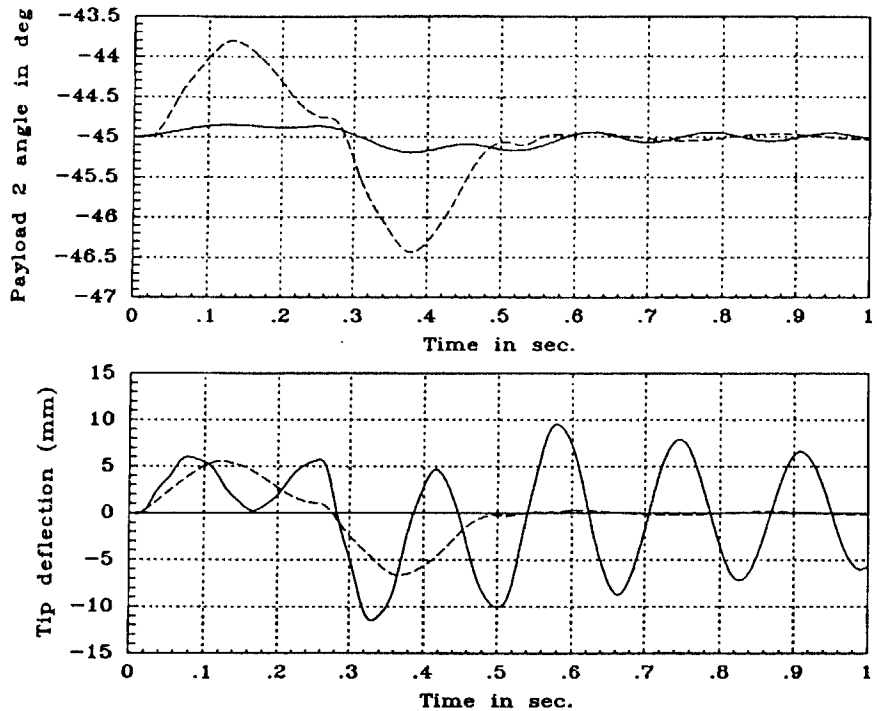
* Evaluate linear control designs on a large order model.
* Evaluate robustness of linear control designs under time-varying dynamics due to large angle and angular-rate articulation.
* Evaluate nonlinear control designs.
* Perform time simulations of laboratory and on-orbit experiments.

THE NONLINEAR EVALUATION MODEL IS CODED IN **DISCOS** AND RESIDES AT CAMBRIDGE RESEARCH, AN ASSOCIATE OF PRA.

* Local experts on multibody simulation programs.
* Quickest way to obtain the nonlinear evaluation model.
* Can partake of their expertise.

Some Results to Date





PD pointing control loops were closed about payload two at a bandwidth equal to twice the fundamental bending frequency; payload one underwent a bang-bang slew.

LOCAL: Better initial response of payload 2 at the expense of exciting flexible bus.

CENTRAL: Steady state response of same order as LOCAL, but flexible bus is not as excited.

BOTH schemes are guaranteed stable.

RESEARCH METHODOLOGY

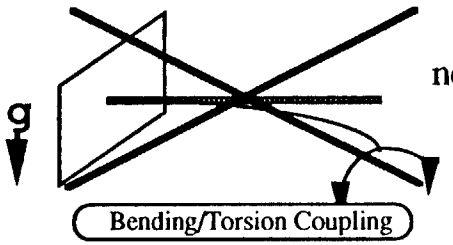
OBJECTIVE:

Identify and quantify the magnitude of the perturbation effects of a gravity field and a suspension system on the dynamics of a suspended space platform model taking into account any effects of scaling.

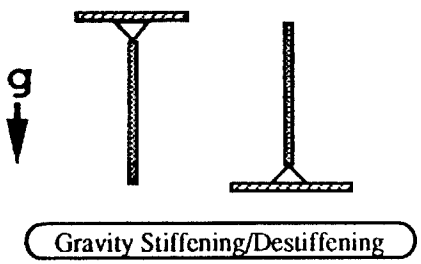
APPROACH:

- Identify the distinct types of gravity/suspension perturbations.
- Identify a non-dimensional gravity field or suspension system influence parameter for each important effect type and perform a parametric analysis of the effect on the system dynamics.
- Compare analytical results with finite element modelling results.
- Rank the effect types in order of impact on the structural dynamics based on the non-dimensional system parameters.

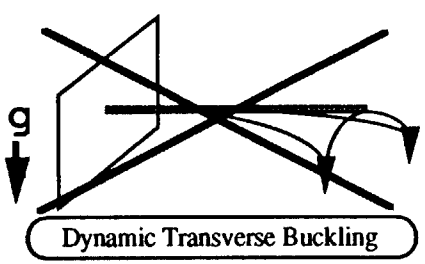
PRESENT GRAVITY/SUSPENSION EFFECTS
MODELLING CAPABILITIES/APPROACH



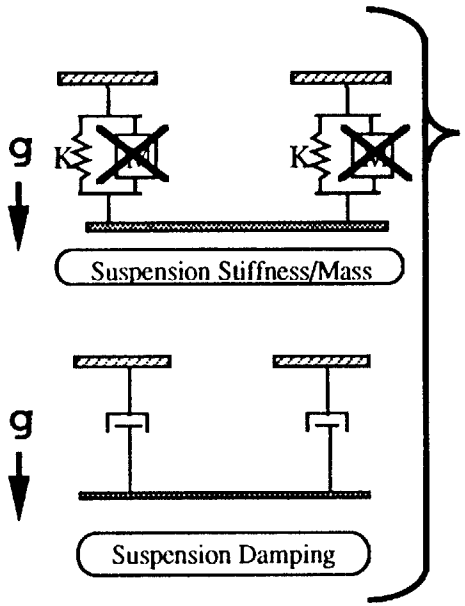
• effect can be made negligeable using a TBD sufficient number of suspension points



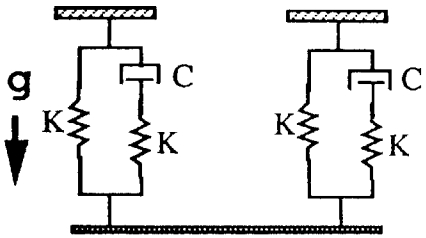
• has been modelled using FEM geometric stiffness techniques and analytically using the assumed modes method

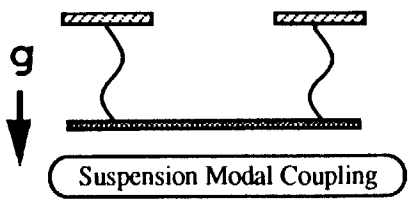


• buckling represents suspension system failure



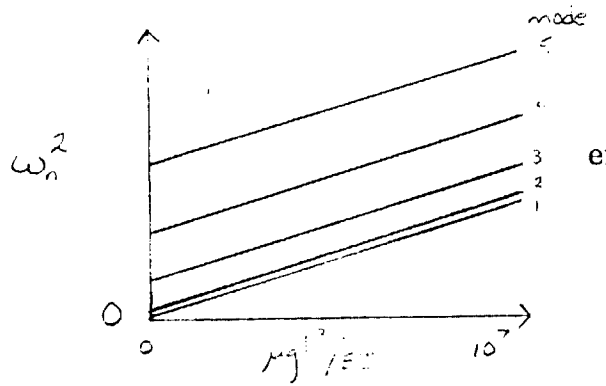
• effects to be combined into a single model of a CSA pneumatic/electric suspension device:



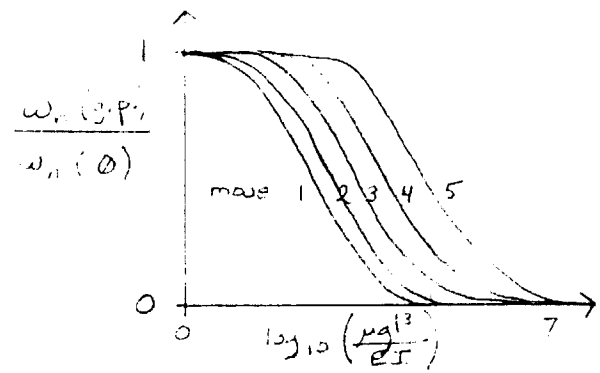


• cable axial, pendular and string mode interactions have yet to be studied or modelled.

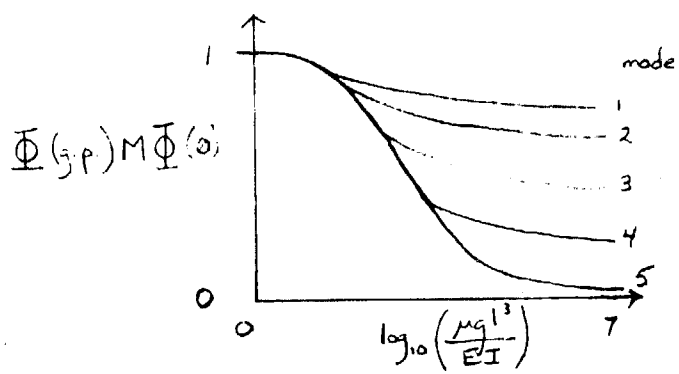
SAMPLE RESULT TYPES YIELDED FROM PARAMETRIC VARIATION STUDIES



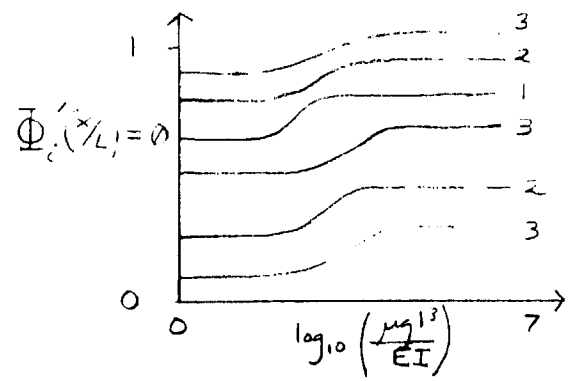
squared eigenvalue



eigenvalue ratio



modal cross-orthogonality



slope node position(s)

+ mode shape transition plots

+ curvature node positions

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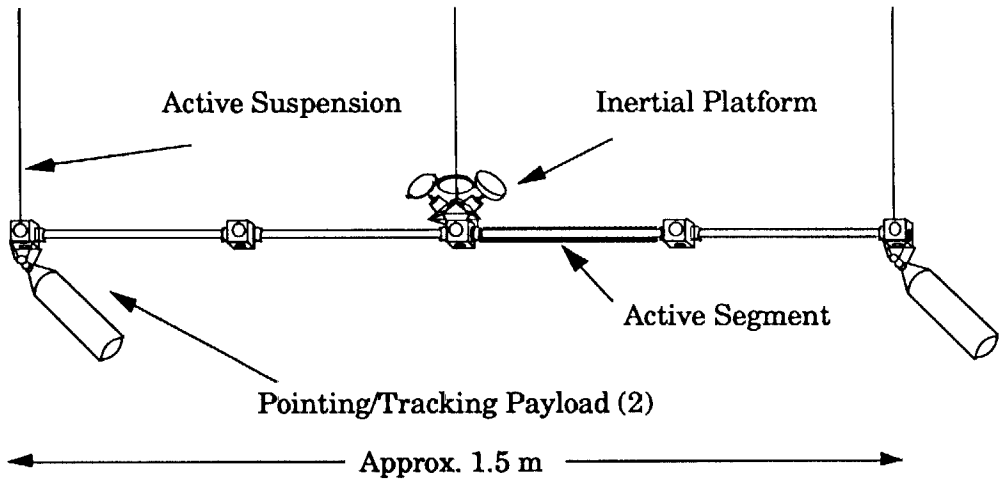
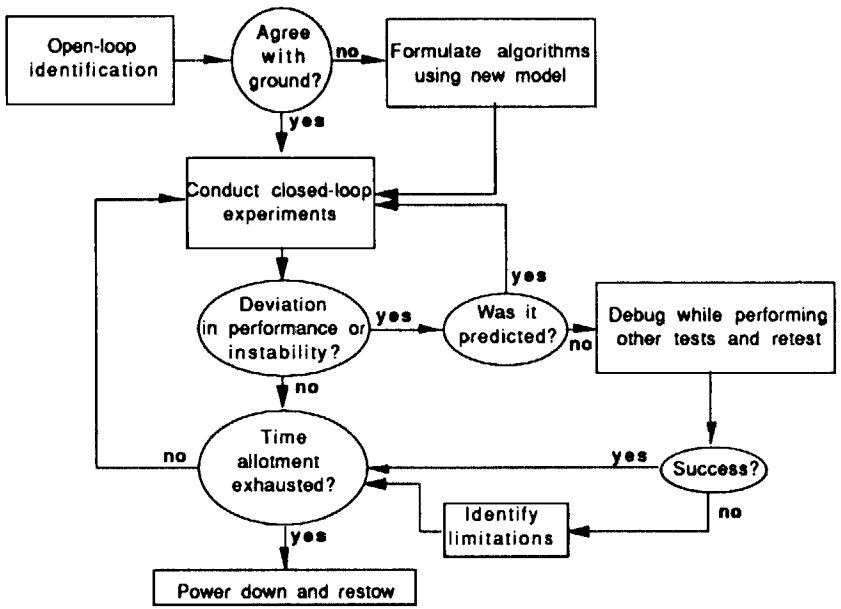
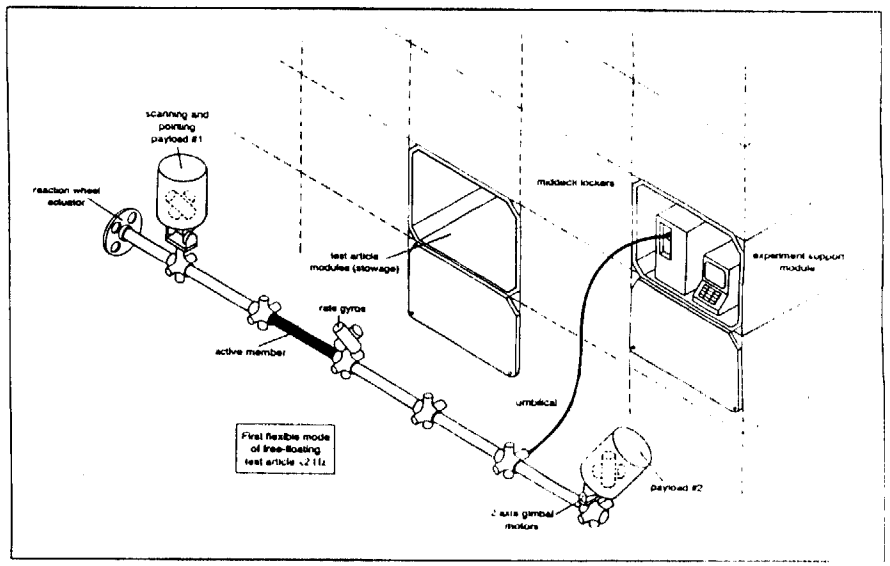
Ground Based Engineering Model Testbed



- Two pointing/tracking payloads with 120 ° motion in two axes.
- Three torque wheels for attitude and structural control.
- Active piezoelectric member for induced curvature actuation.
- 3-axis rate gyroscope packages in each payload and at torque wheel location.
- Three zero spring rate pneumatic/electric suspension devices from CSA engineering with maximum stroke of 63.5 mm.
- AC100 real time control computer from Integrated Systems, Inc.

Flight Testbed





ESM		Test Article	
Weight	54 lbs.	Weight	54 lbs.
Volume, operational	1 Middeck Locker	Volume, operational	30" x 8" x 60"
Volume, stowed	1 Middeck Locker	Volume, stowed	1 Middeck Locker
Power requirement	113 Watts @ +28 VDC	Power requirement	15 Watts
Telemetry	Downlink/uplink	Crew activities	Set-up, operations
Crew activities	Set-up, operations		
Data processing	Performed by ESM		

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Summary

- By comparing performance as a function of control authority between ground and on-orbit testing, perturbations in the dynamics due to the change from 1 to 0-g will be identified.
- By noting the level of control authority where these performance deviations occur, either analytical predictive capabilities or on-orbit identification procedures can be refined.
- The localized configuration reduces feed through of disturbances while CG mounting reduces coupling with bus flexibility.
- Nonlinear analysis on the evaluation model verifies the insights gained from the linear typical section models.
- Parametric studies are being conducted which show changes in dynamic behavior as a function of gravity and mode number.
- The flight testbed has been designed to exploit the unique environment on the STS middeck.
- Ground and flight testbed programs have been formulated to verify a set of CST tools that will allow designers to either be able to predict on-orbit behavior or allow sufficient versatility in the design to allow identification and tuning of the structure on-orbit.