The PACOSS Dynamic Test Article

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ABSTRACT

The Dynamic Test Article (DTA) developed under the Passive and Active Control of Space Structures (PACOSS) program is a test-verified laboratory system for evaluating the behavior and interaction of passive and active control strategies on dynamically complex structures. The pneumatically suspended DTA possesses high modal density in the 1 to 10-Hz frequency range, with moderate levels of passive damping (near 5% modal viscous) designed into the flexible modes. The system also includes a real-time control processor, ten reaction mass actuators, 23 velocity sensors, and a host workstation. Also, 200 accelerometers suitable for modal testing are available for identification and verification of performance.

This presentation describes the DTA system components, capabilities, and overall test results. The DTA has been delivered to the Air Force Institute of Technology where it was assembled for use in further studies of controls/structures interaction and passive damping performance.

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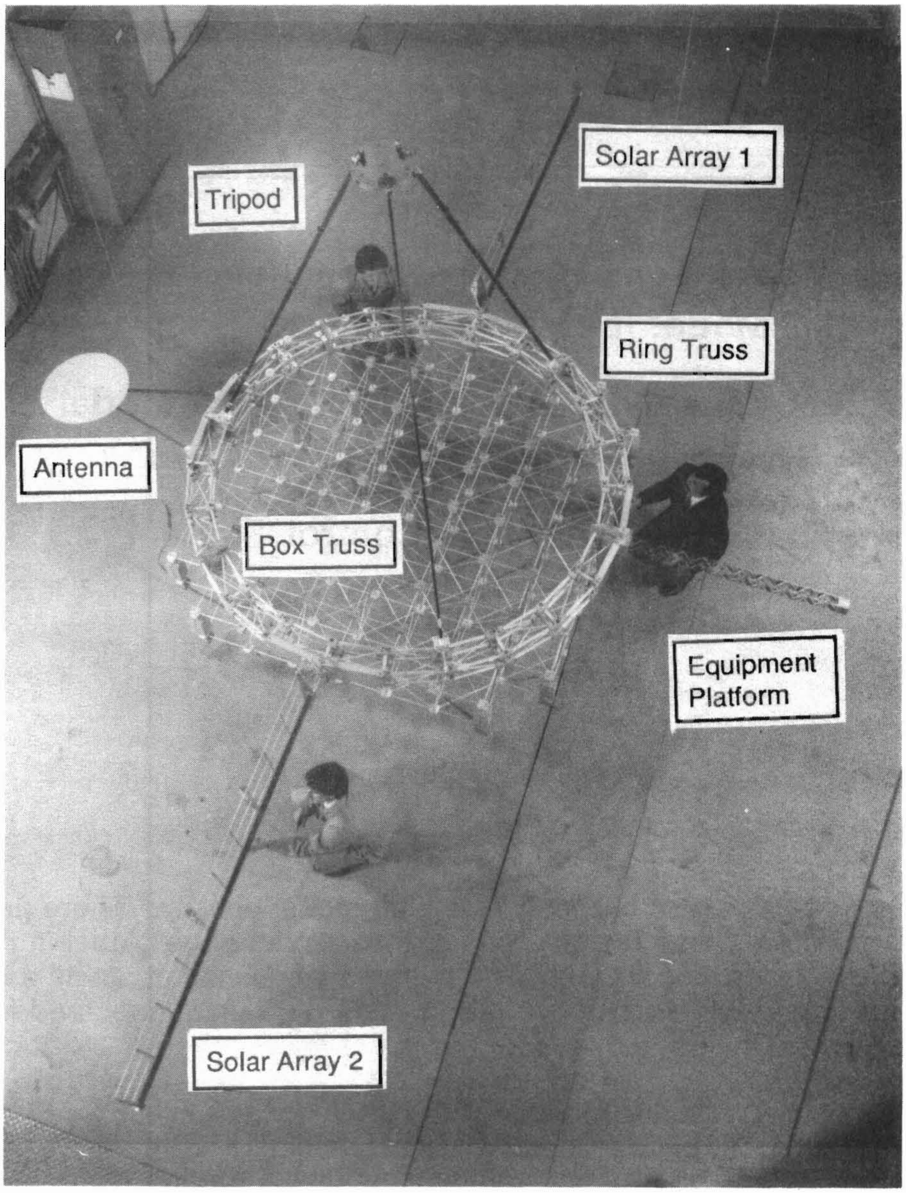
Introduction

- Future Large Space Systems Will Require Vibration Control
- Passive/Active Approach Is Most Effective Means
- DTA Designed As Testbed for Passive/Active Control Strategies

Future large space systems (LSS) will possess high modal density at low frequencies. Mission requirements for some LSS lead to control bandwidths overlapping many closely spaced structural modes. Therefore, some means of vibration control will be necessary to avoid excessive excitation of the flexible modes.

The Passive and Active Control of Space Structures (PACOSS) program has shown that a combined passive and active vibration control approach will result in a simpler system which can be expected to be more robust and reliable than a corresponding system utilizing active control exclusively.

The PACOSS Dynamic Test Article (DTA) was designed to serve as a laboratory testbed for passive and active structural vibration control implementation and testing.



THE PACOSS DYNAMIC TEST ARTICLE

The DTA consists of seven substructures; a box truss representative of a primary reflecting surface, a tripod representing a beam expander/secondary reflecting surface, two solar array simulators, a small truss representing an equipment platform, and a communication antenna simulator. A ring truss serves as the structural backbone tying the other substructures together. All substructures, except the ring truss have passive damping treatments.

Because the DTA is a validation device, sources of inadvertent damping were kept to a minimum through the use of bonded joints and precision bolted joints. Also, to avoid the need for a complicated suspension system, the DTA was designed to withstand one-g when supported from only three suspension points on the ring truss.

DTA Summary

- **High Modal Density at Low Frequencies; 23 Major Flexible Modes between 1 and 10 Hz**
- **Moderate Passive Damping (5 to 10% Modal Viscous) Designed into Structure**
- **Versatile Active Vibration Control System**
- **Extensive Instrumentation**

The primary characteristic of the DTA is high modal density. There are 23 major flexible modes between 1 and 10 Hz. Nine of these modes are global in nature, with several separated by less than 0.2 Hz. The high modal density presents a challenging modeling and control problem, thereby making the DTA a unique testbed for vibration control research.

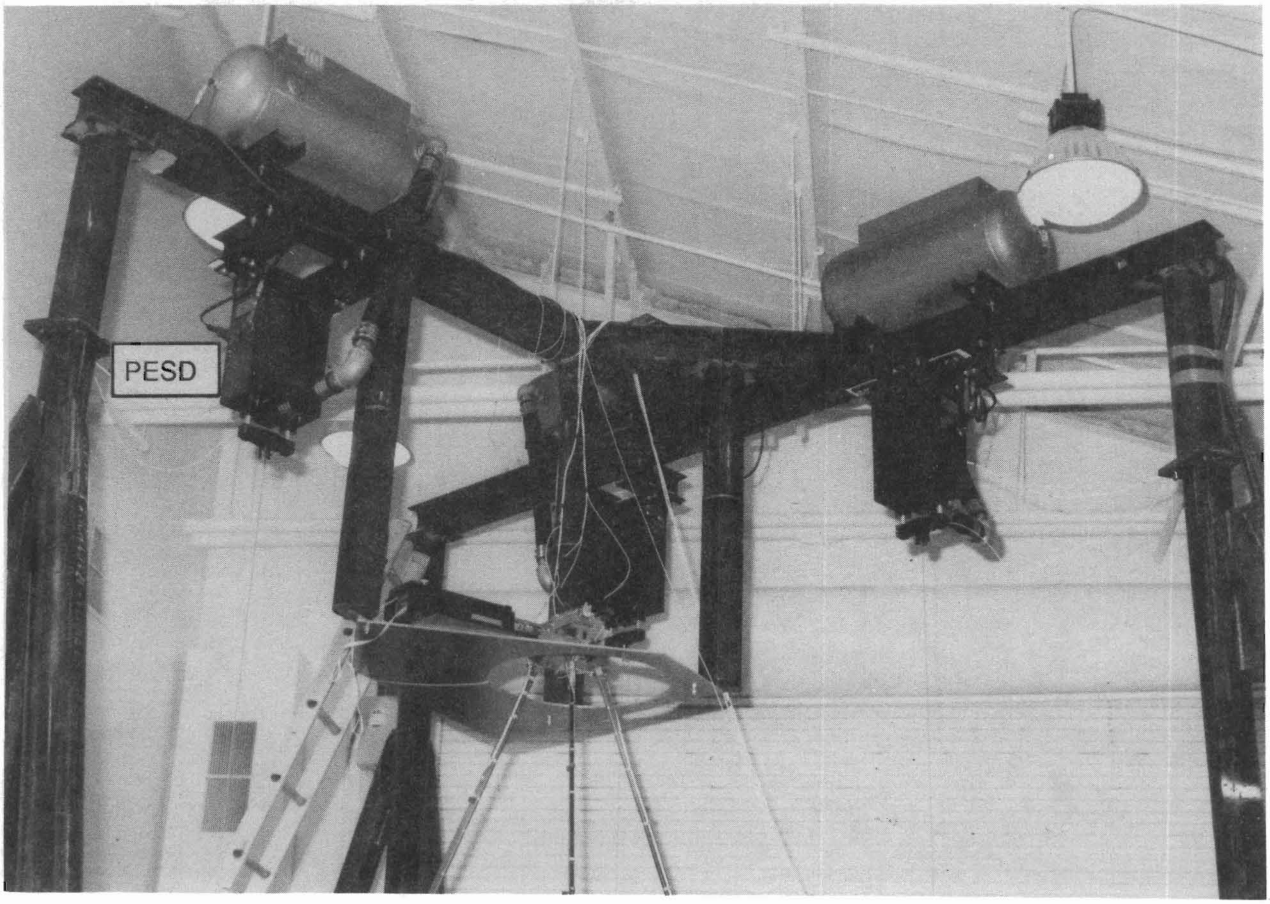
Passive damping was designed into the DTA to achieve 5% to 10% modal viscous damping in the structural modes which participate in the DTA performance metric, the line of sight (LOS). Also, a versatile active vibration control system was developed to allow implementation of a wide array of control laws. To date, five algorithms have been implemented;

Local Direct Velocity Feedback
Modal Space Control with a State Estimator
LQG Optimal Control with Loop Transfer Recovery
$\mathcal{H}_\infty$ (H-infinity) Control
LQG Optimal Control with Residual Mode Filtering

In addition to the active control system instrumentation, nearly 200 Kistler model 8632A5 accelerometers are installed for the purpose of modal testing. These light weight piezoelectric accelerometers are ideal for the 1 to 10 Hz frequency range of interest.

DTA TEST SETUP

This photo shows the DTA during testing in the Controls-Structures Interaction (CSI) Lab at Martin Marietta Astronautics Group's Main Plant. The lab maintains a uniform temperature within 2 degrees F, thereby allowing confident application of viscoelastic material properties (at a given temperature) in analysis of test articles.



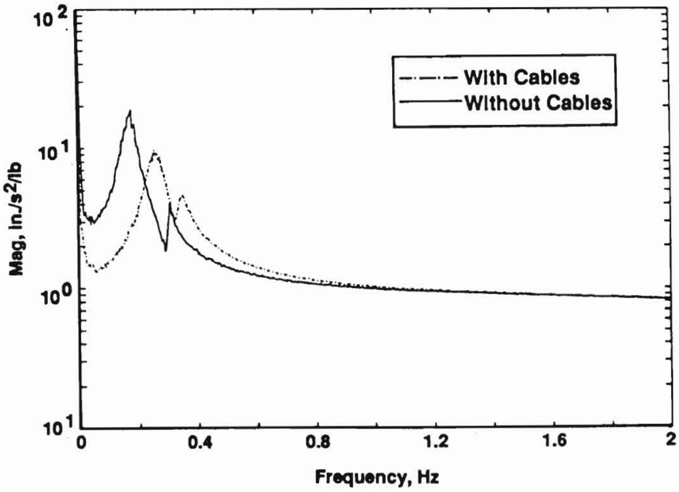
DTA PNEUMATIC-ELECTRIC SUSPENSION DEVICES

The DTA is suspended from three pneumatic-electric suspension devices recently developed by CSA Engineering Inc. The CSA devices provide a soft, virtually friction-free suspension, and are relatively easy to adjust for load ranges from 50 to 350 lbs.

Although an active centering loop is provided on each PESD, the rigid body dynamics of the DTA suspension arrangement, combined with very small restoring forces from control system and instrumentation cabling tended to keep the DTA centered without use of the active loop.

Suspension System Performance

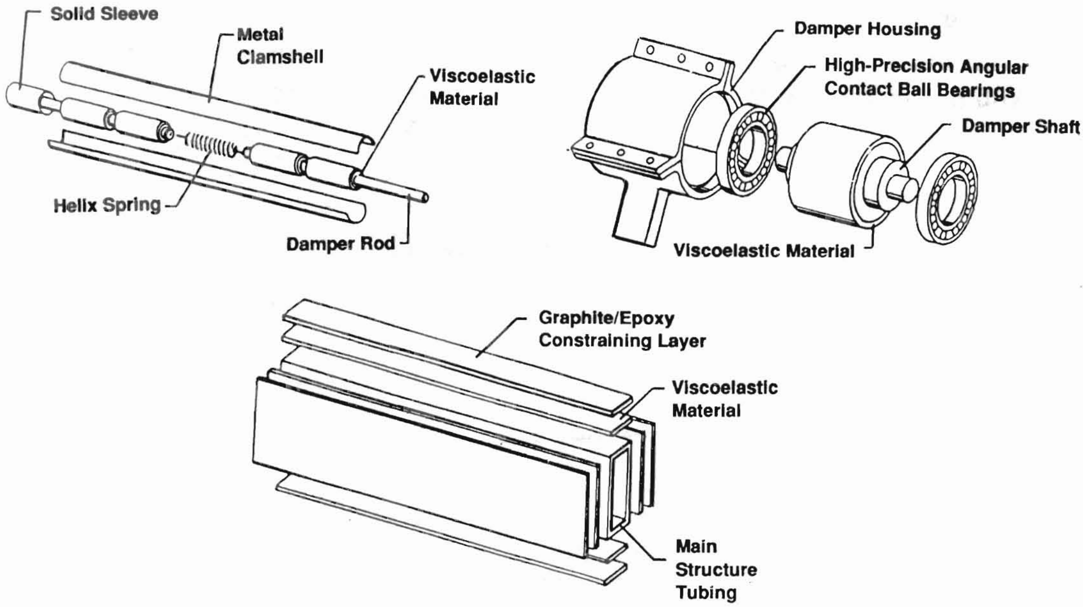
"Roll Mode"	f_n, Hz	ζ %
With Instrumentation Cables	0.26	10
Without Instrumentation Cables	0.17	11
Predicted	0.15	?



This figure shows the success of the PESDs in achieving a low frequency suspension. Also, the effect of modal survey instrumentation cables is apparent. The frequency response function (FRF) shown by the dashed line was measured with approximately 180 microdot cables attached to the Kistler accelerometers mounted on the DTA. The observed resonant frequencies were much greater than predicted by analysis including the PESD stiffness, and pendulum effects. However, as shown by the FRF denoted with a solid line, when the instrumentation cables were removed, the agreement between predicted and measured rigid body frequencies was excellent. Similar results were seen for the other suspension modes.

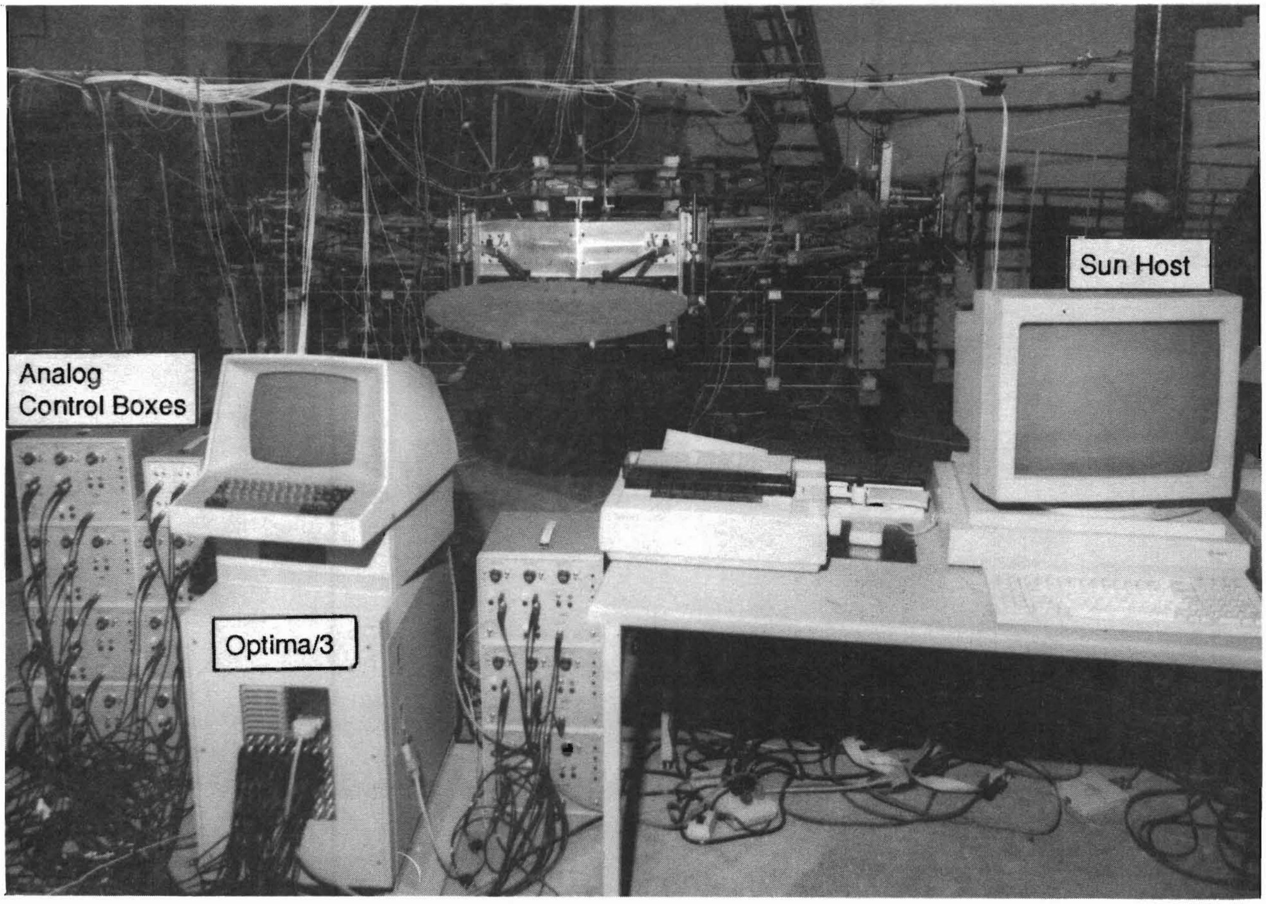
While there is no measurable friction in the PESDs, air movement through a 20-micron filter paper does dissipate energy, thereby giving rise to the apparent damping present in the suspension modes. However, the loss is well modeled by linear viscous damping, and is insignificant with regard to the DTA flexible modes.

DTA Passive Damping



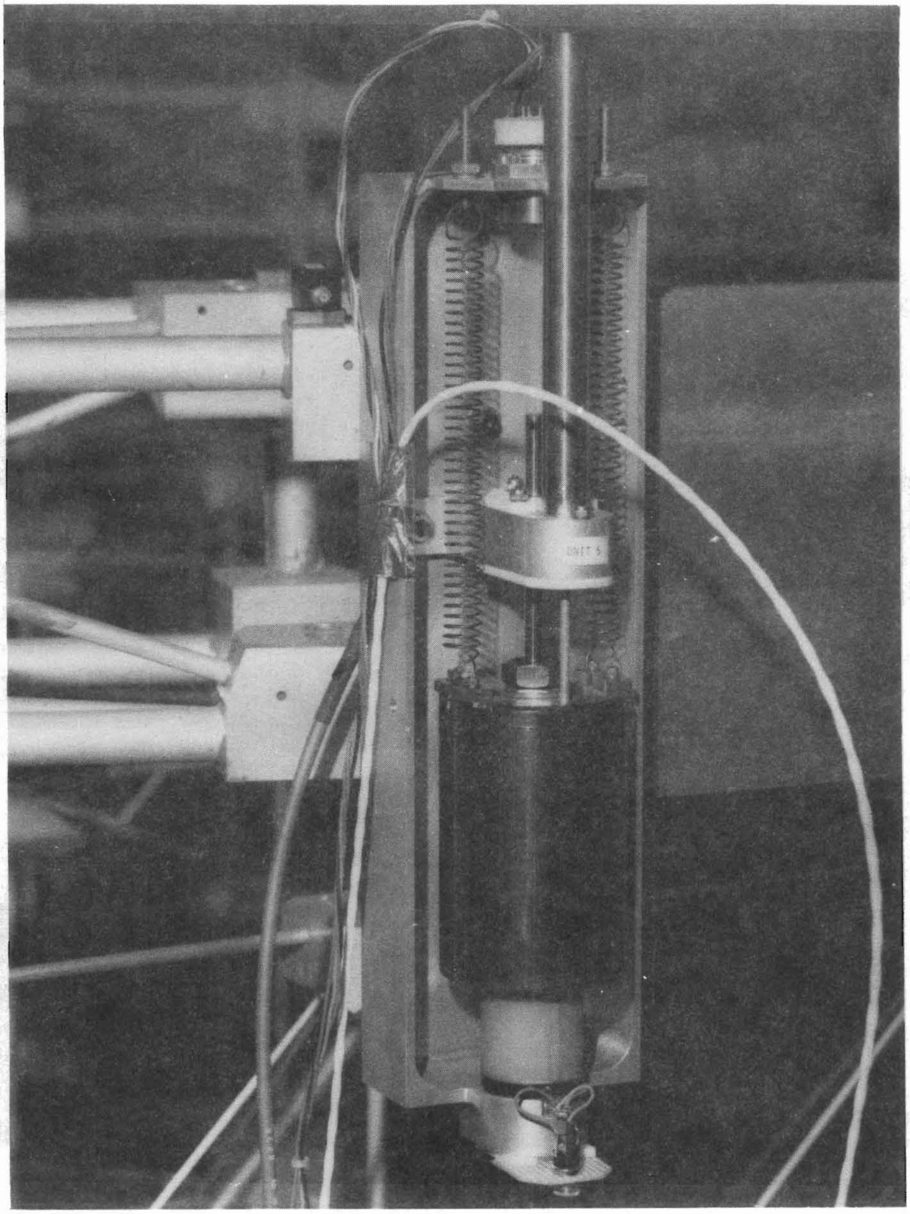
Six different types of viscoelastic damping treatments were applied to the DTA, three of which are shown in this figure. The design and placement of each treatment was based on the modal strain energy method.

Extensional shear dampers are used in the box truss and equipment platform, and are effective in damping lower truss modes. Rotational shear dampers are located at each tripod leg/secondary mirror interface to damp modes involving relative rotation between the legs and mirror. Constrained layer treatments are used on the tripod legs, antenna legs, and solar array masts. The DTA antenna dish has an integral damping treatment. Viscoelastic shear straps are used to further damp vertical bending of the solar array masts, while tuned mass dampers suppress solar array blanket modes.



DTA CONTROL SYSTEM COMPUTERS

This photo shows the DTA active control system equipment. The control processor is an Optima/3 which is based on a Motorola 68030 CPU. The Optima/3 is hosted by a Sun-3 workstation which is used to generate and download an executable control code to the Optima/3. Single-ended analog inputs are sampled by the Optima/3, processed according to the control code, and output. The input and output signal range is +/- 10 volts. DC drift of the DAC is negligible and the noise level is in the 10 to 20 millivolt range. Also shown in the photo are the signal conditioning/current drive control boxes for the actuator/sensor units.

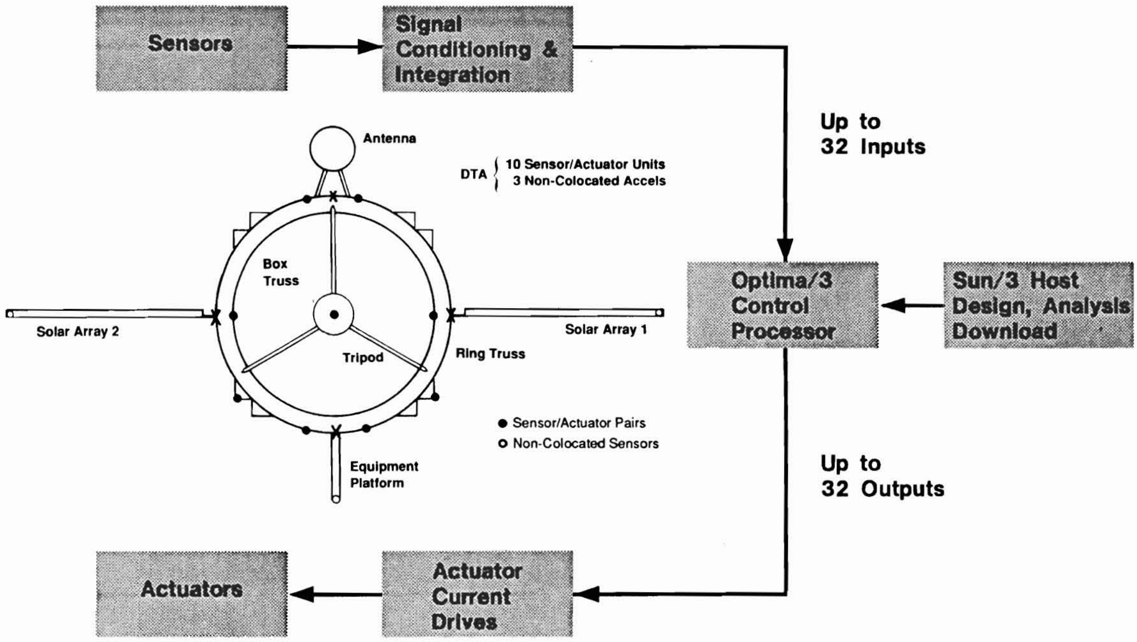


DTA REACTION MASS ACTUATOR

This photo shows an actuator/sensor unit. Each unit consists of a linear motor with a linear velocity transducer (LVT) to measure the relative velocity between the motor mass and actuator frame, and a Sundstrand QA-1400 accelerometer to measure inertial acceleration. The motor mass is supported on springs which give the actuator a 1.5 Hz natural frequency. The actuator stroke is approximately +/- 1 in. The pictured actuator is in a vertical configuration. Four DTA actuators may also be configured for horizontal operation with opposing extensional springs. In the horizontal configuration, the actuator natural frequency is about 0.7 Hz.

The QA-1400 signal is integrated in the signal conditioning electronics via an analog bi-quad filter to provide inertial velocity of the control point. The LVT signal is used to increase the damping of the actuator, and also is integrated to provide a motor mass position feedback allowing adjustment of the actuator f_n from about 1.2 to 1.8 Hz.

Control System Summary

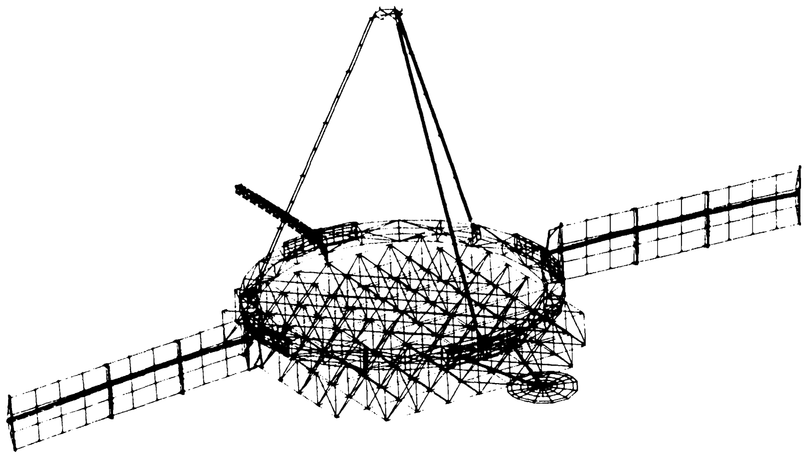


Optima/3 Processing Speed: 64 States, 23 Inputs/10 Outputs: 280 Hz

This figure summarizes the DTA active vibration control system. Each actuator/sensor unit produces two sensor signals (inertial acceleration and relative reaction mass velocity) which are fed to the analog signal conditioning electronics. Also, three non-collocated acceleration measurements are available. The inertial acceleration measurements are integrated and sent to the Optima/3 ADCs along with the LVT signals. The Optima/3 will accept up to 32 input channels, and also output up to 32 channels. In the current DTA configuration, there are 23 inputs, and 10 outputs. The Sun host workstation is used for design, analysis, and download of control algorithms to the Optima processor. Analog outputs from the Optima are sent to the actuator current drives which command a current directly proportional to the command voltage. Finally, the actuators apply a force proportional to the current command on the DTA.

The processing speed of the Optima allowed a 64 state control law with 23 inputs and 10 outputs to be processed at 280 Hz; well above the 10 to 20-Hz bandwidth of control laws applied to the DTA. Thus, it was not necessary to consider discretization effects of the control system.

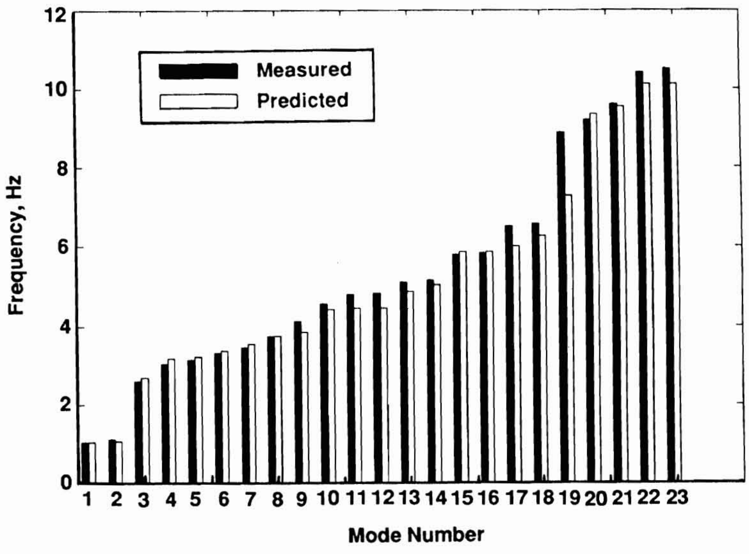
DTA Analytic Model



- **23 Modes Correlated with Test Results**
- **9 Global Modes**

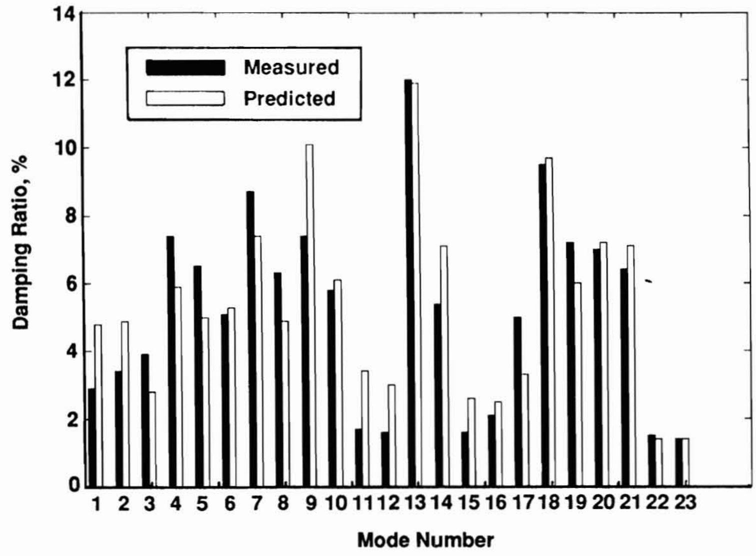
A detailed finite element model of the DTA involving over 10,000 degrees of freedom was developed and test verified during the PACOSS program. Each substructure was modeled and test verified before the full DTA was tested. The 23 major flexible modes between 1 and 10 Hz were successfully identified in the DTA modal survey, and correlated with analytic modes.

DTA Natural Frequencies



Agreement between measured and predicted natural frequencies was excellent for nearly all of the identified modes. This figure presents a bar chart to graphically depict the agreement. All natural frequencies agree to within 5% with the exception of mode 19 which is a local antenna dish mode.

DTA Modal Damping



This figure presents the measured and predicted (via the modal strain energy method) modal damping ratios. The agreement is typically within 20% which is quite good considering the difficulty in determining damping ratios from the measured data. Closely spaced, highly damped modes lead to FRF measurements which cause scatter of nearly +/- 20% in identified damping ratios.

Test Setup and Analysis Validity Checks

- **Instrumentation Cable Effects**
- **Linearity**
- **Closed-Loop Analysis**

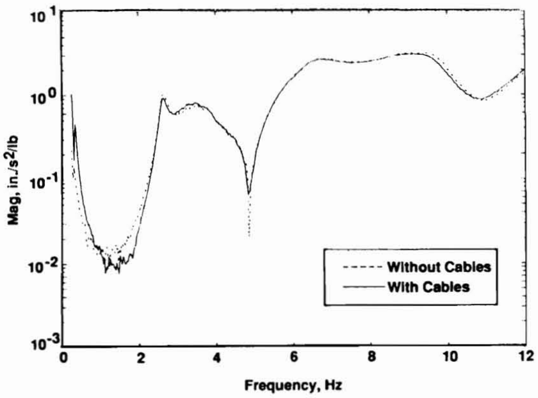
During DTA closed-loop testing, differences between the measured and predicted frequency response functions (FRF) led to an evaluation of the validity of the test setup and analysis techniques. Were the observed differences simply due to analytic model inaccuracies, or were they due to a test setup problem or the real mode model of the DTA? Three issues were investigated:

Possible instrumentation cable effects on DTA flexible modes
DTA and control system linearity
Real versus complex modes used in the DTA model.

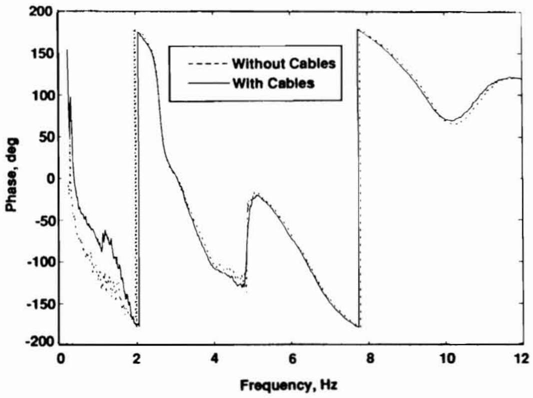
Instrumentation Cable Effect

Typical DTA FRF

Magnitude



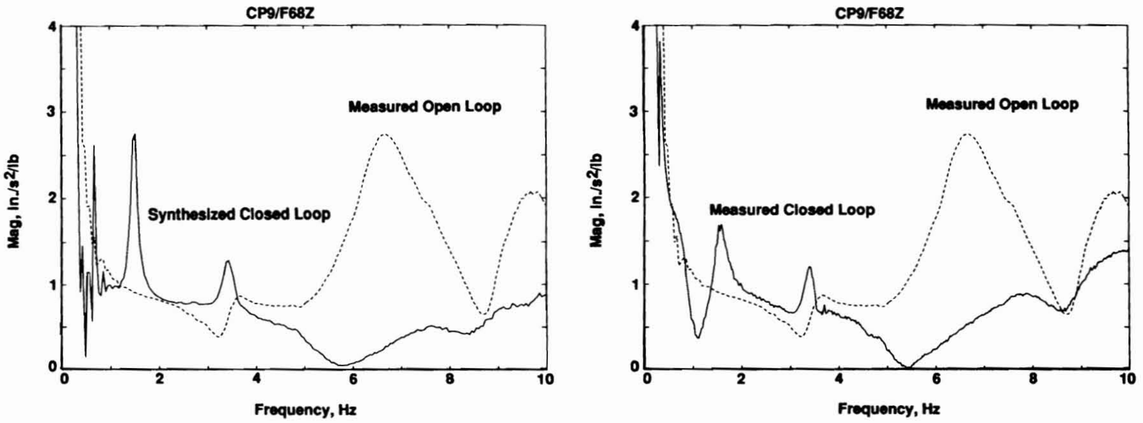
Phase Angle



Possible instrumentation cable effects were investigated by removing nearly all of the over 180 microdot cables from the DTA. The plots shown in this figure are FRFs taken before and after removing the cables. Clearly, the instrumentation cables have a negligible effect on the DTA dynamics above 2 Hz.

Synthesized Closed–Loop FRFs

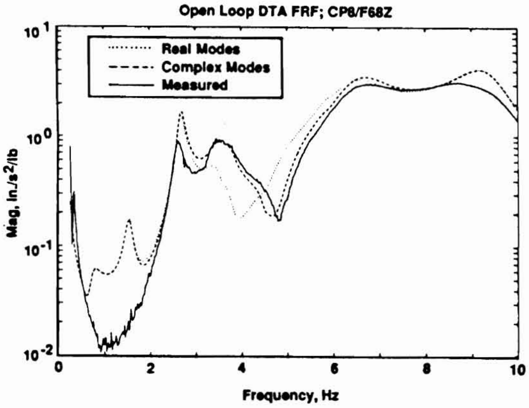
- **Form Closed–Loop FRFs from Open–Loop Measurements and Analytic Compensator**

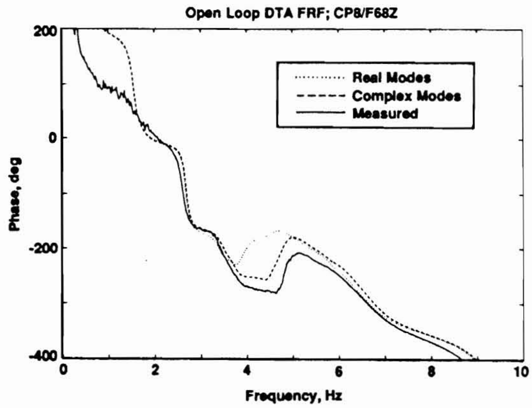


To investigate the linearity and function of the DTA control system, closed-loop FRFs were synthesized using the analytic compensator transfer functions, and measured open-loop FRFs between the DTA control points. The idea here is that if the control system is functioning as modeled, and the DTA is a linear system, the synthesized FRFs should agree with the actual closed-loop measured FRFs. This figure demonstrates good agreement between a synthesized and measured FRF using the LQG/LTR control law, thereby indicating that the control system indeed performs as designed and modeled, and that the DTA behaves as a linear system.

Complex Modes

- **Couple Compensator to DTA Modeled with Real and Complex Modes**





As previously mentioned, the DTA model used for control law design and analysis was generated using real modes. However, some sample studies indicated that in the presence of closely spaced modes and relatively high damping, closed-loop results can be significantly altered if complex modes are used in the plant model rather than real modes.

To investigate the effect of complex modes in the DTA analysis, complex modes for the DTA were calculated from the reduced DTA mass and complex stiffness matrices. The reduction was performed via the Guyan technique using only the real part of the stiffness matrix. The figure shows three open-loop FRF plots; an actual measurement, the corresponding analytic FRF computed using real modes/MSE approach, and the analytic FRF computed using complex modes. Note that the FRF from complex modes generally agrees better with the measurement, particularly in the 3 to 5 Hz range. Not coincidentally, the 3 to 5 Hz range possesses the highest modal density of the DTA and encompasses many global modes.

Although the open-loop agreement is improved when complex rather than real modes are used in analysis of the DTA, the closed-loop results did not change as significantly. Many of the closed-loop anomalies seen during DTA testing were not explained by using complex modes, and the overall agreement between test and analysis was not greatly improved.

Conclusion

- **DTA Exhibits Characteristics of Future LSS**
- **Analytic Model Is Quite Good**
- **Control System Behaves Linearly**
- **DTA Will Be Set Up at Air Force Institute of Technology for Further Passive/Active Research**

The DTA exhibits the dynamic characteristics expected of future LSS: high modal density at low frequencies. Passive damping designed into the structure provides a somewhat more forgiving system for investigation of active control algorithms. Also, further passive control approaches can be implemented due to the substructure assembly of the DTA. Thus, the DTA is an excellent testbed for continuing research of LSS structural vibration control, both passive and active.

The analytic model of the DTA is test verified up to 10 Hz and predicts open-loop DTA behavior relatively accurately. However, it may be insufficient for accurate prediction of the performance of high authority modern control laws. Any further model improvement would most likely involve empirical tuning, since the finite element model has been exhaustively reviewed and refined based on DTA dimensions and element tests.

The DTA control system behaves linearly and is highly versatile. While only linear constant coefficient control laws have been implemented thus far, the Optima/3 is capable of implementing any control algorithm that can be coded in "C", including adaptive control.

The DTA has been set up at the Air Force Institute of Technology for further passive/active controls research.