IN-HOUSE EXPERIMENTS IN LARGE SPACE STRUCTURES
AT THE
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
FLIGHT DYNAMICS LABORATORY

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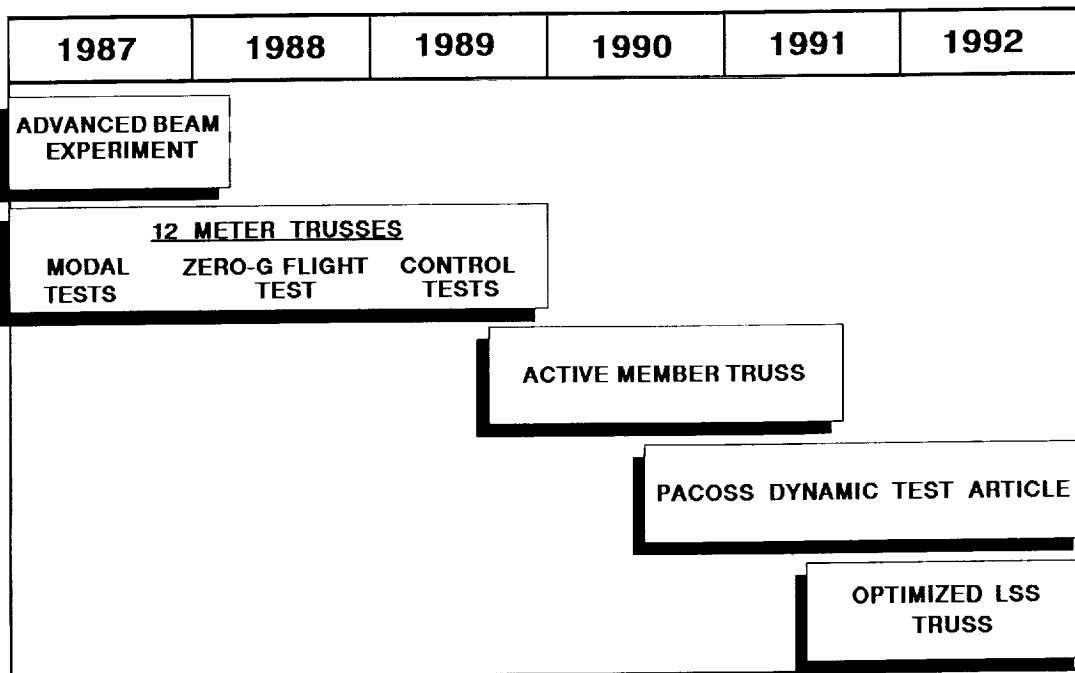Columbus, Ohio

Introduction

The Structures Division of the Air Force Wright Aeronautical Laboratories Flight Dynamics Laboratory is conducting an inhouse exploratory development program in the dynamics and control of large space structures (LSS). The effort, entitled "Large Space Structures Technology Program," was initiated in 1985 to investigate several technical areas important to the development of future LSS. These areas include ground suspension and test methods, passive and active vibration control approaches, and sensors and actuators for vibration control. The program is being performed in the Structural Dynamics Branch. Support for active control development is provided by the Ohio State University, under contract.

The overall objective of the Large Space Structures Technology Program is to establish a capability in the Structures Division for dynamic analysis and testing of large, flexible space structures with passive and active vibration control. The program approach is to conduct a series of experiments addressing the areas of ground testing, passive and active vibration control, and sensors and actuators. The figure depicts the schedule for these experiments. The first experiment, the Advanced Beam Experiment, evaluated the performance of active vibration control approaches on a bending-torsion cantilever beam equipped with two pairs of linear momentum exchange actuators. The 12 Meter Trusses provide a test bed for several experiments in modal testing and active control of large, low frequency truss structures with significant passive damping. The Active Member Truss Experiment will address the effectiveness of active members in providing low frequency vibration control in truss structures. In mid-1990, the PACOSS Dynamic Test Article (DTA) will be set up as a test facility for the evaluation of system identification and active control approaches for structures with significant passive damping. The DTA was developed on the Passive and Active Control of Space Structures (PACOSS) contract. The final experiment in the program is the Optimized LSS Truss which will be a modular truss test bed for evaluating optimized structures with passive and active control.

INHOUSE EXPERIMENT SCHEDULE

1987	1988	1989	1990	1991	1992

ADVANCED BEAM EXPERIMENT

12 METER TRUSSES

MODAL TESTS   ZERO-G FLIGHT TEST   CONTROL TESTS

ACTIVE MEMBER TRUSS

PACOSS DYNAMIC TEST ARTICLE

OPTIMIZED LSS TRUSS

Advanced Beam Experiment

The Advanced Beam is a bending-torsion beam active vibration control experiment. The objective is to experimentally evaluate the performance of linear momentum exchange actuators and popular control approaches on a simple structure with multiple, low frequency modes. The experiment incorporates a vertically oriented slender aluminum beam, cantilevered at the top from a stiff frame. Control forces are provided by two pairs of actuators mounted on an aluminum disk at the beam free end. The aluminum disk serves to reduce the fundamental torsion mode frequency while providing an actuator mounting surface. A piezoelectric accelerometer is collocated with each actuator as a sensor. The actuators are modified versions of the VCOSS II design now in use at the NASA Marshall Space Flight Center's facility.

.75"X1.5"x72" BEAM

END PLATE WITH 4 ACTUATORS AND COLLOCATED ACCEL'S
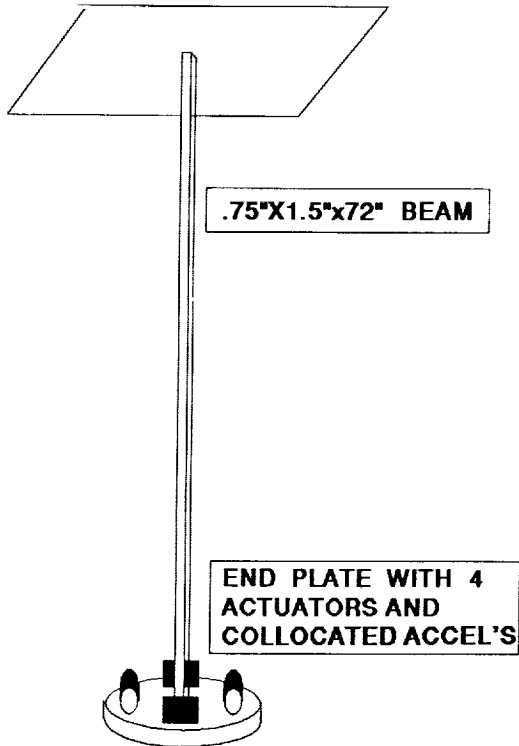
OBJECTIVE

DEMONSTRATE ACTIVE VIBRATION CONTROL ON A SIMPLE STRUCTURE WITH:

- NONGROUNDED SENSORS AND ACTUATORS

- MULTIPLE, LOW FREQUENCY MODES

APPROACH

TEST A SLENDER CANTILEVER BEAM WITH END MASS

CONTROL BENDING AND TORSION MODES

Advanced Beam Experiment Hardware

The Advanced Beam hardware is shown in the figure. The support frame for the beam is mounted to a seismic table located in the vibration test facility at the Flight Dynamics Laboratory. The two pairs of linear momentum exchange actuators can be seen mounted on the disk at the free end of the beam. Each pair of actuators can be commanded in phase to control one bending plane while either pair can be commanded out of phase to control torsion. The beam has fundamental bending frequencies of approximately 1.3 Hz and 1.6 Hz in the two bending planes and a fundamental torsion frequency of about 13 Hz.
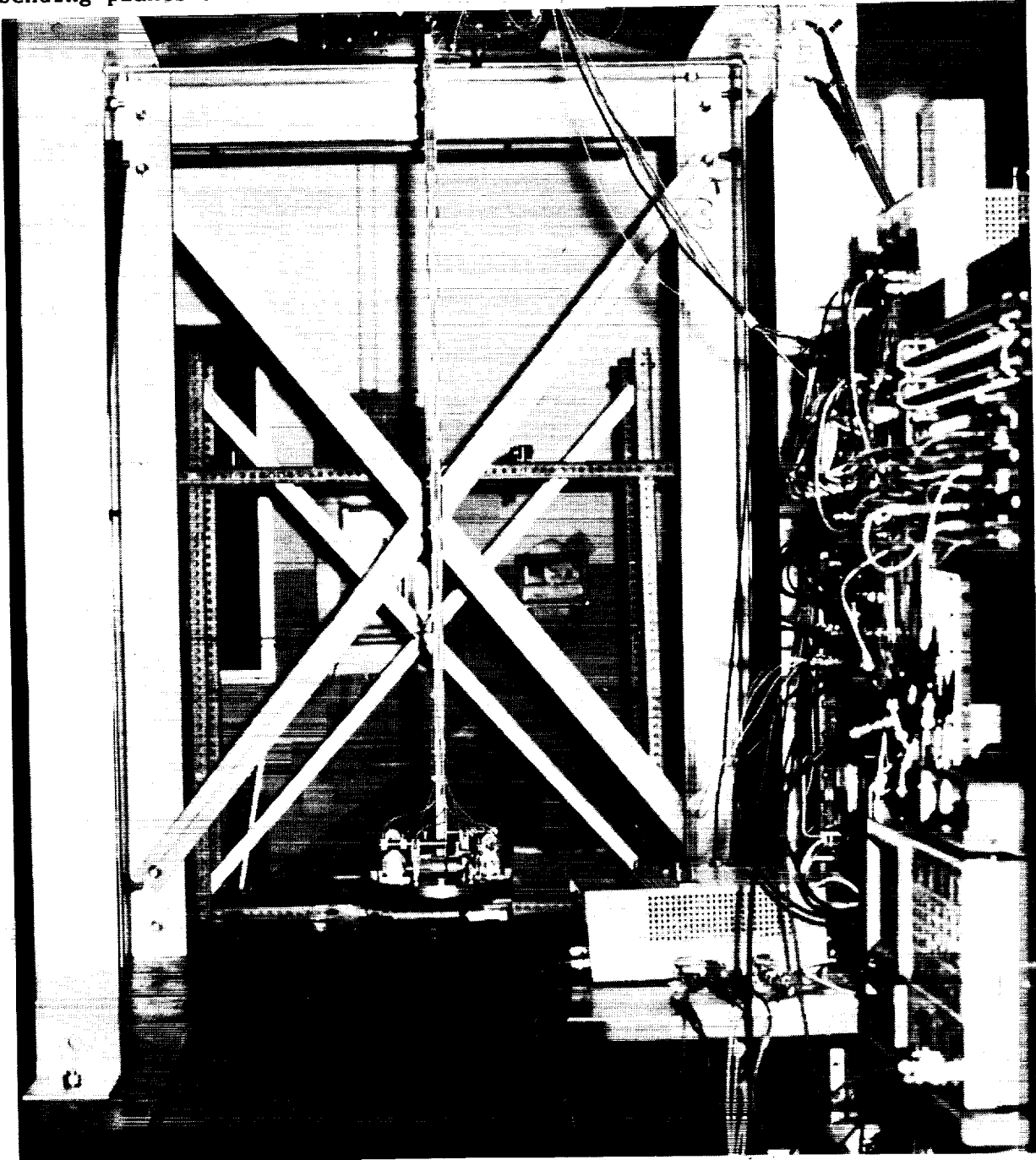
Ohio State University Work on the Advanced Beam Experiment

The Ohio State University provided considerable effort in support of the Advanced Beam Experiment. The effort included both analytical and experimental development of hardware and control system design and testing. They developed and verified an analytical model of the actuator as well as analog compensator circuitry to provide acceptable actuator dynamic response. They also developed a mathmatical model of the total system and corrected it with open loop test results. Several control approaches were developed for the beam, as listed in the figure. Controller performance was evaluated analytically and three controllers were tested; HAC/LAC, Maximum Entropy Optimal Projection (MEOP), and decentralized LQG with frequency shaping.

- **DEVELOPED ANALYTICAL AND EXPERIMENTAL ACTUATOR MODELS**

- **DESIGNED ACTUATOR COMPENSATOR**

- **DEVELOPED BEAM ANALYTICAL MODEL**

- **DESIGNED AND PERFORMED SIMULATION OF SEVERAL CONTROLLERS**
  - HAC/LAC
  - LQG/LTR
  - MEOP
  - VARIABLE STRUCTURE CONTROL
  - PARAMETER ROBUST LQG
  - DECENTRALIZED LQG

- **TESTED THREE CONTROLLERS ON THE BEAM**
  - HAC/LAC
  - MEOP
 - DECENTRALIZED LQG / FREQUENCY SHAPING

Advanced Beam Experiment Conclusions

Active control performance testing on the Advanced Beam Experiment was completed in April 1988. Several conclusions can be drawn from the completed work. A well characterized dynamic system was achieved. Initial analytical models agreed well with open-loop test and were improved based on the test data. Compensation circuitry designed to "tame" actuator dynamics worked reasonably well in practice, although a better actuator design might have eliminated the need for compensation altogether. Active modal damping in excess of 10% was achieved in the fundamental bending modes of the beam. Although higher damping might be expected, 10% is reasonable given the limited actuator output available. The actuators were the single biggest limiting factor in active control performance. The momentum exchange design is inherently limited in low frequency force output. The actuators were rated at over 4 pounds force output, but could only develop rated output above approximately 10 Hz. The actuators were capable of only 0.1 pounds force at the lowest beam frequency of 1.3 Hz. In addition, the actuators were relatively massive compared to the beam alone. This significant mass tended to limit modal displacement at the beam free end, and therefore control authority in other than the fundamental bending modes was severely limited. Finally, actuator dynamics increased open-loop damping in the fundamental bending modes. This is not necessarily bad, but it tended to mask the increase in modal damping achieveable though active control.

- **A WELL CHARACTERIZED SYSTEM WAS ACHIEVED**

- **ACTUATOR COMPENSATION WORKED REASONABLY WELL**

- **ACTIVE MODAL DAMPING OF OVER 10% WAS ACHIEVED**

- **ACTUATORS LIMITED ACTIVE CONTROL PERFORMANCE**

  - **LIMITED LOW FREQUENCY FORCE OUTPUT**

  - **POOR AUTHORITY IN HIGHER MODES**

  - **ACTUATORS INCREASED OPEN-LOOP DAMPING**

12 Meter Truss Modal Tests

The 12 Meter Truss Experiment is investigating ground test methods and active control approaches for large, low frequency structures. The trusses are 12 meter long truss beams; one with relatively high modal damping, the other with light damping. A series of modal tests is being conducted on the trusses to evaluate modal parameter test and suspension methods for lightly and heavily damped truss structures. Both trusses have been tested in a vertical orientation, cantilevered to the floor. Modes in the 0 to 50 Hz frequency range are being identified and compared with finite element model predictions. The undamped truss will then be tested in a horizontal orientation, suspended on soft springs, to simulate the zero gravity space environment. Data from both test configurations are being used to improve the model of the undamped truss for subsequent active control analysis and testing. After completion of ground testing, the undamped truss will be tested in the NASA Johnson Space Center's zero-gravity test aircraft to obtain true zero-g modal parameters.
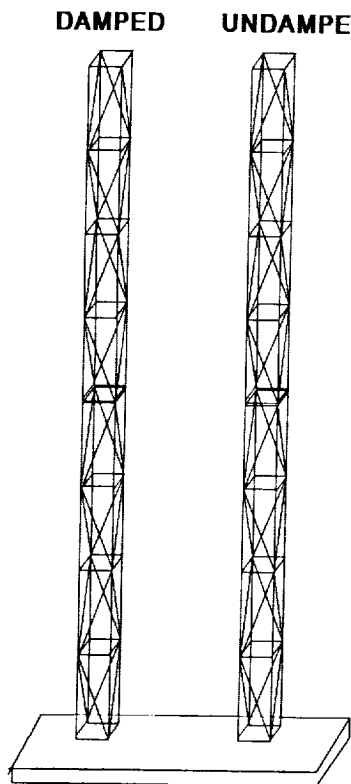
DAMPED **UNDAMPED**

OBJECTIVES

EXPERIMENTALLY DETERMINE THE MODAL PARAMETERS OF LIGHTLY AND HEAVILY DAMPED TRUSS STRUCTURES

USE MULTIPLE BOUNDARY CONDITION TEST RESULTS TO IMPROVE ANALYTICAL MODELS

APPROACH

TEST TWO, 12 M LONG TRUSS BEAMS, ONE UNDAMPED AND ONE WITH VISCOELASTIC DAMPERS

TEST THE TRUSSES IN VERTICAL CANTILEVER AND HORIZONTAL FREE-FREE CONDITIONS

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12 Meter Truss Vertical Cantilever Test Configuration

The undamped 12 meter truss is shown in the figure in the vertical cantilever test configuration. The truss can be seen near the center of the figure with access scaffolding mounted close to it on three sides. The undamped truss consists of a welded aluminum tube frame with bolt-in diagonal members of Lexan plastic. Lexan has a relatively low loss factor which results in modal damping values of less than .5% of critical damping for the lower order modes of the truss. Low damping coupled with fundamental bending frequencies of approximately 2 Hz provides a structure with dynamic characteristics representative of future large space structures. The damped truss has a welded aluminum frame identical to the undamped truss, but has aluminum diagonal members with viscoelastic dampers instead of the Lexan tubing. The diagonal members are arranged in the truss to maximize their modal strain energy content in the lower order modes and therefore maximize damping.
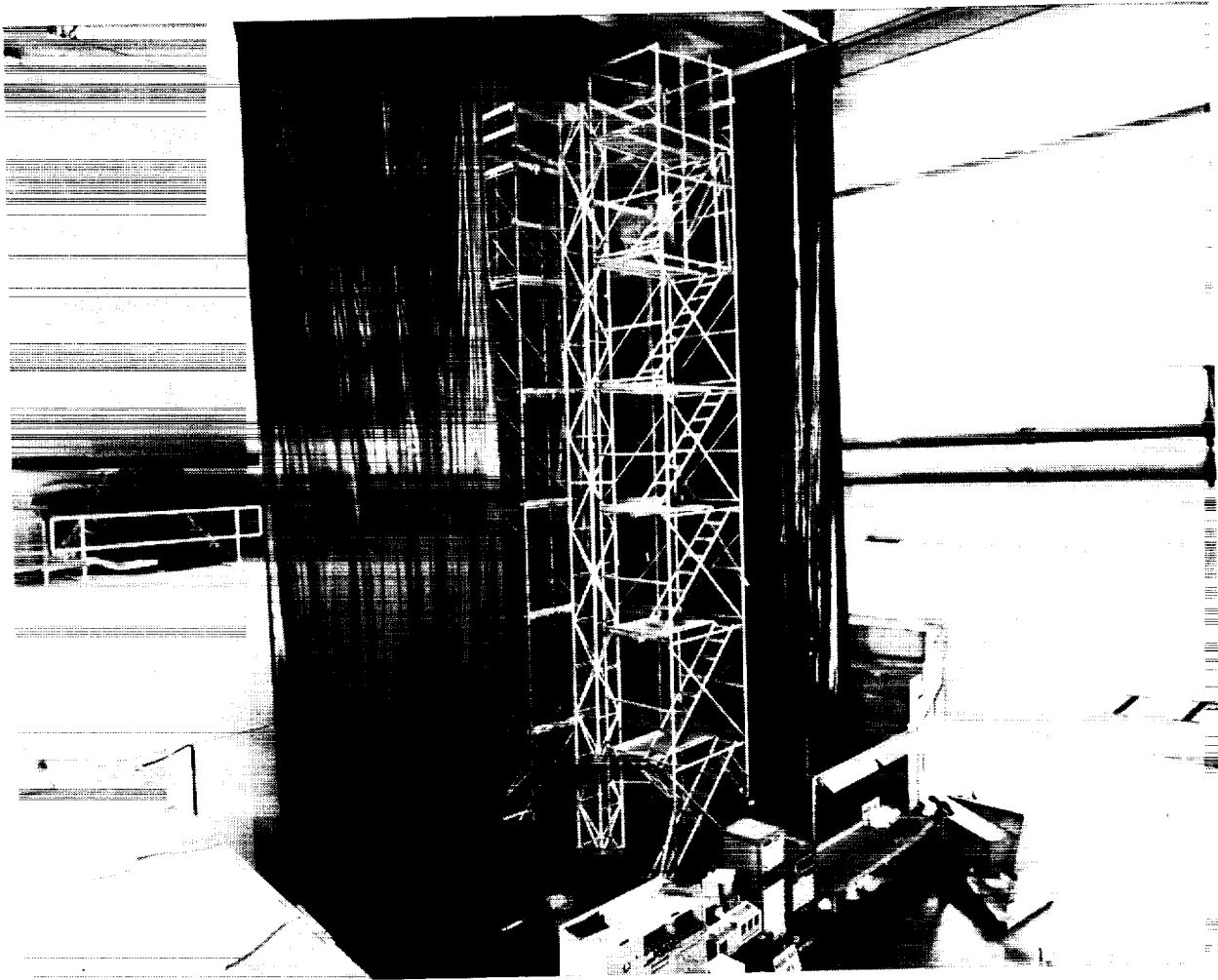
Undamped 12 Meter Truss Modal Test Results

Modal testing of the undamped 12 meter truss in the vertical cantilever configuration has been completed. Measured frequencies and modal damping values for the lowest 6 modes are listed in the figure along with predicted frequencies from a finite element model. The bending modes occur in pairs with nearly coincident frequencies, as predicted by the model. However, the model overestimates the fundamental bending frequencies by more than 10%. In contrast, the model underestimates the first torsion frequency by 11%. These discrepancies are partially due to the boundary conditions at the truss base which are modelled as clamped but actually provide some flexibility. Additional error is likely due to the lack of detail in the modelling of the truss joints. Results from the upcoming horizontal, free-free test of the truss will help separate these boundary condition effects from other model parameters. Measured modal damping values are in the range of .1% to .5% of critical damping, as desired.

| MODE | FREQUENCY (HZ) | | | DAMPING (%) |
	TEST	PREDICTED	ERROR (%)	TEST
IST X BENDING	2.26	2.48	+9.5	.19
1ST Y BENDING	2.25	2.50	+10.9	.18
1ST TORSION	7.10	6.34	-10.8	.33
2ND X BENDING	10.72	10.90	+1.7	.18
2ND Y BENDING	10.72	11.00	+2.6	.21
2ND TORSION	21.27	19.04	-10.5	.27

Damped 12 Meter Truss Modal Test Results

Modal testing of the damped 12 meter truss in the vertical cantilever configuration is nearly completed. Measured frequencies and modal damping values for the lowest five truss modes are tabulated in the figure. Predicted frequencies and damping values are included in the figure for comparison. The Modal Strain Energy method was used to predict modal damping from finite element models incorporating 2 Hz and 10 Hz viscoelastic properties. The analysis is thus valid for modes which occur close in frequency to the VEM frequency used. The agreement between predicted and measured frequency for the bending modes is reasonably good. The predictions for all modes except 1st X bending are from a preliminary model based on 72 deg. F viscoelastic properties while the 1st X data are from an improved model which incorporated data for the exact test temperature. The damping estimate for the 1st X bending mode is in error by a factor of two while the the higher modes show even larger errors. These errors in predicted damping are most likely due to the unmodelled flexibility at the truss base. The 1st torsion mode, which is predicted to have almost 50% damping, has not yet been identified.

	FREQUENCY (HZ)			DAMPING (%)	
MODE	TEST	PREDICTED	VEM	TEST	PREDICTED
1ST X BENDING	1.87	1.88 *	2	4.3	8.6 *
1ST Y BENDING	1.91	2.03	2	4.1	16.4
1ST TORSION	**	4.35	2	**	42.7
1ST TORSION	**	6.40	10	**	47.0
2ND X BENDING	10.6	10.18	10	6.6	25.8
2ND Y BENDING	11.2	10.29	10	7.4	27.2

* CORRECTED MODEL RESULTS

** MODES NOT YET IDENTIFIED DUE TO HIGH DAMPING

A modal test of the undamped 12 meter truss will be performed in a horizontal configuration suspended from zero spring rate mechanisms (ZSRM's) to simulate the zero gravity conditions in space. The test configuration is illustrated in the figure. The truss will be suspended on flexible cables from two ZSRM's as shown. The ZSRM's act as very soft springs which uncouple the truss vibration response from suspension dynamics in the vertical direction. The ZSRM design being used was developed at NASA and has been adapted from a device currently in use at Martin Marietta Corporation. The suspension cables provide nearly free motion in the horizontal plane. Modal data measured from this test will be used in combination with the zero-g flight test data to evaluate the performance of the ZSRM's and to improve the undamped truss finite element model.

ZERO SPRING RATE MECHANISMS

UNDAMPED 12 METER TRUSS
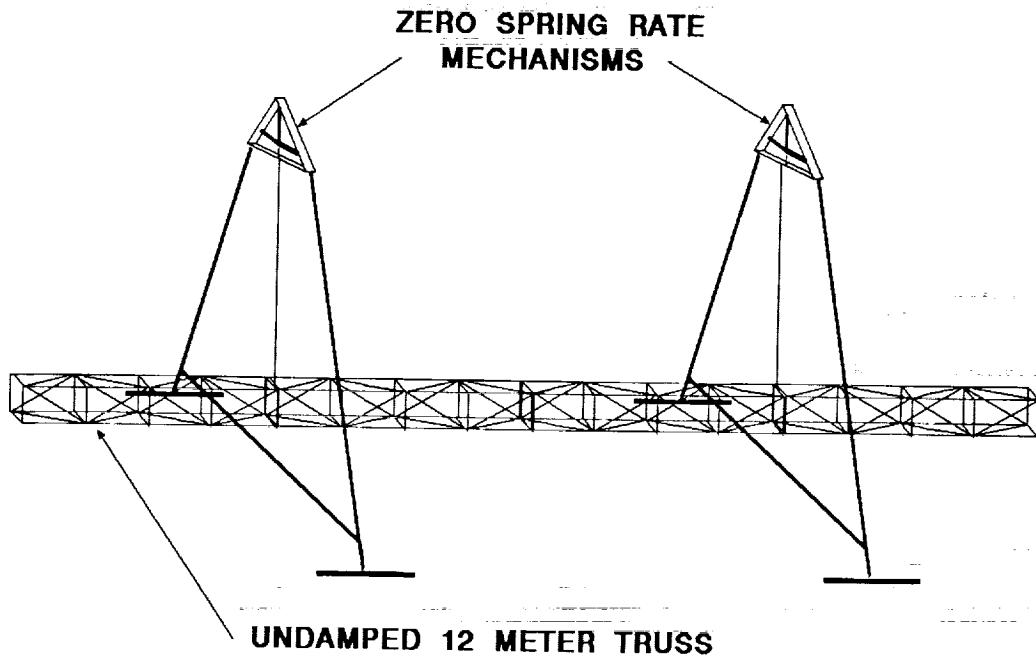
12 Meter Truss Active Vibration Control

Active vibration control testing will be performed on the undamped 12 meter truss following completion of all modal tests. The objective of this testing is to evaluate the performance of several leading control approaches on a large, low frequency truss beam with significant passive damping. The undamped truss will be fitted with sensors and actuators and mounted in the vertical cantilever configuration. Damped diagonal members from the damped truss will be selectively substituted for the Lexan diagonals in the undamped truss to provide a structure with adjustable passive damping. Several leading control approaches will be applied to the truss and their performance with different levels of passive damping will be measured. Control design and implementation will be provided by the Ohio State University. A photodiode optical sensor will be used to monitor truss tip displacement as a measure of controller performance. Active control approaches will be implemented on a new real-time control computer system at the Flight Dynamics Laboratory.

LIGHT SOURCE

SENSOR AND
ACTUATOR
STATIONS

PHOTODIODE
ARRAY SENSOR
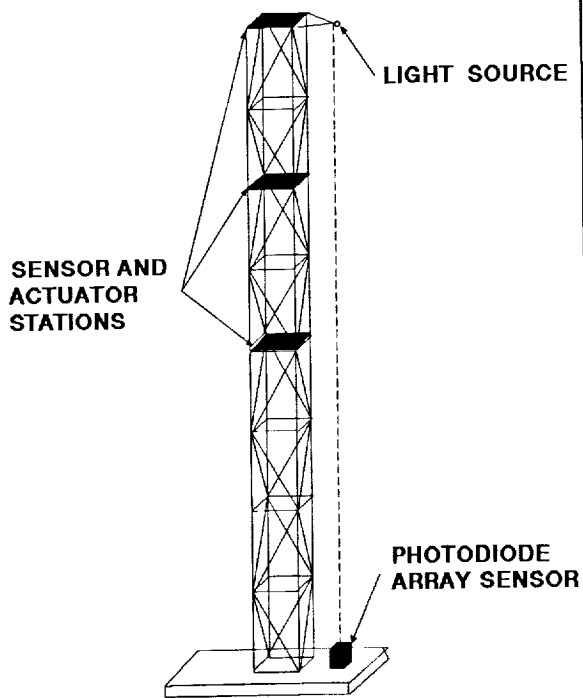
OBJECTIVES

ASSESS CONTROLLER PERFORMANCE ON A
LARGE TRUSS BEAM

MEASURE THE EFFECT OF PASSIVE
DAMPING ON CONTROLLER PERFORMANCE

EVALUATE NEW CONTROL COMPUTER
ARCHITECTURE

APPROACH

MOUNT SENSORS AND ACTUATORS ON THE
UNDAMPED TRUSS

TAILOR MODAL DAMPING BY ADDING
DAMPER MEMBERS

TEST CONTROLLERS AT SEVERAL LEVELS
OF PASSIVE DAMPING

12 Meter Truss Sensor and Actuator Locations

Eight collocated pairs of sensors and actuators will be fitted to the undamped 12 meter truss to provide active vibration control forces. Linear momentum exchange type actuators will be used. Structural velocity signals will be obtained by integrating the output of linear accelerometers collocated with each actuator. The locations of the eight sensor/actuator pairs is shown in the figure. Two pairs of actuators will be positioned at the truss tip, with one pair parallel to each bending plane. Each pair can be commanded in-phase to control bending response while either pair can be commanded out-of-phase to provide a moment to control torsion response. Single pairs of actuators oriented parallel to the bending planes will be positioned at the truss 3/4 and mid-station locations. These actuators will provide bending mode control only.
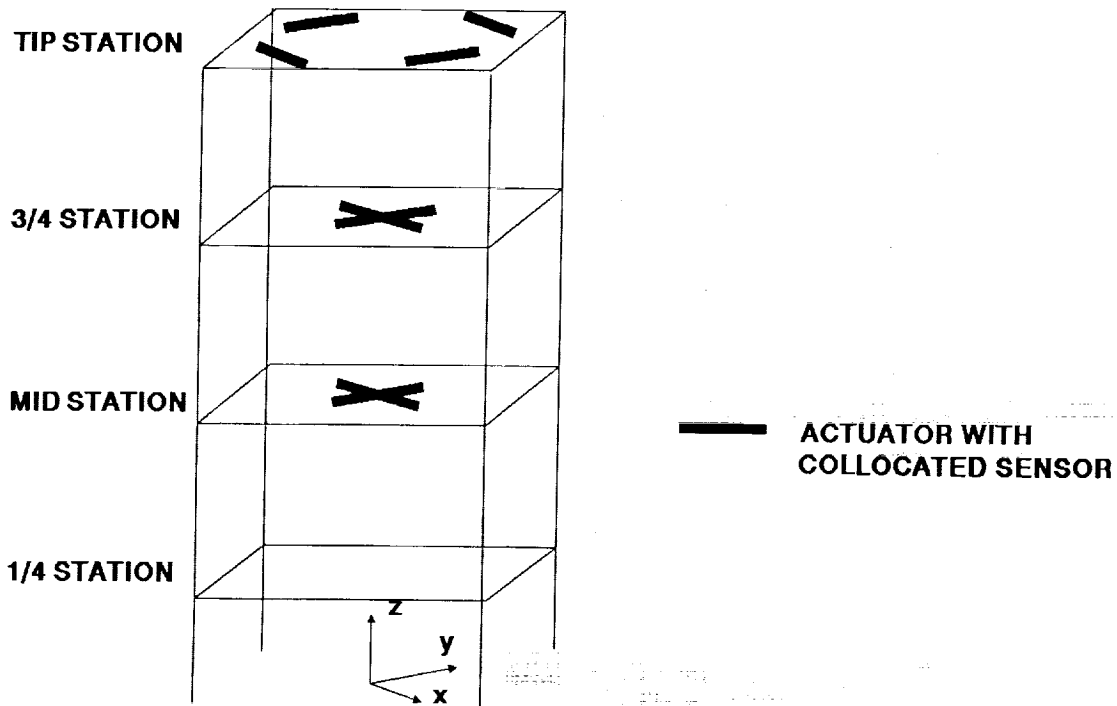
12 Meter Truss Actuator

Linear momentum exchange actuators will be used to provide control forces on the 12 meter truss. The actuator design is shown in the figure. This design is a modified version of the actuator developed at Martin Marietta Denver Aerospace on the Passive and Active Control of Space Structures (PACOSS) program. The actuator is a linear DC motor with the permanent magnet field mounted on low friction shafts and the armature fixed to a support housing. The PACOSS design has been modified to provide dual support shafts for the moving mass instead of the original single shaft. This eliminates the hole though the proof mass required for the single shaft and restores the 40% loss in output due to the hole in the permanent magnet. Proof mass centering is provide by mechanical springs. A linear velocity transducer (LVT) is used to measure relative velocity between the proof mass and the structure. The relative velocity is fed back through the actuator with an adjustable gain to provide damping in the actuator resonance. The actuator is capable of 1 pound force output in the frequency range of 2 Hz to 100 Hz.
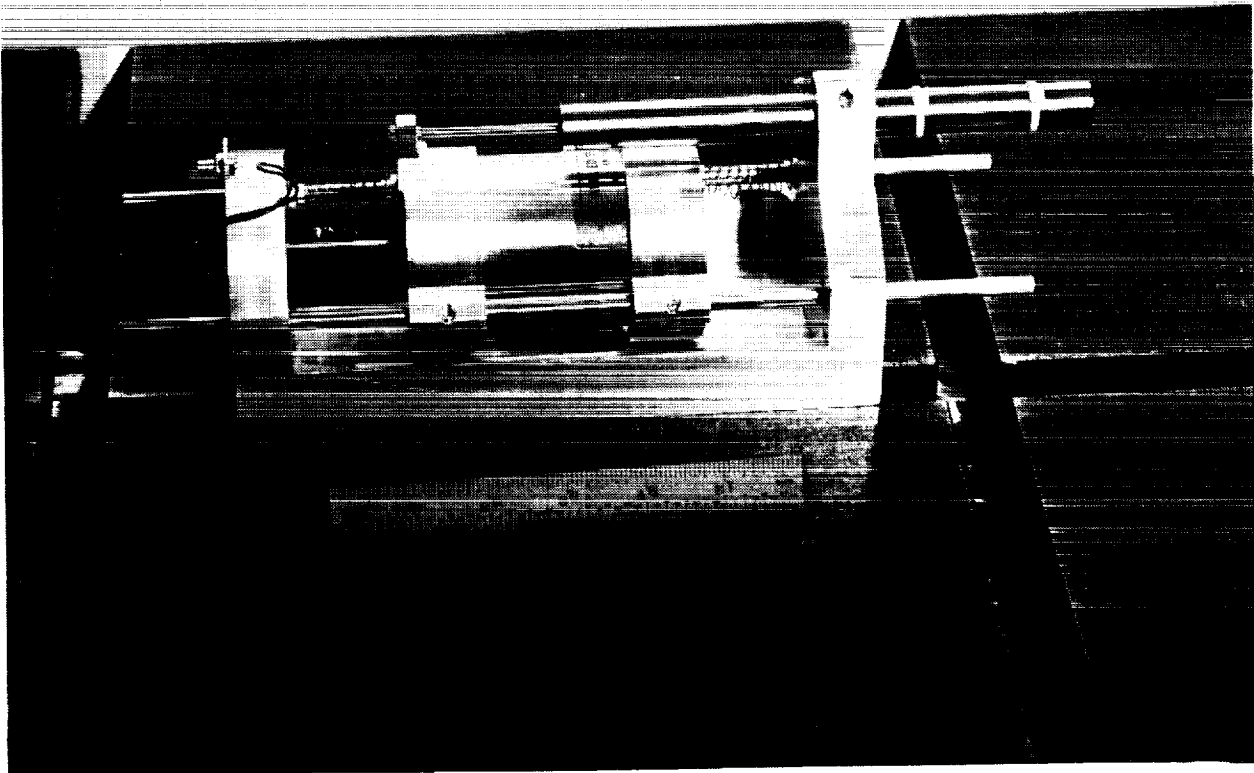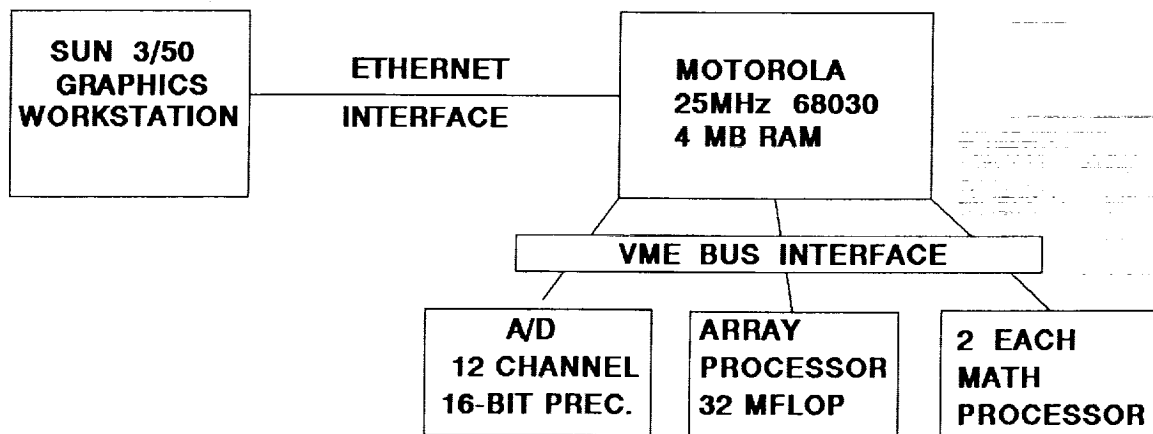

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

A new digital computer system will be used to implement the active control approaches on the 12 meter truss and other future experiments at the Flight Dynamics Laboratory. The new system is based on the architecture that will be used to conduct Space Shuttle based control experiments. This architecture is based on the fact that the computer which executes the real-time control will not be directly accessible to the experimenter. It will be accessed only through data links and intermediate computers from a remote console on the ground. This is in contrast to the typical laboratory where a high speed development computer is fitted with data acquisition interfaces and real-time support modifications to its operating system. Such laboratory systems do not provide the necessary environment to develop experience for future flight experiments. The new system consists of two basic components; a development system and a real-time controller. The development system is a graphics workstation which is used for software design and simulation, system supervision and data analysis. The real-time controller is a fast, "black box" computer which executes the control and captures response data. The controller can be accessed only through a data interface from the development system. The controller has the same CPU as the development system so that software compiled on the development system will execute directly. A block diagram of the new system with some of the details of the real-time controller is shown in the figure.

DEVELOPMENT SYSTEM

REAL-TIME CONTROLLER

```
+----------------+               +------------------+
| SUN 3/50       |   ETHERNET    | MOTOROLA         |
| GRAPHICS       |               | 25MHz  68030     |
| WORKSTATION    |   INTERFACE   | 4 MB RAM         |
+----------------+               +------------------+
```

VME BUS INTERFACE

| A/D 12 CHANNEL 16-BIT PREC.	ARRAY PROCESSOR 32 MFLOP	2 EACH MATH PROCESSOR

Active Control Design for the 12 Meter Truss Experiment

Several active vibration control approaches are being pursued for the 12 Meter Truss Experiment. This work is being performed by Umit Ozguner and Steven Yurkovich of the Ohio State University under contract. The control approaches can be categorized as either centralized or decentralized types. In the centralized catagory, the design approaches being studied are Loop Transfer Recovery (LTR), Maximum Entropy / Optimal Projection and static output feedback. The decentralized approaches are Overlapping Decomposition, Total System Synthesis and Component Modal Synthesis. Also of interest in the future is the Auto-tuning Hierarchy control design. The figure portrays the several control design approaches being investigated. The control approaches shown in shaded blocks in the figure have been studied extensively in simulation runs on a preliminary finite element model of the control configured truss. The designs are implemented on a 28th order model made up of the 8 actuator modes and the lowest 4 bending and 2 torsion modes of the truss.
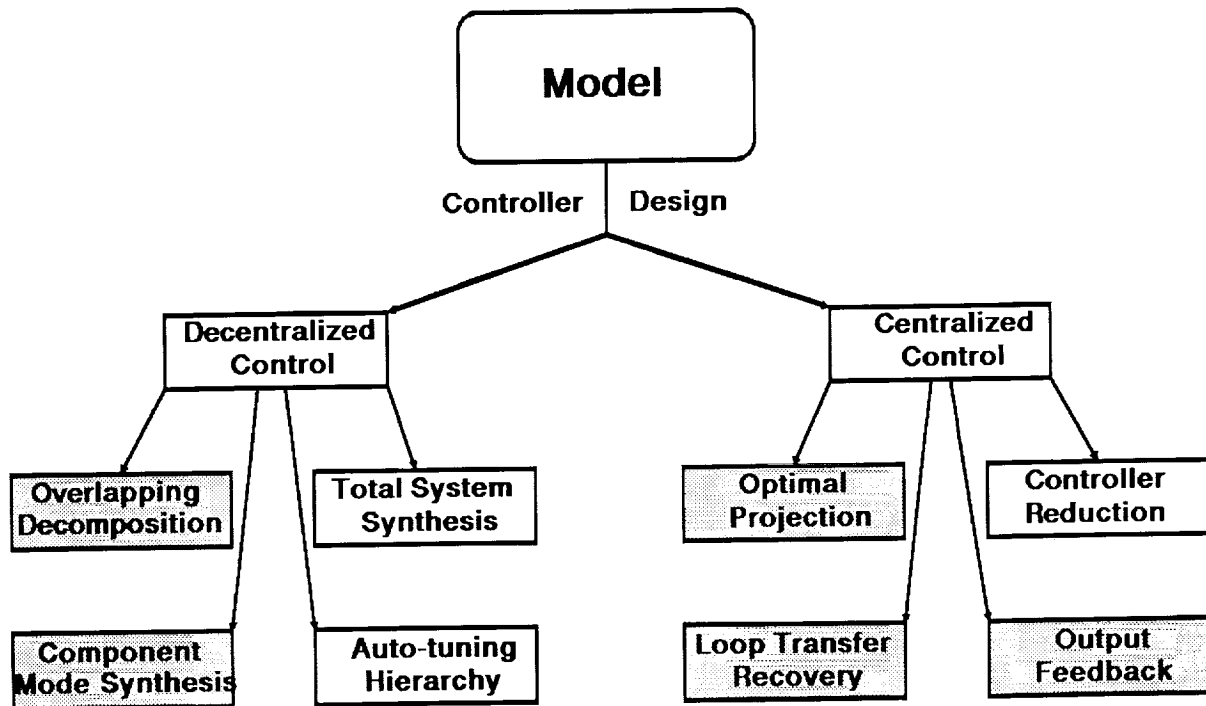
12 Meter Truss Active Controller Performance Predictions

Closed loop simulations have been performed on several of the active control approaches being pursued for the 12 Meter Truss Experiment. The approaches include the centralized techniques of LQG,* LTR, MEOP and static output feedback and the decentralized techniques of Overlapping Decomposition and Component Modal Synthesis. Closed loop damping estimates based on these control approaches are tabulated in the figure for the lowest 6 modes of the truss. The estimated open loop modal damping values are listed for comparison. The results for LQG, LTR and static output feedback are listed as a single column in the table since the results of these three apporaches were nearly identical. Several observations can be made from the data. First, and most importantly, every control approach resulted in a significant increase in modal damping over open loop for every mode except 2nd torsion. Generally speaking, all the controllers did a better job of adding damping in the 2 first bending modes than in the higher modes and the decentralized approaches were better at adding damping to all six modes of interest than the centralized approaches were. These simulations will be compared to test data when the experimental hardware becomes operational in April or May 1989.

*Linear Quadratic Gaussian (LQG).

	OPEN-LOOP	LQG, LTR, OUTPUT FEEDBACK	MEOP	OVERLAPPING DECOMP	COMPONENT SYNTHESIS
1ST X BENDING	.80	9.36	4.49	8.02	7.24
1ST Y BENDING	.95	9.35	4.64	7.91	7.15
1ST TORSION	.15	0.96	0.95	6.46	6.54
2ND X BENDING	.16	1.45	1.38	3.19	2.97
2ND Y BENDING	.18	1.43	1.37	3.10	2.93
2ND TORSION	.11	0.17	0.17	1.01	1.02

Summary

In summary, the Flight Dynamics Laboratory is committed to an inhouse, experimental investigation of several technical areas critical to the dynamic performance of future Air Force large space structures. The Advanced Beam Experiment has been sucessfully completed and provided much experience in the implementation of active control approaches on real hardware. A series of experiments is under way in evaluating ground test methods on the 12 meter trusses with significant passive damping. Ground simulated zero-g response data from the undamped truss will be compared directly with true zero-g flight test data. The performance of several leading active control approaches will be measured and compared on one of the trusses in the presence of significant passive damping. In the future, the PACOSS Dynamic Test Article will be set up as a test bed for the evaluation of system identification and control techniques on a complex, representative structure with high modal density and significant passive damping.

- **ADVANCED BEAM PROVIDED VALUABLE EXPERIENCE**

  - **LINEAR ACTUATOR DYNAMICS**

  - **CONTROLLER PERFORMANCE IN HARDWARE**

- **12 METER TRUSS MODAL TESTING IN PROGRESS**

  - **DATA FROM MULTIPLE BOUNDARY CONDITIONS**

  - **HIGH DAMPING IN TORSION MODES OF DAMPED TRUSS**

  - **ZERO-G FLIGHT TEST DATA TO COMPARE WITH GROUND TEST**

- **12 METER TRUSS ACTIVE CONTROL EXPERIMENT IN PREPARATION**

  - **8 ACTUATOR/SENSOR PAIRS**

  - **TEST SEVERAL ACTIVE CONTROL APPROACHES**

  - **EVALUATE CONTROLLER PERFORMANCE IN THE PRESENCE OF PASSIVE DAMPING**