Description of and Preliminary Tests Results for the Joint Damping Experiment (JDX)[1]

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ABSTRACT

An effort is currently underway to develop an experiment titled Joint Damping Experiment (JDX) to fly on the Space Shuttle as Get Away Special Payload G-726. This project is funded by NASA's IN-Space Technology Experiments Program and is scheduled to fly in July 1995 on STS-69. JDX will measure the influence of gravity on the structural damping of a three bay truss having clearance fit pinned joints. Structural damping is an important parameter in the dynamics of space structures. Future space structures will require more precise knowledge of structural damping than is currently available. The mission objectives are to develop a small-scale shuttle flight experiment that allows researchers to: 1) characterize the influence of gravity and joint gaps on structural damping and dynamic behavior of a small-scale truss model, and 2) evaluate the applicability of low-g aircraft test results for predicting on-orbit behavior. Completing the above objectives will allow a better understanding and/or prediction of structural damping occurring in a pin-jointed truss. Predicting damping in joints is quite difficult. One of the important variables influencing joint damping is gravity. Previous work has shown that gravity loads can influence damping in a pin-jointed truss structure. Flying this experiment as a GAS payload will allow testing in a micro-gravity environment. The on-orbit data (in micro-gravity) will be compared with ground test results. These data will be used to help develop improved models to predict damping due to pinned joints. Ground and low-g aircraft testing of this experiment has been completed. This paper describes the experiment and presents results of both ground and low-g aircraft tests which demonstrate that damping of the truss is dramatically influenced by gravity.

INTRODUCTION

Utah State University is currently developing an experiment titled Joint Damping Experiment (JDX) to fly on the Space Shuttle as Get Away Special Payload G-726. This project is funded by NASA's IN-Space Technology Experiments Program and is scheduled to fly in late July 1995. The objectives of JDX include development of a small-scale shuttle flight experiment which allows researchers to characterize the influence of gravity and joint gaps on structural damping and dynamic behavior of a small-scale truss and application of nonlinear finite element modeling capability to simulate the measured behavior. This will allow a better understanding and/or prediction of the structural dynamics occurring in a pin-jointed truss.

TRUSS DESIGN

A photograph of the JDX truss is given in Figure 1. The bottom of the truss is attached to a base plate which attaches to the GAS Experiment Mounting Plate (EMP) and thus provides a cantilevered boundary condition for that end of the truss. A rigid plate is attached to the top bay of the truss to provide a tip mass which lowers the natural frequencies. The excitation system can preferentially excite three modes in the truss; two bending modes and a torsional mode. The two bending modes are the two lowest frequency modes of the truss. These two bending modes are described as "bend 1" and "bend 2" modes. The lacing of the struts separates the two bending mode frequencies so each can be easily identified. The torsional mode consists of a rotational motion about the long axis of the truss. The small plates attached to the tip mass in Figure 1 are used by the excitation system. The damping and dynamic characteristics are observed by recording the free decay of the modes.

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The strut and joint design for an "unlocked" joint is illustrated in Figure 2. The aluminum struts can be adjusted in length by turning the threaded strut tubes. The joints utilize press-fit hardened steel inserts to minimize joint wear. Hardened steel shoulder bolts are used for joint pins. The gap in the joints can be adjusted by using different diameter shoulder bolts. The JDX truss also uses "locked" joints which do not permit any deadband motion or rotations. The locked joint design is similar to Figure 2 except no inserts are used and the shoulder bolts are oversized such that they must be press fit into the joint. Additionally, shims are installed between the clevis and tang pieces and the shoulder bolt is tightened to apply a high preload across the joint interface. Impacting and macro-slip damping mechanisms are not present in the locked joints. By locking only a portion of the joints in the truss, a method of tailoring truss dynamics is obtained.

The initial tests of the JDX truss showed that with all the joints unlocked, the vibration modes were almost obscured with high frequency hash. The high frequency hash was a caused by impacting of the numerous truss joint gaps. It was clearly shown that only a few unlocked joints in a truss would dramatically influence the dynamic behavior. The flight model configuration of the truss has only eight unlocked joints located at the top of the first bay as illustrated in Figure 3.

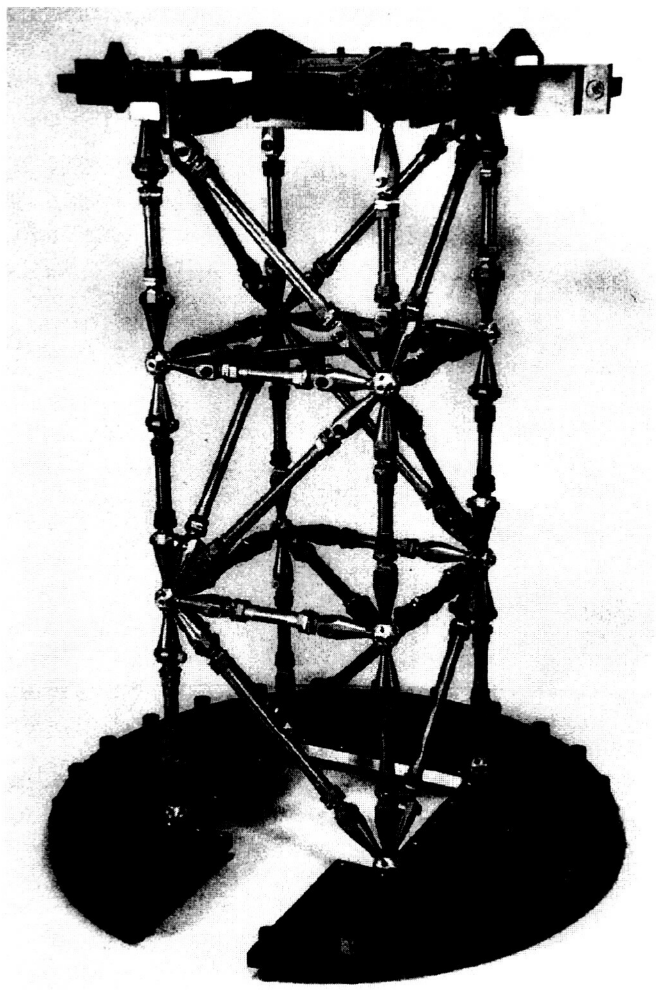

Figure 1. Photograph of the JDX truss.

The nominal radial clearance between the pins and the strut inserts in the JDX flight mode truss design was

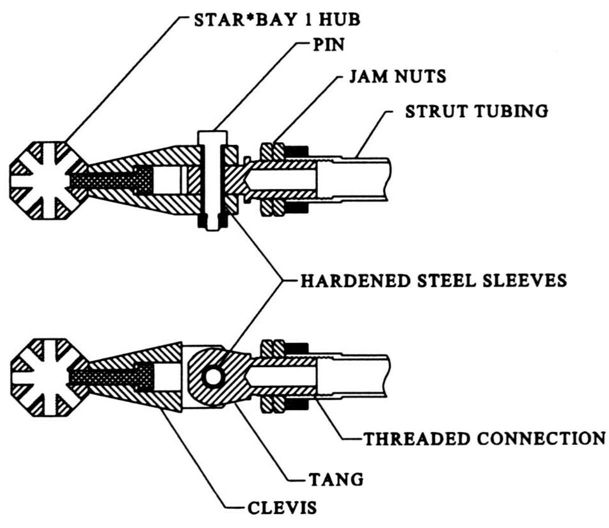

Figure 2. Illustration of the pinned joint design.

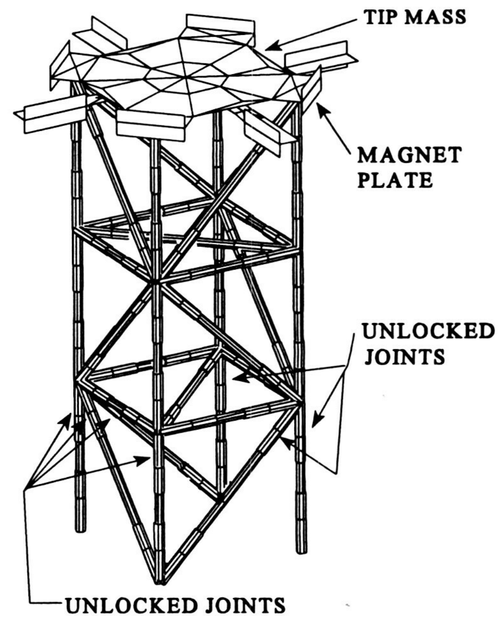

Figure 3. Location of unlocked joints.

0.0003 inch. This represents a very close fit for a 0.1875 inch pin. This is essentially the largest pin which could be freely inserted into the joint. Figure 4 illustrates quasi-static pull tests of a JDX strut which has a pinned joint on one end and a locked joint on the other. The hysteresis behavior of the strut with two different pin diameters are shown in Figure 4. The 0.00025 inch radial pin gap represents the class of fit used in the flight model truss. The quasi-static tests using the 0.00025 inch radial gap shows no clear display of deadband, but significant hysteresis due to friction. Imprecision in the assembly of the strut masks the deadband in these tests, as compared with the 0.00055 inch radial gap. Although the gap in the joint is small, the dynamic effects on the truss remain significant. The quasi-static tests in Figure 4 do not reflect the dynamic behavior. Ferney and Folkman[1] reported an initial series of force-state-map tests of the JDX struts which demonstrate that the joint gaps give rise to multiple rebounds during dynamic loading.

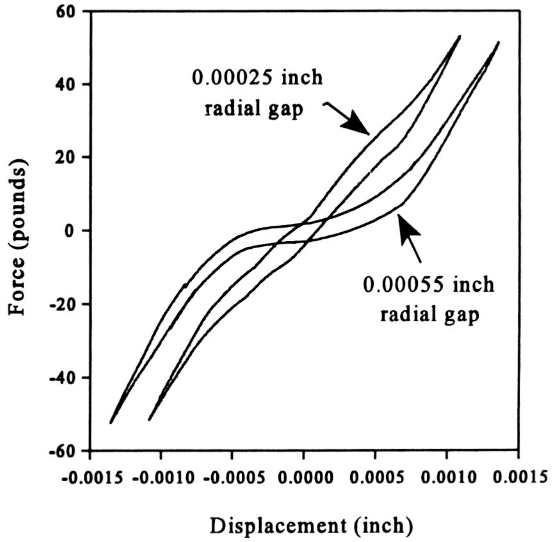

Figure 4. Hysteresis in quasi-static pull tests of a JDX strut.

EXPERIMENT DESCRIPTION

JDX consists of the three-bay truss shown in Figure 1 and associated hardware for truss excitation and measurement of oscillations. The experiment is located inside a 5 cubic foot GAS canister. Figure 5 is an illustration of the experiment which shows some of the major components which make up the experiment. Figure 5 is a sectional view such that some of the components "inside" the experiment are illustrated. Figure 6 is a photograph of the experiment.

Truss excitation system can preferentially excite two bending vibration modes and a torsional vibration mode. The excitation assembly consists of a framework which supports linear actuators, linkages, and electromagnets. Some of the framework is illustrated in Figure 5. The top plate and the vertical support posts are used to support most of the excitation hardware. A "box" placed inside the middle truss bay is also used to support linear actuators. This box is mounted to the battery box.

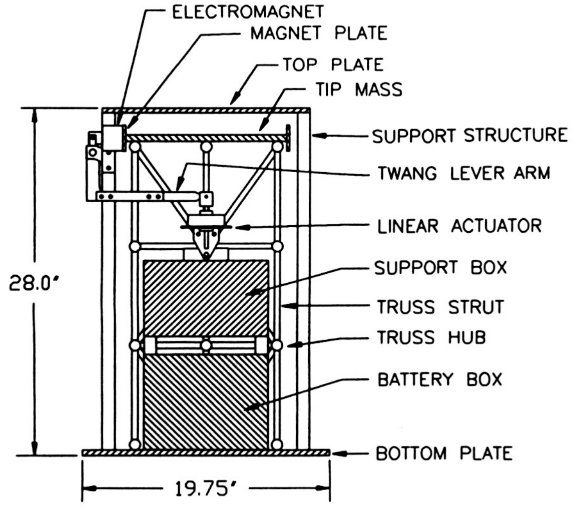

Figure 5. Illustration of major components of the JDX experiment.

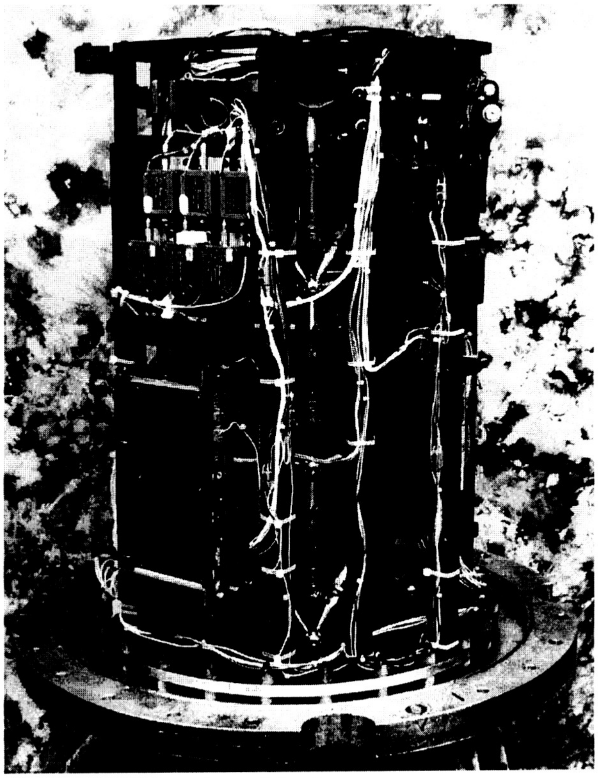

Figure 6. Illustration of the truss.

The linear actuator shown in Figure 5 is used to excite a "bending" mode. The actuator pushes on the lever arm which rotates about a pivot point. The lever arm is attached to the electromagnet. When the actuator pushes up on the lever arm, the electromagnet is displaced horizontally. The magnet is brought into contact with a plate attached to the tip mass and then power is applied to the magnet. Retracting the magnet will displace the truss in a shape resembling a bending mode. After displacing the truss, power to the electromagnet is removed which releases the tip mass and excites a vibration mode. This is described as a "twang" excitation method. The JDX experiment has other excitation system components similar to that shown in Figure 5 which will excite a bending mode in a direction perpendicular to the first and a torsional mode.

A mechanism for truss-tip support during launch and reentry is used to protect the truss from launch and reentry vibrations. The truss is locked by a one inch diameter stainless steel pin which can be inserted into a sleeve attached to the tip mass.

The controller/datalogger system controls the operation of the experiment by performing a set of preprogrammed instructions. These operations include the movement of linear actuators, energizing/de-energizing electromagnets, and measuring data. The experiment controller used is a Campbell Scientific CR10 Measurement and Control Module. This module has very low power consumption (0.7 mA quiescent) and can provide switching control and measurement operations. The CR10 when combined with Campbell Scientific SDM-CD16 Control Port Modules, can switch on and off the power for all the devices, including the five linear actuators and four magnets used in the experiment. The CR10 data acquisition rate is limited to about 1000 Hz. which is not adequate for recording the decays of the truss. For high speed data measurement, a Campbell Scientific CR9000 measurement module was utilized. The CR9000 has a measurement bandwidth of 100,000 samples per second with a resolution of 16 bits. The CR9000 contains 2 MBytes of EEPROM for program and data storage. The CR9000 has a high power consumption (0.5 A) and thus is only powered up during measurement operations. Accelerations of the tip mass are detected by the use of Kistler KBeam accelerometers, model 8302A10 with a 10 g full scale range. Three accelerometers are mounted to the tip mass to record the decay of the truss. Three additional accelerometers are attached to the base plate to monitor vibration or motion input to the experiment from the Space Shuttle. All the accelerometers are recorded at a rate of 3000 Hz. on each accelerometer channel.

Power for the experiment is provided by Gates sealed lead acid batteries. The batteries are contained in a sealed battery box that is vented using the standard GAS battery box vent system. Figure 5 shows that the battery box is located inside the first (or lowest) bay of the truss. The batteries consist of a combination of D and X cells which formed four, 12 volt battery packs.

EXPERIMENT OPERATION

During the Shuttle flight, a baroswitch is attached to Relay A and will be activated at an altitude of 50,000 feet. The experiment controller will then be power up when the baroswitch closes. After a one hour time delay, the truss is unlocked. Then the controller then monitors its built-in clock, the GAS relay B, and the battery box temperature. It is desired to conduct the twang tests during a time period in which vehicle accelerations are minimized (an astronaut sleep period). The experiment is also limited in that if it gets too cold waiting for a sleep signal, it might not function properly. The experiment begins the twang test sequence when one of the three following events occur:

1. An astronaut low g signal has been received (closure of relay B at the beginning of a sleep period).
2. 18 hours has passed since the closure of the baroswitch.
3. The temperature of the experiment drops below a lower limit value.

When the controller determines it is time to start the experiment procedure, it will perform the following:

1. Move all electromagnets to their preset stop positions.
2. Perform approximately 10 twang tests for each mode shape.
3. Record experiment temperature during the tests.
4. Lock the truss by activating a linear actuator.

The experiment shall continue to monitor experiment temperatures during the flight. Prior to the end of a Shuttle mission, an astronaut shall set Relay A to latent. When Relay A becomes latent the controller will be powered down.

ORIENTATION FOR GROUND TESTING

Because gravity can influence the behavior of a pinned joint, ground tests of the JDX truss were conducted with the truss in two orientations with respect to the gravity vector. Figure 7 illustrates the 0° and 90° truss orientations. The 0° orientation minimizes the gravity preload in the struts. Although the preload in the truss is minimized in the 0° orientation, it is not zero since the joints must still support the weight of the truss. The 90° orientation provides the maximum gravity induced strut preloads. It is important that the truss was carefully assembled such the preloads due imprecise strut lengths are virtually eliminated. That is, if gravity loads are removed, the deadband region is easily traversed. This turns out to be a difficult procedure in that the strut lengths must be set near the same level of accuracy as the joint pin gaps. In practice, this is difficult to obtain but can be closely approximated.

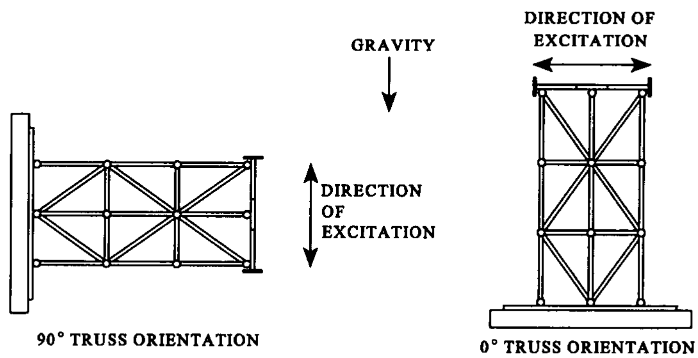

Figure 7. Illustration of 0° and 90° test orientations.

TEST RESULTS

Ground tests of the flight model JDX tests are illustrated in Figures 8, 9, 10, and 11. These figures are plots of accelerations of the tip mass in the direction of the excitation. The free decay of the bend 1 mode with all joints locked is illustrated in Figure 8. Low damping and a typical exponential decay is observed. Figure 9 shows the initial decay over a 1 second time period. Because the JDX truss is displaced and released from rest, a there is a small amount of higher mode content which quickly damps out. Figure 10 illustrates the decay of the bend 1 mode for a truss in the 0° orientation with eight unlocked joints. Note the rapid decay and the large amount of high frequency hash in the decay. Also the frequency is about 10% lower when compared with the truss will all locked joints. Figure 11 illustrates the decay of the bend 1 mode with the truss in the 90° orientation and with eight unlocked joints. Note that damping is decreased relative to the 0° orientation test but the damping is still much greater than that of a locked truss. Note how the initial decay is not symmetric about the equilibrium position. The accelerometers produce a DC output and since the accelerometer is oriented in the direction of the gravity vector, it reads approximately 1 g at equilibrium. An acceleration of 0 g's coincides with the position where the joints supporting the weight of the truss would traverse their deadband region. Clearly, when the highly loaded joints traverse the deadband region, the dynamics of the truss are greatly modified. The damping is reduced significantly when the amplitude of the peak accelerations drops below 1 g since the active joints remain under preload at all times. At small amplitudes, the damping approaches that of the truss with all joints locked. The bend 2 mode recorded similar behavior.

The results reported above are similar to those reported earlier for the JDX engineering model truss[2]. Damping of the truss can be inferred from the logarithmic decrement of the decay if we treat the truss as a single degree of freedom system and assuming energy is not transferred to other modes. Reference 2 reports the logarithmic decrement of the bend 1 mode for the locked, 0°, and 90° truss orientations as a function of acceleration amplitude. It was reported that:

1) damping rates can change by a factor of 2 to 5 as a result of simply changing the orientation of a truss;
2) the addition of a few unlocked joints to a truss structure can increase the damping by a factor as high as 40;
3) damping is amplitude dependent;
4) at low amplitudes the damping in the 90° orientation approaches that of the locked truss.

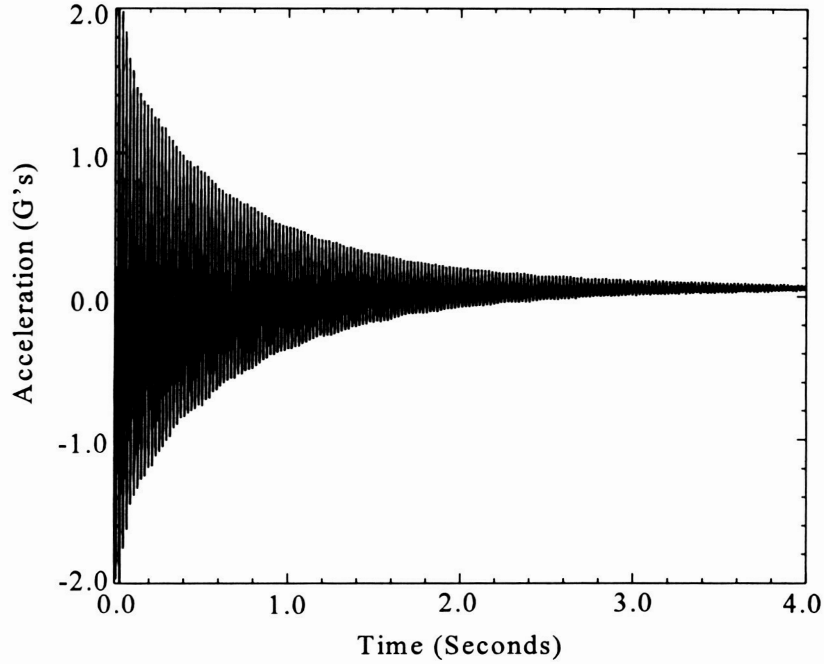

Figure 8. Decay of the bend 1 mode with the truss in a 0° orientation with all joints locked.

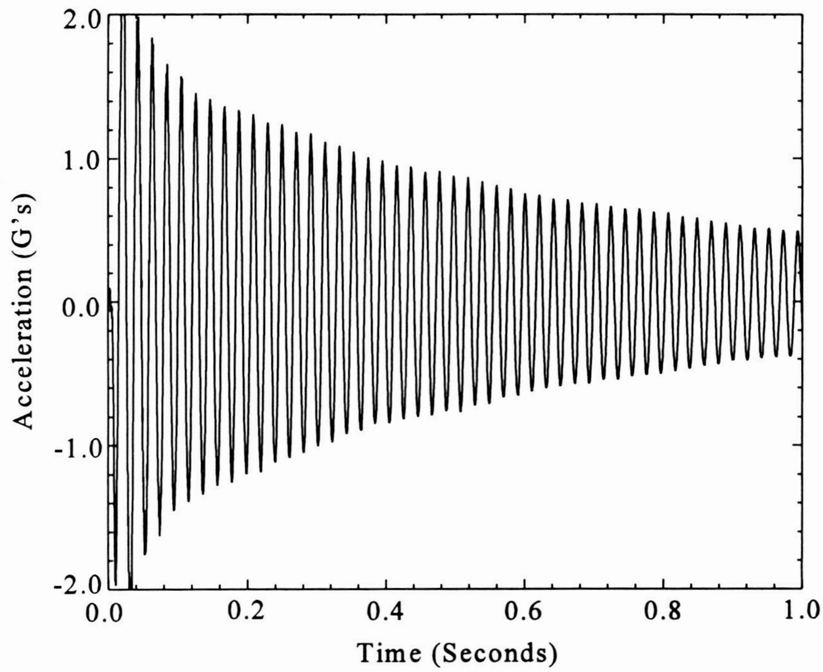

Figure 9. Initial decay of the bend 1 mode with the truss in a 0° orientation with all joints locked.

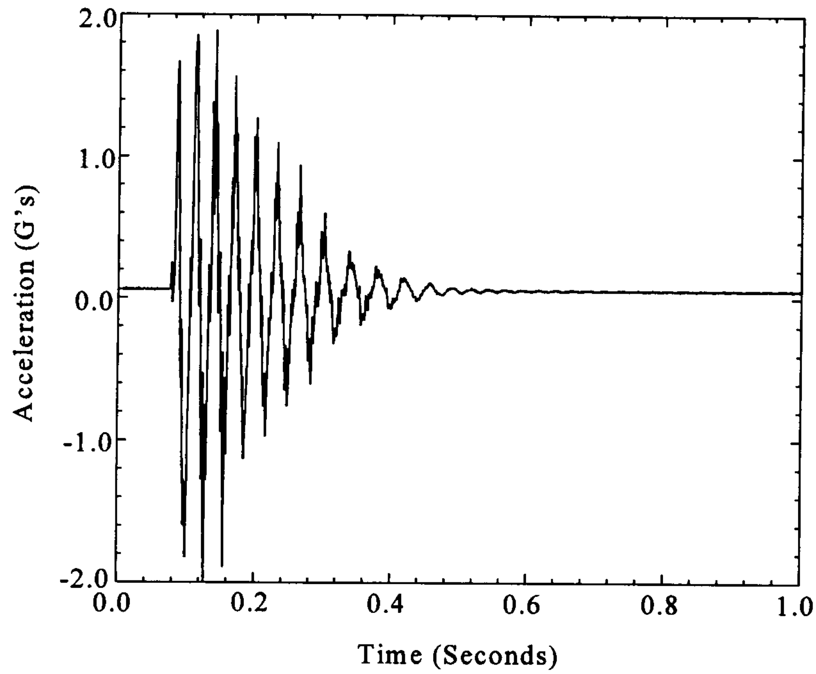

Figure 10. Decay of the bend 1 mode with the truss in a 0° orientation and 8 unlocked joints.

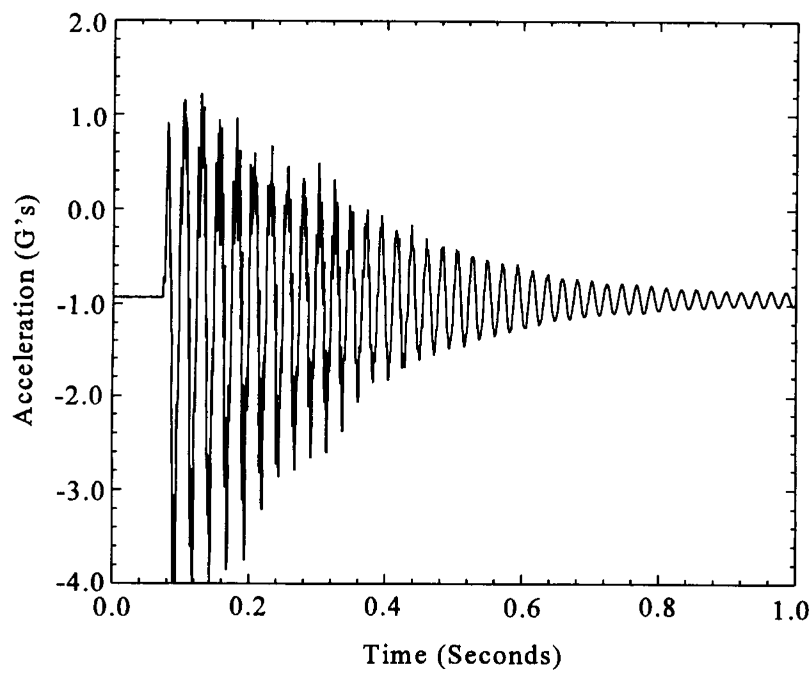

Figure 11. Decay of the bend 1 mode with the truss in a 90° orientation and 8 unlocked joints.

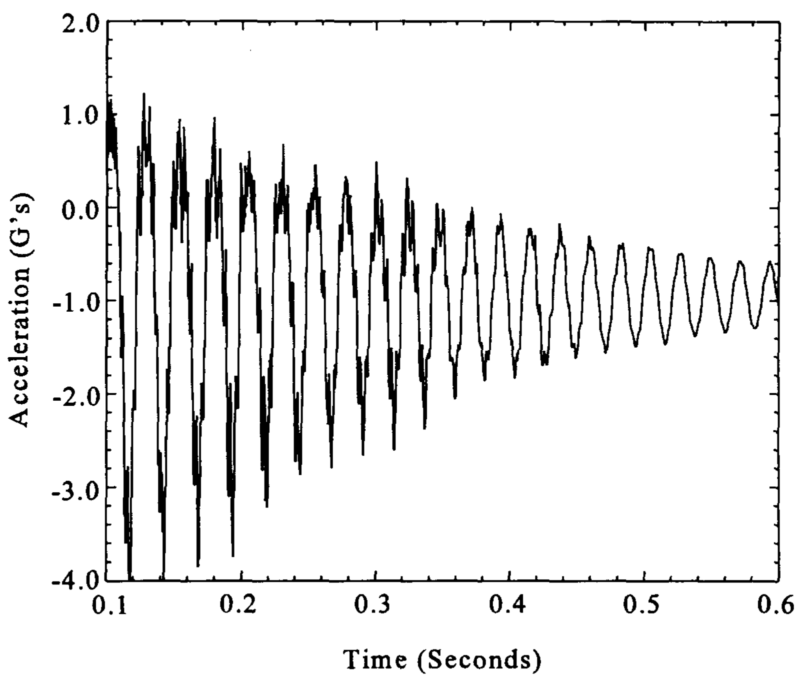

Figure 12. Initial decay of the truss in the 90° orientation with eight unlocked joints.

At low amplitudes, strut preloads may discourage a macroslip mode of friction damping as well as impacting. In this case, one would expect the damping to approach that of a locked joint. Although the damping becomes smaller at low amplitudes in the 0° truss orientation with unlocked joints, it is still significantly higher than the truss with locked joints.

The high frequency hash in Figures 10 and 11 is suspected to be caused by impacts occurring in the joints. This is more clearly shown in Figure 12 which shows the first 0.6 seconds of the decay in Figure 11 for the 90° truss orientation. Figure 12 shows that the occurrence of the high frequency hash corresponds to the traversal of the deadband region. After approximately 0.4 seconds, the highly loaded joints can no longer traverse the deadband region and the high frequency hash becomes greatly diminished.

Although the test results indicated that impacting is a significant source of damping in pinned joints, friction is also suspected to provide a significant source of energy dissipation. The joints which carry the majority of the load in the 90° orientation tests with unlocked joints should not be traversing the deadband zone after the amplitude drops below 1 g. Lightly loaded joints in the truss could still be traversing the deadband zone, but the magnitude of the impacts ought to be small. Thus, much of the damping from the 90° tests with unlocked joints is suspected to be predominately from a friction mechanism.

LOW-G AIRCRAFT TESTS

Tests have been conducted with the JDX truss on NASA's KC-135 aircraft which can produce approximately 20 seconds of micro-gravity during its parabolic flight path. Tests were conducted with the experiment mounted to the aircraft and with it free floated in the aircraft. The aircraft floor is not very stiff and the vibrations transmitted to the experiment from the aircraft made tests with the experiment mount to the aircraft floor of little value. The free-float tests isolated the experiment from aircraft vibrations, but it is needed to approximately simulate the cantilever boundary condition of the truss at the base plate. This could be accomplished by attaching a large rigid mass to the base of the experiment. However, safety concerns limited free-float items to under 600 pounds. To that end, approximately 350 pounds of steel plates and framework were attached to the experiment base, and a canister simulating a GAS canister, bringing the total mass to about 550 pounds. This mass gives a reasonable approximation to a cantilevered boundary condition which allows comparison of free-float data with data from ground tests. Figure 13 is a photograph of a free-float test. Figure 14 illustrates the decay of the bend 1 mode for the truss with eight unlocked joints in a free-float test. Comparing Figures 10 and 14 shows that damping is higher in microgravity than in 1-g with a 0° truss orientation. A close examination of Figure 10 shows that low amplitude vibrations continue until approximately 0.7 seconds. Figure 14 shows no observable accelerations after about 0.4 seconds. The low amplitude accelerations are very readily damped. In a 0° truss orientation test in 1-g, the truss has the lowest level of gravity induced preloads. These preloads prevent the traversal of the deadband region in the joints in 1-g tests. In the free-float tests, the struts have no preloads present even low amplitude oscillations traverse the deadband region of the joints. When the deadband region is traversed, damping is greatly increased.

Figure 13. Photograph of a free-float twang test.

SHUTTLE FLIGHT STATUS

At the time this article was written, the experiment has been delivered to KSC for integration on the Space Shuttle Endeavor and is waiting for flight.

CONCLUSIONS

An experiment to characterize the influence of gravity on damping of a truss using pinned joints has been constructed and delivered for flight testing on the Space Shuttle. The three bay truss is cantilevered from a mounting plate attached to the GAS EMP and has a tip mass attached to the free end to lower the resonant frequency. The damping of the truss is inferred from the measured free decay. The experiment contains a mechanism to excite two bending modes and a torsional mode.

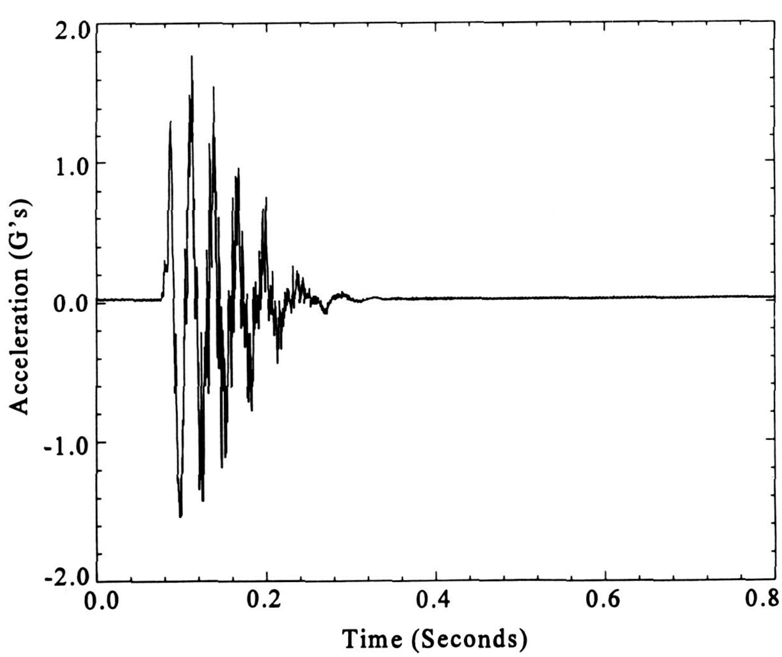

Figure 14. Decay of the bend 1 mode during a free-float tests with eight unlocked joints.

If a truss structure utilizes a pinned joints with clearance fit pins, the joints can become the primary source of damping in the structure. The resonant frequency and driving of higher modes are also significantly influenced. Measured data for a three bay truss containing eight pinned joints was presented. The measured data clearly shows that as gravity induced preloads are decreased, damping increases. Impacting is demonstrated by the observation of high frequency hash in the decay data. Driving of higher modes by impacting is suspected to be a significant source of damping. High preloads caused by gravity in the 90° truss orientation ground tests can prevent impacting in the joints carrying the majority of the loads (as long as the amplitude of the oscillations is smaller than 1 g). Damping in this time period should be dominated by friction losses. Measured data confirms that friction damping is a significant factor. Measurements during low-g aircraft tests show that damping is further increased as gravity loads are removed from the structure. The above conclusions assume the truss has been carefully assembled so that no preloads are induced during assembly so that as gravity loads are removed, strut preloads go to zero and joints can traverse their deadband zone.

REFERENCES

1. B. D. Ferney and S. L. Folkman, "Results of Force-state Mapping Tests to Characterize Struts Using Pinned Joints," *Proceedings of the 36th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, April 1995, AIAA-95-1150.

2. S. L. Folkman, E. A. Rowsell and G. D. Ferney, "Gravity Effects on Damping of a Truss Using Pinned Joints," *Proceedings of the 35th AIAA Dynamics Specialists Conference*, April 1994, AIAA-94-1685.