Gravity Effects on Damping of a Space Structure with Pinned Joints

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An area of concern for the design of large space structures is the amount of structural damping that will be present. The joints used to assemble a large, light-weight structure like the space station will provide some damping; however, an accepted methodology for predicting joint damping is yet to be established. This paper documents a research effort at Utah State University to better understand joint damping in large space structures. A miniature tetrahedral truss was constructed that uses pinned joints. A large tip mass was attached to the truss to lower the natural frequency to a range associated with the space station. Considerable ground testing has been conducted to characterize the damping of the truss in a 1-*g* environment in different orientations and in a vacuum. It was determined that the contribution of air to structural damping was insignificant for this truss. These experiments show that gravity can dramatically influence the damping produced.

Introduction

MOST of the proposed designs for large space structures use light-weight flexible trusses to link together various modules. Since maneuvering or docking operations could likely excite several low-frequency vibration modes and the structure will be very lightly damped, difficult control problems are expected. Accurate prediction of structural damping will be very important in the design of large space structures. Optimizing the damping will aid in the control of the structural response.

It is well recognized that structures with pinned or bolted joints (similar to those proposed for the large space structures) have significantly higher damping rates than identical structures with "welded" or tightly clamped joints. Unfortunately, joint damping is very dependent on many variables such as joint design and condition of joint interfaces; thus, predicting the amount of damping is difficult.

Measured damping data from truss design prototypes is needed to construct empirical prediction models. Since joint damping is dependent on joint loads, gravity will influence damping measurements. Thus, on-ground measurements of damping will be in error by an uncertain amount. A data base of in-orbit and on-ground tests will establish the magnitude of ground-based damping measurement errors, help establish ground testing guidelines, and allow critiquing of damping prediction models.

Damping in Large Space Structures

The future research needs of large space structures was the topic of the entire September-October 1984 issue of the *Journal of Guidance, Control, and Dynamics*. Nurre et al.[1] outlines many of the problems with control of large space structures and notes that ground testing of a complete structure is probably not feasible. He recommends ground testing of individual components to characterize the complete structure and lists the following key issues in the structural dynamics testing area.

1) Zero-*g* effects.
2) Low natural frequencies with high modal density.
3) Joint/interface characteristics.
4) Damping (distributed and lumped).
5) Thermal vacuum effects.
6) Large space structure experiment excitation methods.

Ashley[2] notes that the primary sources for damping for large space structures could be fit into three categories: 1) material damping, 2) damping at joints and interconnections, and 3) artificially introduced damping (dashpots). For small amplitudes, material damping can often be modeled as independent of stress level. Such is not the case for joint damping. Simple models (i.e., Coulomb friction with macroslip) predict the rate of energy dissipation to be dependent on the normal loads across the interface of a joint. This would infer that gravity should increase damping rates. However, if joints allow some slippage, a 1-*g* load could prevent or reduce the amount of slippage that would occur and thus reduce damping. If one assumes that joints provide a significant portion of the total system damping, then the influence of 1-*g* loads during ground testing ought to be considered.

The amount of damping that joints could provide for large space structures is uncertain at this time. Ashley[2] postulates that material damping will dominate over joint damping for very large space structures. However, his conclusion is based on the assumption that joint damping is proportional to a characteristic length of the structure squared. Generally, joint damping via Coulomb friction is dependent on the number of joints, which is proportional to structure volume as is material damping. If the lengths of individual truss members are held constant, the relative contributions of material and joint damping should not change with structure size. Plunkett[3] gives a recent summary of friction-damping knowledge and reports that "several studies have shown that joint and connection damping is the most important mechanism for energy dissipation in most real structures."

Models of Friction Damping

Models of friction damping generally fall into two categories; microslip and macroslip. Macroslip models assume no damping occurs until there is relative motion between two interfaces. Relative motion occurs when the forces parallel to the interface exceed the Coulomb frictional force, which is

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proportional to the force that is normal to the interface. This classic friction damping model was analyzed by Den Hartog.[4] His analysis indicates that for small loads the energy dissipated increases linearly with displacement. Beards[5] discusses how to optimize joint damping by maintaining an optimum joint load during rotational macroslip. He reports that significant damping rates can be obtained when joints are allowed to undergo rotational slippage. However, some static stiffness is sacrificed when rotational slip is allowed.

Microslip models predict friction damping due to localized, microscopic slippage. Because of surface imperfections, interface contact pressure is not uniformly distributed. This allows localized slippage while the overall joint remains "locked." For example, when material damping measurements are made using cantilever beam specimens, a prime concern is how the specimen is clamped to the "wall" such that microslip contributions are minimized. Damping due to microslip would typically be less than from macroslip. Plunkett[3] reports we are far from being able to predict damping due to microslip.

Proposed Joint Designs

Joint designs are largely influenced by the methods used to construct the truss in space. If the truss is constructed by deployment or unfolding of truss components, the joints usually use pinned joints. Figure 1 illustrates a proposed deployable joint design. Current plans for the space station use erectable rather than deployable trusses. Figure 2 illustrates a proposed space station joint that could be assembled by a push and a twist of a collet.

A pinned joint design would allow rotational slippage about the pin axis. This rotational slippage could be exploited to maximize joint damping by preloading the joint bolts and running the joints dry (unlubricated). Drawbacks of this approach include permanent offset of the truss due to residual Coulomb friction and fretting corrosion of the joints. Using a viscoelastic material in the joints could provide a significant source of viscous damping, but this approach also has adverse affects such as the inability to maintain proper alignment of the structure.

The erectable joint illustrated in Fig. 2 would provide rotational stiffness in all directions, unlike pinned joints. However, some limited slippage could occur as rotary loads are applied. The amount of slippage would be related to how tightly the joint could be secured by an astronaut during assembly of the truss.

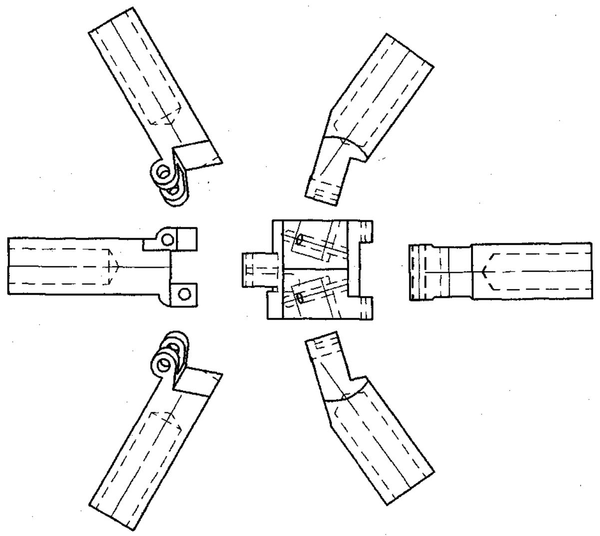

Fig. 1 A joint for a deployable structure.[6]

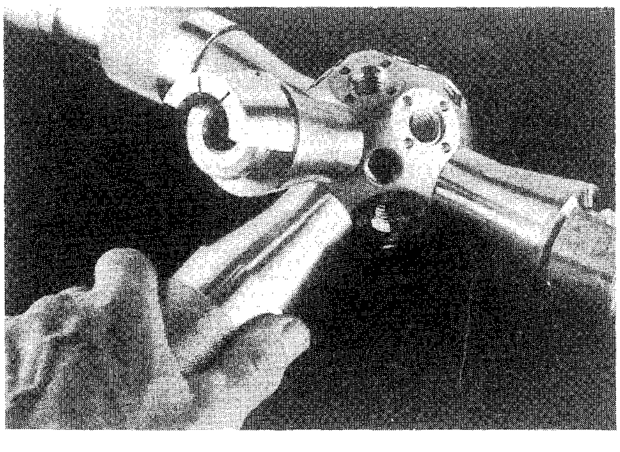

Fig. 2 Proposed space station joint. (Photo by Bruce Frisch, courtesy of *Aerospace America*.)[7]

Truss Damping Experiment Design

During the past year, a simple truss damping experiment has been designed and constructed at Utah State University. Figure 3 shows photographs of the experiment. The experiment consists of a cantilevered tetrahedral truss inside of a vacuum cell. Figure 4 illustrates the truss design. The truss is mounted to one wall of the vacuum cell and has a large mass attached to the other end of the truss to lower the resonant frequencies. The basic criteria in the experiment design was to assemble hardware that could be ground tested and tested in a microgravity environment. The experiment will be one of six Getaway Special (GAS) experiments from Utah State University in a large GAS canister on a future mission of the Space Shuttle. This will allow damping measurements to be made in microgravity and a vacuum. The truss uses very simple pinned joints and is constructed entirely from 6061-T6 aluminum except for

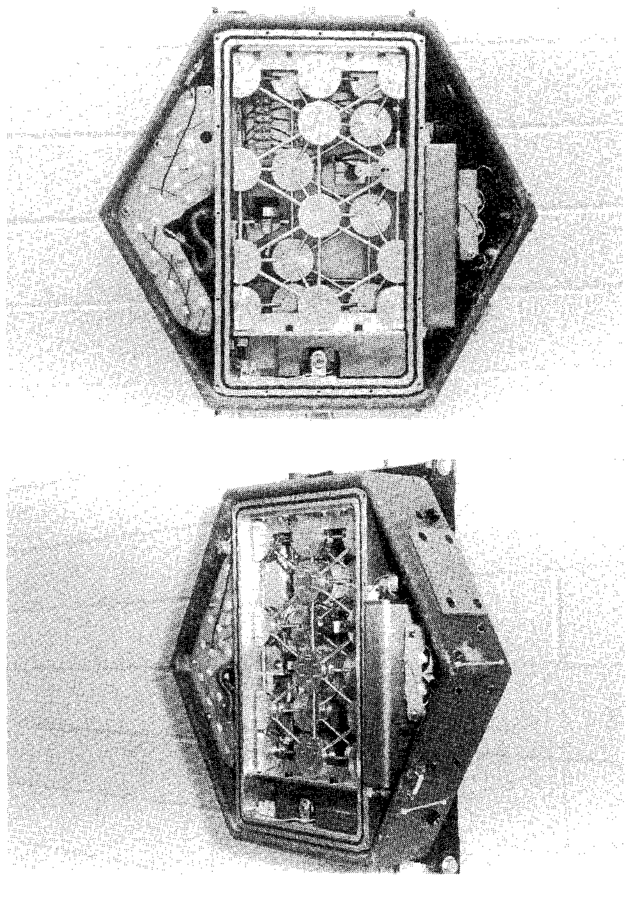

Fig. 3 Truss damping experiment at Utah State University.

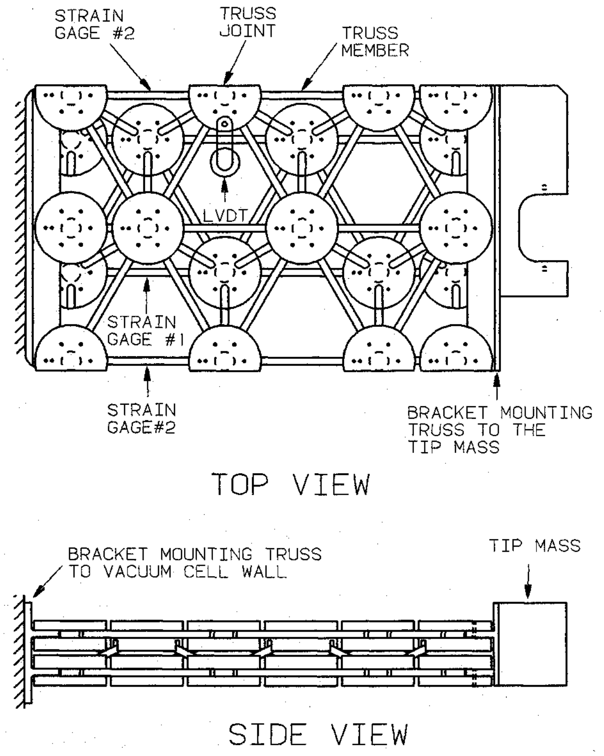

Fig. 4 The truss design.

the pins, which are stainless steel. Excitation is provided by a solenoid with the plunger mounted to the tip mass and the coil mounted to the vacuum cell. The resulting decay of oscillations is measured by strain gauges and a linear variable displacement transducer (LVDT). The truss has a fundamental natural frequency of about 15 Hz. Because the truss is quite flexible, additional structural support is needed during launch and reentry. To provide this support, the tip mass is locked during launch and re-entry by a locking mechanism operated by a stepper motor inside the vacuum cell. The experiment controller and data acquisition system is a Campbell Scientific CR-10 data logger. Recorded data will be stored in EEPROM and downloaded after the flight for detailed analysis. Batteries are used to provide power for the experiment. The vacuum cell is vented to space through a GAS purge port so that air damping is eliminated.

This project is being conducted on internal funding, which is very limited. The joint design selected was one that would be inexpensive to fabricate. This dictated that the joints be very large relative to the truss members. Although these simple joints do resemble the one illustrated in Fig. 1 for a large space structure, they are substantially different. Thus, damping data that is obtained would be of qualitative rather than quantitative value. A version using the actual joint design would be needed for quantitative value. The truss design incorporates the following features:

1) As many joints as possible are used to increase the amount of joint damping. It was desired to have joint damping dominate over other sources of damping.

2) The clearance between the truss members and the joint pins is maintained within 0.0005 and 0.0015 in.

3) The truss does not possess closely spaced vibration modes. This allows excitation of primarily a single vibration mode and thus eases data reduction.

Ground Testing

The truss was subjected to static and dynamic tests. The static tests were performed to measure the load vs deflection characteristics of the truss. The dynamic tests measured the damping of the truss.

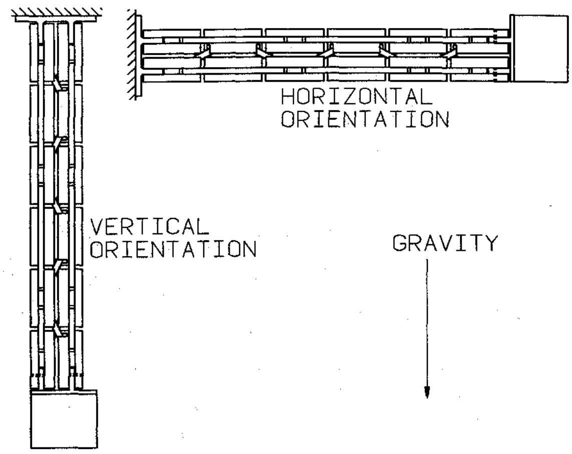

Fig. 5 Vertical and horizontal truss orientations.

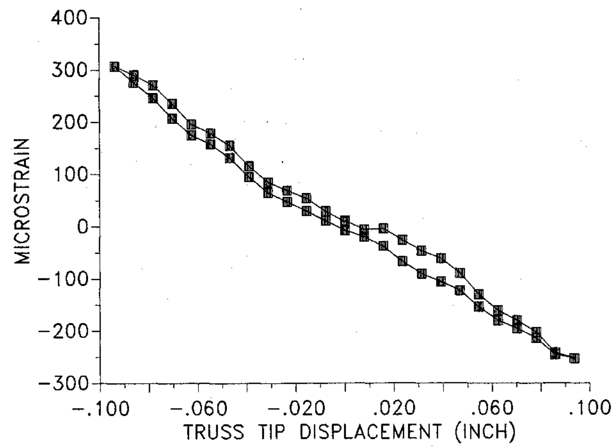

Fig. 6 Output from strain gauge 2 vs truss tip deflection for a static test with a vertical truss orientation.

Description of Static Tests

The static tests consisted of deflecting the tip of the truss a known amount in the direction normal to the plane of the truss and measuring the strains produced and the output of an LVDT used to measure displacements. The locations of the strain gauges and the LVDT are illustrated in Fig. 4. These tests were done with the truss in either a vertical or a horizontal orientation. Vertical and horizontal orientations are illustrated in Fig. 5. The vertical orientation of the truss would provide the smallest gravity loads in the truss members, whereas the horizontal orientation would provide the maximum member gravity loads.

Static Test Results

Figures 6 and 7 illustrate the static test results for the vertical and horizontal orientations, respectively. These figures clearly show the hysteresis occurring between the displacement at the tip of the truss and strains in truss members. The hysteresis is attributed to the clearance between the holes in the truss members and the joint pins. This clearance allows small displacements to occur within the joints, and the friction, which resists this motion, causes the strain/displacement relationship on the loading path to change slightly from the unloading path. The displacements in Fig. 7 are measured relative to the equilibrium position for a horizontal orientation. In moving from a vertical to a horizontal orientation, the truss tip was displaced approximately 0.125 in. due to the gravity load. Note that the overall strain/displacement relationship is slightly nonlinear in both Figs. 6 and 7.

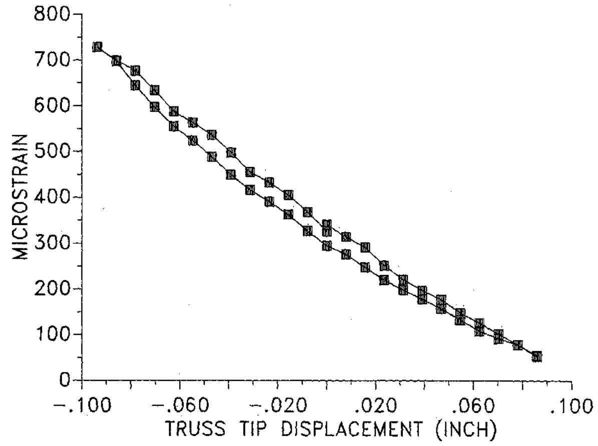

Fig. 7 Output from strain gauge 2 vs truss tip deflection for a static test with a horizontal truss orientation.

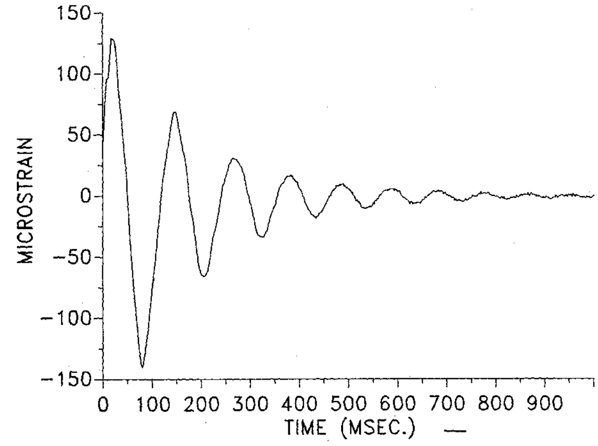

Fig. 9 Typical time history for output from strain gauge 2 for a vertical truss orientation at 0.001 torr pressure.

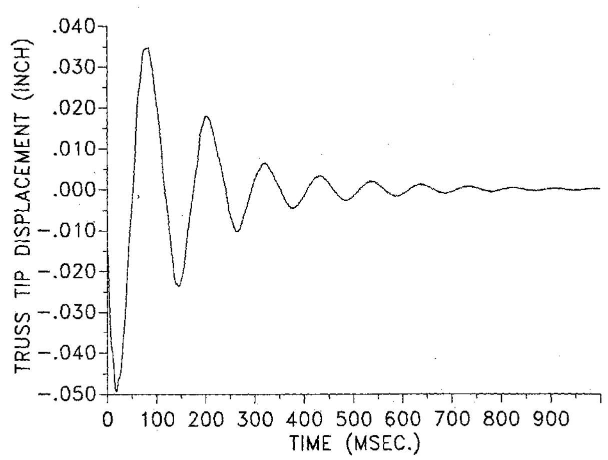

Fig. 8 Typical time history for output from the LVDT for a vertical truss orientation at 0.001 torr pressure.

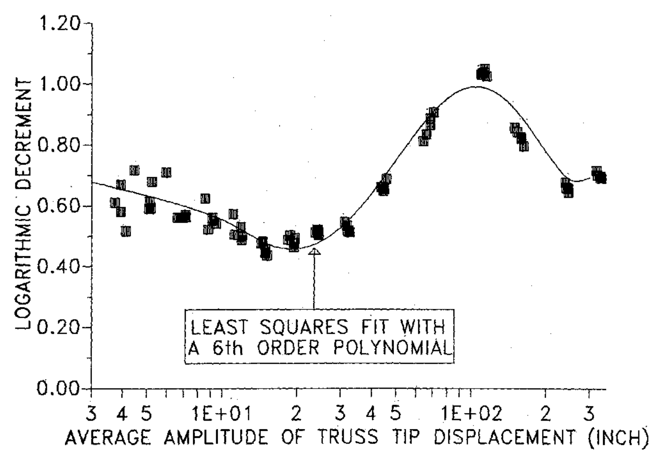

Fig. 10 Logarithmic decrement vs average amplitude data from the output of the LVDT for a vertical truss orientation at 0.001 torr pressure.

The hysteresis and nonlinear strain-displacement relationship should be expected to occur in pin-jointed structures where relative motion can occur. The ability to predict the behavior illustrated in Figs. 6 and 7 using nonlinear finite-element models is felt to be the first step in understanding the dynamic behavior of the structure.

Description of Dynamic Tests

Damping characteristics of the truss were measured by exciting the truss with the solenoid and then measuring the resulting decay of the oscillations. To insure that the solenoid or the LVDT were not influencing the damping measurements because of either eddy current generation or friction between the plunger and coil assemblies, damping measurements were made by manually exciting the truss with the solenoid and LVDT removed and measuring the decay of the oscillations using the strain gauges. The tests showed no change in the decay data when the solenoid and LVDT were properly installed. Damping measurements were made with the truss in three orientations: vertical, horizontal, and at 45 deg relative to horizontal.

The oscillation decay data measured from the strain gauges and the LVDT were digitally recorded on the Campbell Scientific CR-10 controller at a rate of 500 samples/s. The data was downloaded to a computer for postprocessing. The damping of the truss was quantified by computing the logarithmic decrement as follows:

$$\delta = 1/n \ \ln(X_0/X_n) \tag{1}$$

where

δ = logarithmic decrement
n = number of cycles
X_0 = maximum amplitude at some initial reference point
X_n = maximum amplitude after n cycles

Initial tests showed that the truss rapidly dampened the induced oscillations, and the damping produced is amplitude dependent. Therefore, the logarithmic decrement data was computed for a single cycle (i.e., $n = 1$) to extract as much of the amplitude dependence as possible. To illustrate the amplitude dependence of the damping data, the logarithmic decrement data was plotted as a function of the average amplitude (i.e., the average of amplitudes used to compute the logarithmic decrement). The average amplitude is defined as follows:

$$X_a = (X_0 + X_1)/2 \tag{2}$$

where

X_a = average amplitude

The data were also low-pass digitally filtered to remove noise, which becomes significant in the very low amplitude portion of the oscillation decay.

Dynamic Test Results

Figures 8 and 9 illustrate typical time histories of the LVDT and a strain gauge, respectively. Fourier transforms of the time history data showed only the fundamental mode was present throughout the decay. No higher modes were detected. The data acquisition system used did not permit sampling more than one sensor per test. Thus all the data presented in this section are from separate tests. Figures 10 and 11 illustrate the logarithmic decrement data for an LVDT and a strain gauge plotted as a function of the average amplitude. The data points shown in Figs. 10 and 11 are decay data from 5 separate tests, thus illustrating the repeatability of the damping data. As shown in Figs. 10 and 11, a least-squares fit of the damping data to either a fourth- or sixth-order polynomial was made to simplify presenting the measured results.

A summary of the damping data acquired from ground testing is illustrated in Figs. 12, 13, 14, and 15. Figure 12 illustrates the influence of truss orientation and air on damping data measured by the LVDT. The truss orientations in Fig. 12 were vertical, horizontal, or 45 deg from horizontal. At each truss orientation, tests were run at either a vacuum of approximately 0.001 torr or in air at local atmospheric pressure (about 12.5 psia). Damping data from the LVDT and three strain gauges are compared in Figs. 13, 14, and 15 for truss orientations of vertical, 45 deg, and horizontal, respectively. All tests in Figs. 13, 14, and 15 are at local atmospheric pressure.

Discussion of Results

The several important observations can be drawn from the damping data presented in Figs. 12, 13, 14, and 15.

First, the truss is very highly damped at large oscillation amplitudes. A typical value for material damping in aluminum would be $\delta = 0.0013$. Thus, the measured damping data are up to 800 times greater than typical material damping values.

Second, Fig. 12 clearly shows the damping contribution due to air is small compared to the other sources of damping. Thus, the primary source of damping is attributed to the joints.

Third, the damping is very dependent on the orientation of the truss (i.e., vertical, horizontal, etc.), and thus damping data could change by a factor of up to 4 just due to gravity loads. The maximum damping occurs with the truss in the vertical orientation when joint loads are minimized. It is in this orientation that the loads in the joints are fully reversed each cycle and the slippage that can occur in the joints is maximized. In the horizontal orientation, gravity causes a preloading of the structure such that during the dynamic tests conducted, many of the joints do not undergo load reversal (i.e., tension to compression) each cycle. Thus, slippage in the joints is minimized in the horizontal orientation. This would indicate that as gravity induced joint preloads are increased, the amount of macroslip decreases. It is not obvious that increasing gravity loads would decrease damping.

Fourth, as shown in Fig. 13, each of the sensors gave significantly different measurements of damping with the truss in a vertical orientation. This result brings into question what types of sensors are appropriate for measuring damping in this truss. Damping measurements are normally related to the energy dissipated per cycle. Theoretically, in a truss with welded joints and undergoing small displacements, the logarithmic decrement of the decay of either measured strains or displacements

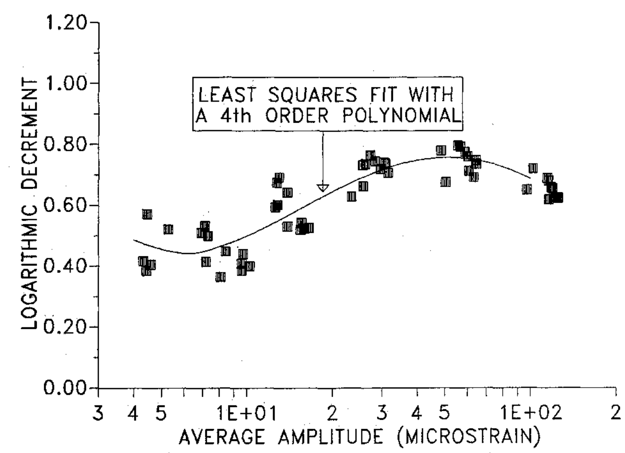

Fig. 11 Logarithmic decrement vs average amplitude data from the output of strain gauge 2 for a vertical truss orientation at 0.001 torr pressure.

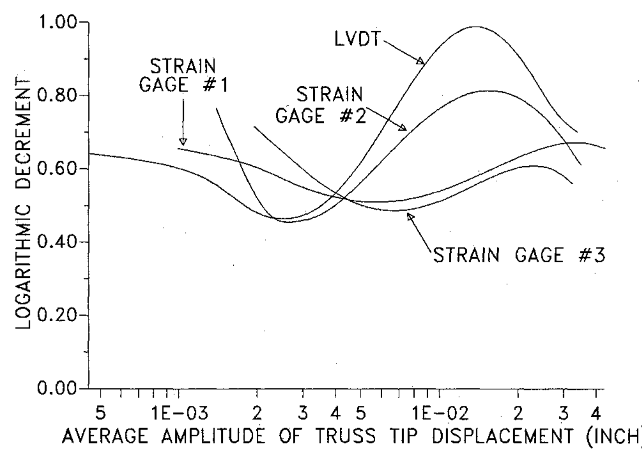

Fig. 13 Summary of least-squares curve fits to the damping data for the truss in a vertical orientation at local atmospheric pressure.

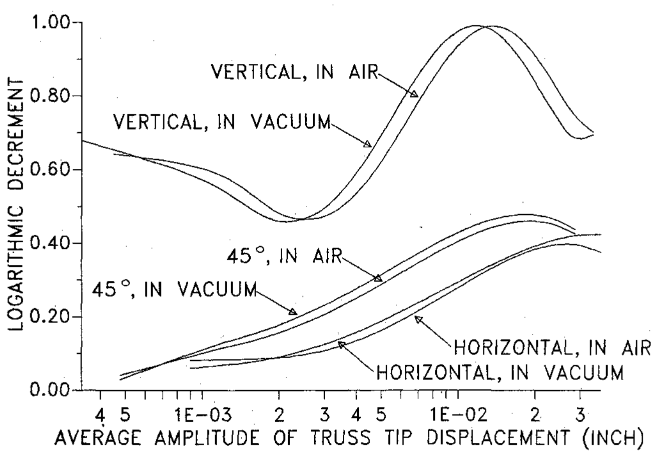

Fig. 12 Summary of least-squares curve fits to the damping data from the output of the LVDT.

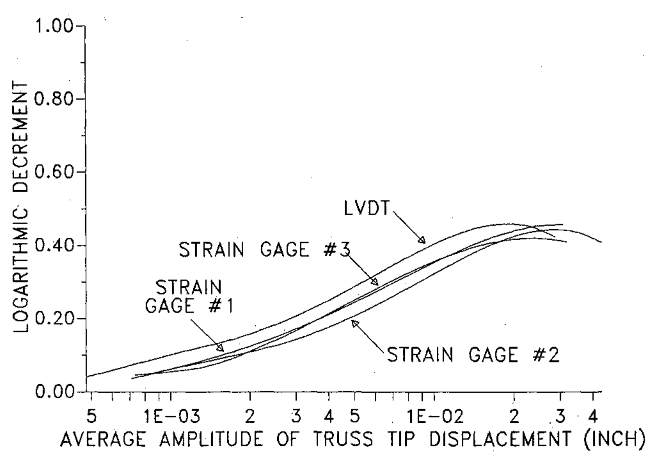

Fig. 14 Summary of least-squares curve fits to the damping data for the truss in a 45 deg orientation at local atmospheric pressure.

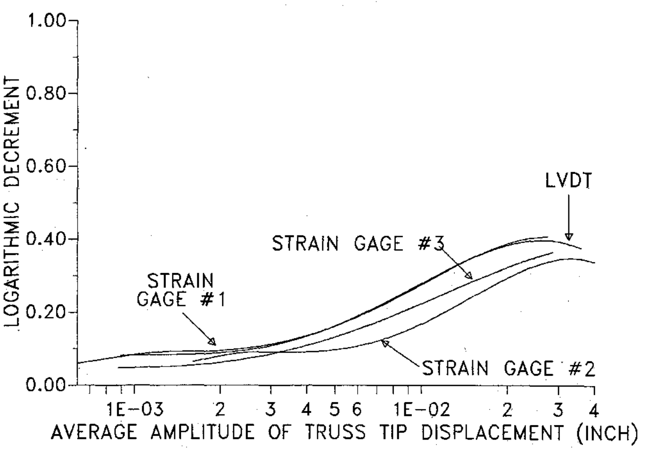

Fig. 15 Summary of least-squares curve fits to the damping data for the truss in a horizontal orientation at local atmospheric pressure.

should have a linear relationship to the dissipation of energy. The joint slippage that occurs in the vertical orientation makes the relationship between energy dissipation and sensor measurements more complicated, and further investigation in this area is needed. Good agreement between the sensors occurs for the horizontal and 45 deg orientations as shown in Figs. 14 and 15. This would indicate that as preloads remove joint slippage, the influence of the joints slippage on damping is reduced, and the truss behaves more like a truss with welded joints.

Fifth, the measured damping in the horizontal and 45 deg orientations becomes much smaller when the amplitudes become small.

Conclusions

It is difficult to extrapolate the behavior of the truss in this study to other truss designs. The primary value of the acquired data will be as a data base to which analytical damping models can be compared. An effort is currently under way at Utah State University to build a nonlinear finite-element model of the truss, which will include gap elements to model the macroslip that is occurring. However, the following general conclusions may be drawn from this effort:

1) Joints can produce large damping rates if some macroslip in the joints can be tolerated.

2) Joint damping is amplitude dependent and may become small at small amplitudes if the joints are preloaded.

3) Gravity loads acting on ground tests of components of a large space structure can significantly change the damping.

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