DAMPING OF A LARGE SPACE PLATFORM

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ABSTRACT

An investigation of the damping needed to satisfy stringent settling time requirements typical of several classes of large space platforms was conducted. The method investigated for decreasing the settling time was to use composite materials for the structure and to then increase the damping of certain critical members. In general, composites are more stiff and have higher material damping than aluminum; therefore, a composite structure will have decreased settling time compared to an aluminum structure. This investigation showed that by using composite materials the platform settling time can be reduced by a factor of more than two. This reduced settling time does not satisfy the more stringent settling time requirements of some spacecraft; therefore, more damping can be added to further reduce the settling time. The damping in each critical member has to be increased beyond what is usually available from passive or active means alone. Therefore, both passive and active damping will be required. The degree to which each will be utilized is being determined in an ongoing controls-structure interaction (CSI) program at McDonnell Douglas Space Systems Company.

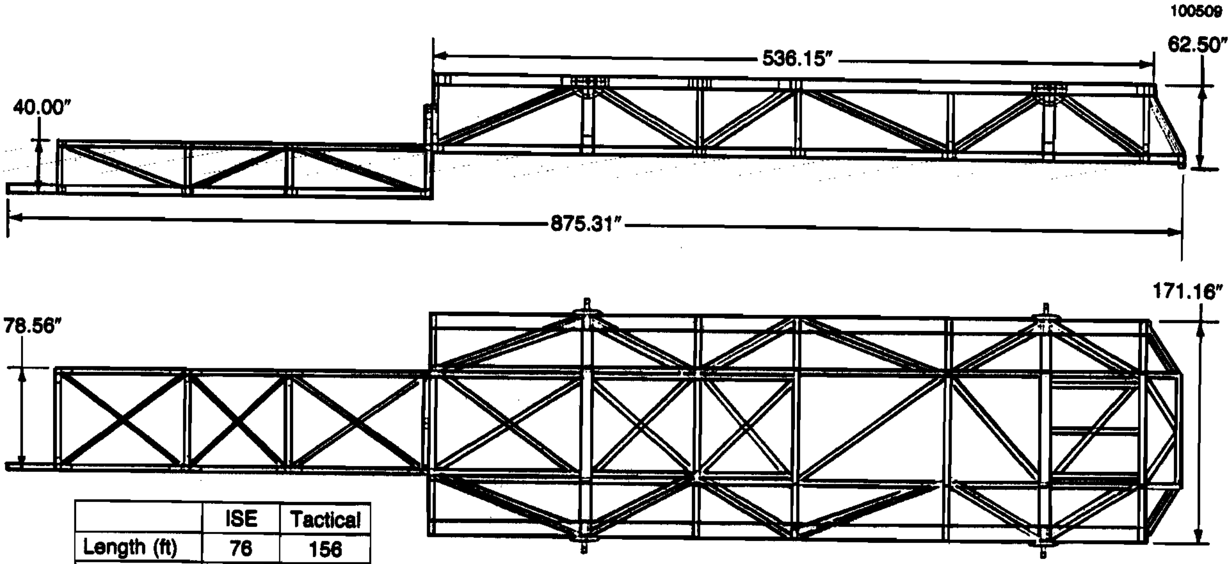
INTRODUCTION

Space truss structures suitable for large space platforms, such as required by the space station, large deployable reflectors, and space-based weapon systems, can have strict performance requirements, which include (1) minimum structural weight to minimize launch costs, (2) survivability in the natural and hostile space environment, and (3) very short settling times for structural vibrations caused by rapid maneuvers of the platform to maximize observation and/or firing time. The settling time was chosen as the primary performance requirement in this investigation. Designs and methods for achieving the required performance in the more stringent cases have not yet been demonstrated. The high specific stiffness and damping of composite materials make them ideal candidates for applications that require increased performance. The increase in performance due to the composite material alone, however, only will satisfy some less stringent requirements, such as those of the initial phase of the space station; for more stringent requirements, such as those of a tactical neutral particle beam (NPB) platform, a larger increase is needed.

An investigation of how much damping is needed to satisfy these requirements was conducted. The role of passive damping in the satisfying of the requirements was also studied. The primary method investigated for increasing the damping of the platform, and thereby increasing its performance, was to increase the damping of certain critical members. This approach showed that by increasing the damping of only a few critical members, which were determined by looking at the amount of strain energy in the members, the damping of the whole platform could be significantly increased. The damping in each critical member had to be increased beyond what is probably available from passive or active methods alone. Therefore, both passive and active damping will be required. The degree to which each will be utilized is being determined in an ongoing controls-structures interaction (CSI) effort. The first part of that study looked at the interaction of passive damping and active damping on the space station.

DAMPING REQUIREMENTS

The existing preliminary design of the Neutral Particle Beam Integrated Space Experiment (NPB-ISE) truss structure was used as a baseline in the investigation. A detailed NASTRAN model of the NPB platform was developed before the NPB program was cancelled, therefore, in order to save time and money this model was used as the baseline space platform model. The material used in the baseline platform was aluminum. The physical properties of the baseline platform are on Figure 1. The settling time was selected for determining the damping needed to satisfy space platform mission requirements. The settling time is defined in the present context as the time between the end of the slew maneuver of the platform and the residual vibration amplitudes becoming less than the allowable deformations. The settling time is a function of the inverse of the product of specific stiffness and damping of the structure. The time required for the reduction of dynamic structural deflections to an acceptable level is shortened as the specific stiffness and damping increase. Compared with aluminum, advanced composite materials have up to 7 times the specific stiffness and up to 10 times the damping [1,2]. Plotted in Figure 2 is the bending vibration



	ISE	Tactical
Length (ft)	76	156
Weight (lbs)	41,000	140,000

Figure 1. NPB Physical Properties

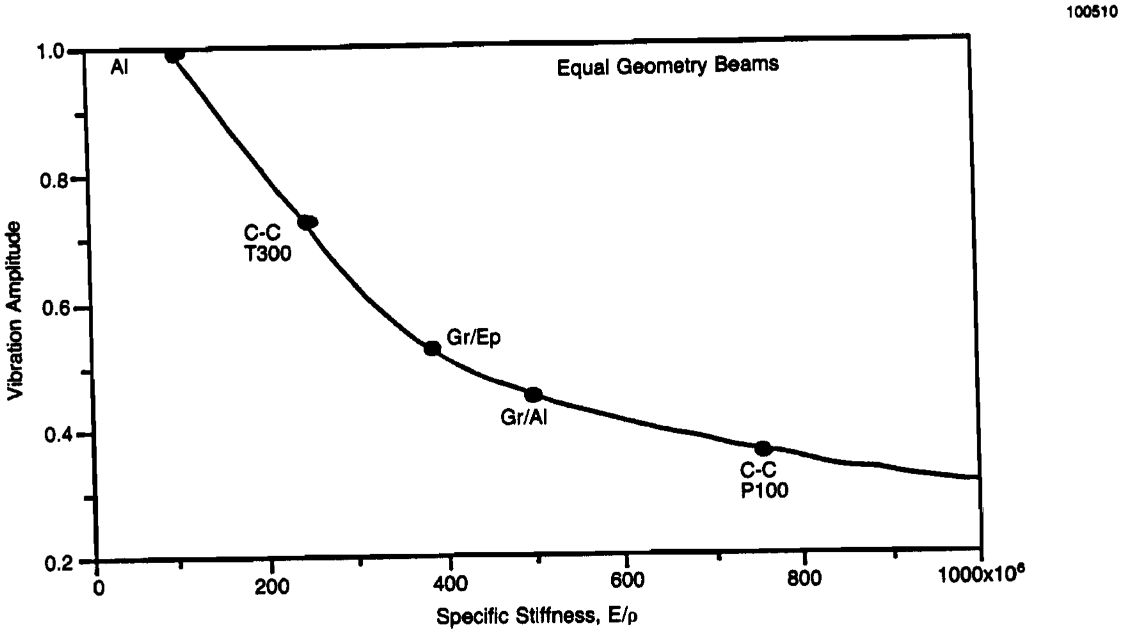


Figure 2. Amplitude of Vibration Versus Specific Stiffness. Amplitudes Normalized with Respect to Aluminum

amplitude as a function of material specific stiffness for equal geometry beams subjected to the same excitation. Plotted on top of this curve are several points representing typical composite materials and the curve is normalized with respect to the amplitude of an aluminum beam. Figure 2 shows that by using a composite material the amplitude of the response can be significantly reduced without even considering damping. The use of materials with higher specific stiffness to reduce the amplitude of the structural response to acceptable levels may be good enough for some applications but is still far from good enough for the more stringent requirements of a space-based weapon system, which is the technology driver in this case.

The baseline NPB model structural members were redesigned for several composite materials. The members were resized such that the total platform weight remains constant for each design. Then the performance of each is evaluated based on settling time. There are two displacements that settling time depends on, one is the initial displacement due to the residual vibration and the other is the displacement requirement at the point of interest. The initial displacement depends on the external excitation, in this case the slew maneuver forcing function. Therefore, to obtain an initial displacement typical of a tactical NPB space platform during operation a slew maneuver and corresponding thruster forces had to be selected. The typical slew maneuver selected was 10 degrees pitch in less than one second. The thrusters were chosen to be located at the four corners of the main part of the platform, as shown in Figure 3. The thruster forces and firing profile had to be chosen such that the required slew maneuver produced typical initial displacements. The thruster firing profile selected was a bang-bang type tuned to the fundamental frequency of the platform, as shown in Figure 3b. The tuning of the thruster firing profile gives reasonable initial displacements and is a first cut at optimizing the thruster firing profile. If the tuning is not done,

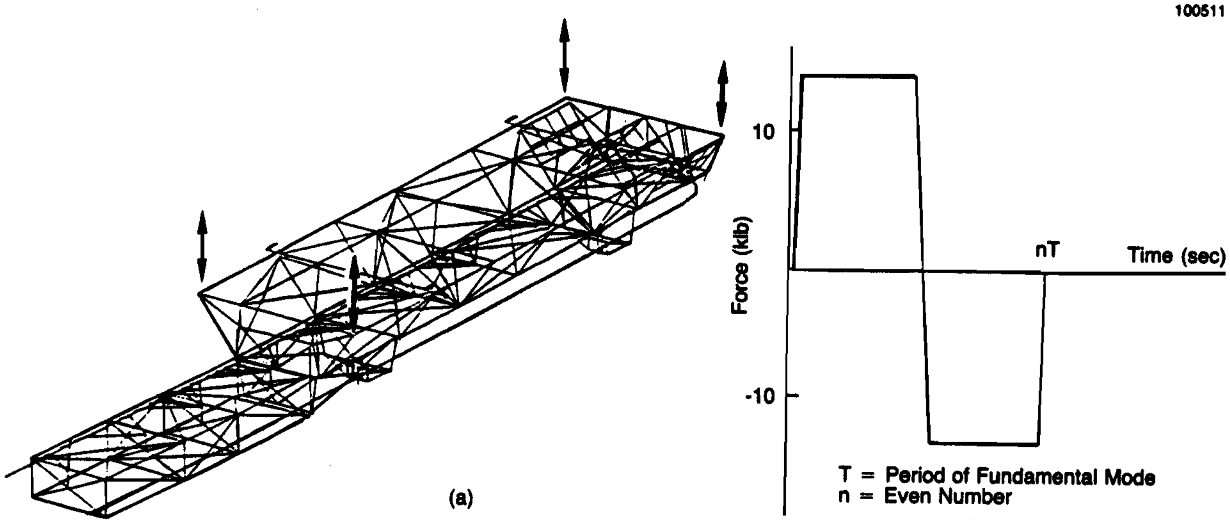


Figure 3. (a) Thruster Locations and Directions, (b) Force Profile for Each Thruster

then unusually large displacements result from the residual vibration, as shown in Figure 4. The resulting magnitude of the thruster forces is about 13,000 pounds at each of the four thruster locations. These are large forces and they induce large stresses in the structure.

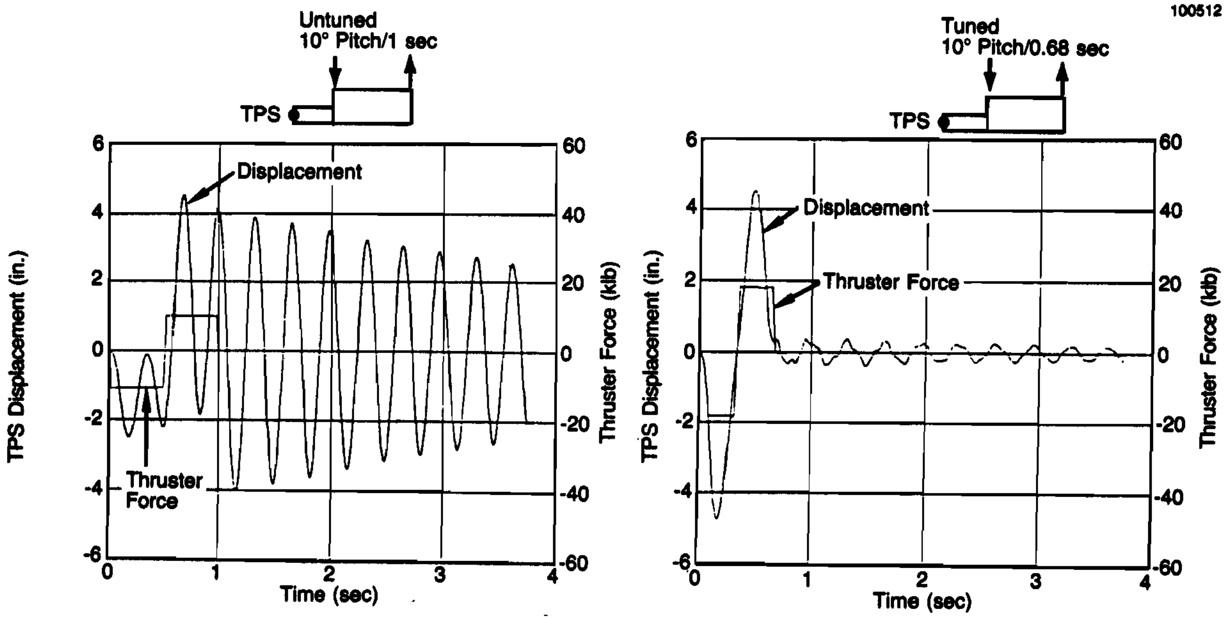


Figure 4. Thruster Tuning Effects on Structural Residual Vibration Amplitude at the Tracking and Pointing System (TPS) Location

The performance of the baseline truss, i.e., the NPB-ISE platform, was determined using the slew maneuver described above. The fundamental frequencies, slew maneuver, thruster force, damping, and settling times are given in Table 1. The settling time for the aluminum baseline platform vibration amplitudes to decrease to below the 0.001 inch requirement at the tracking and pointing system (TPS) location is about 250 seconds, which is about 600 times greater than required.

Two advanced composite materials were selected so that a comparison with the performance of the baseline platform could be made. The materials selected were graphite-epoxy (Gr/Ep) and graphite-aluminum (P100-Gr/A1). These materials were chosen because their properties are typical of advanced materials. The baseline truss members were redesigned for each of these materials so that the weight of the structure would remain constant for comparison purposes.

The results for the performance evaluation are given in Table 1, along with the results of the aluminum baseline platform. The settling time is a function of the inverse of the product of the frequency of vibration and the damping at the frequency. Therefore, the larger the frequency and damping, the shorter the settling time. Considering the frequency data alone the most promising candidate material seems to be the graphite-aluminum. Because of its high specific stiffness, it has the highest fundamental frequencies and thus the shortest settling time if the damping of the materials considered was the same. The damping of the materials, however, is not the same. The aluminum and the graphite-aluminum have approximately equal damping factors[1], while the graphite-epoxy can have many times the damping of aluminum depending on the layup of the composite[2]. Therefore, both the graphite fiber composites are good candidate materials. Assuming typical damping ratios for the materials gives settling times on the order of hundreds of seconds, which is much larger than the required settling times. Therefore, assuming that

Table 1. Performance Evaluation Based on NPB-ISE NASTRAN Model

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Primary Structural Material		Al	Gr/Al	Gr/Ep
Fundamental Frequencies (Hz)	Longitudinal Bending	2.96	6.15	4.96
	Torsion	4.75	10.04	8.02
	Transverse Bending	5.63	11.78	9.50
Tuned 10° Pitch Slew Maneuvering Time, T_M (sec)		0.676	0.650	0.812
Required Thruster Force (klbs)		13.0	13.5	10.8
Material Damping, ζ (%)		0.1	0.1	0.35
Total Time: Slew Initiation to Weapon Firing, T_T (sec)		1.1	1.1	1.1
Calculated Settling Time, T_S (sec)		247	119	43
Required Settling Time, T_R (sec) ($T_M+T_R \leq T_T$)		0.424	0.450	0.288
Ratio of Calculated to Required Settling Time, T_S/T_R		583	264	149

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these are the materials that will be used on SDI-type platform structures, one way to decrease the settling time is to increase the damping in the structure.

If damping is to be added to the structure to decrease the settling time, the question is how much damping is needed in the structure? Using the data in Table 1, the total damping needed by the NPB platform structure is plotted as a function of the required settling time for the candidate materials in Figure 5. For the graphite-aluminum platform the total damping needed is about 20 to 30 percent. The mechanisms from which the damping is coming have not been specified at this point. This 20 to 30 percent represents the energy dissipation rate that is required to meet the settling time specification for the NPB platform. The damping mechanisms can be passive, active, or a mix of the two depending on the application and design of the structure.

One way of increasing the damping of the structure is to introduce high damping into certain critical members. These members are selected based on the magnitude of the strain energy in them in response to the slew maneuver; those selected as most critical are the ones with the most strain energy and the least critical are those with the least. In the model a certain number of critical members, which originally have a nominal damping ratio of one percent, are replaced with members having much higher damping ratios. Plotted in Figure 6 is the damping ratio of the overall structure as measured by the response decay at the TPS position as a function of the number of replaced members. The members are replaced with other members having 10, 20 and 40 percent damping ratios. As can be seen from Figure 6, it only requires relatively few members to be replaced with higher damping members to make a significant difference in the damping of the total structure. For example, looking at Figure 6, if there exist members that have a

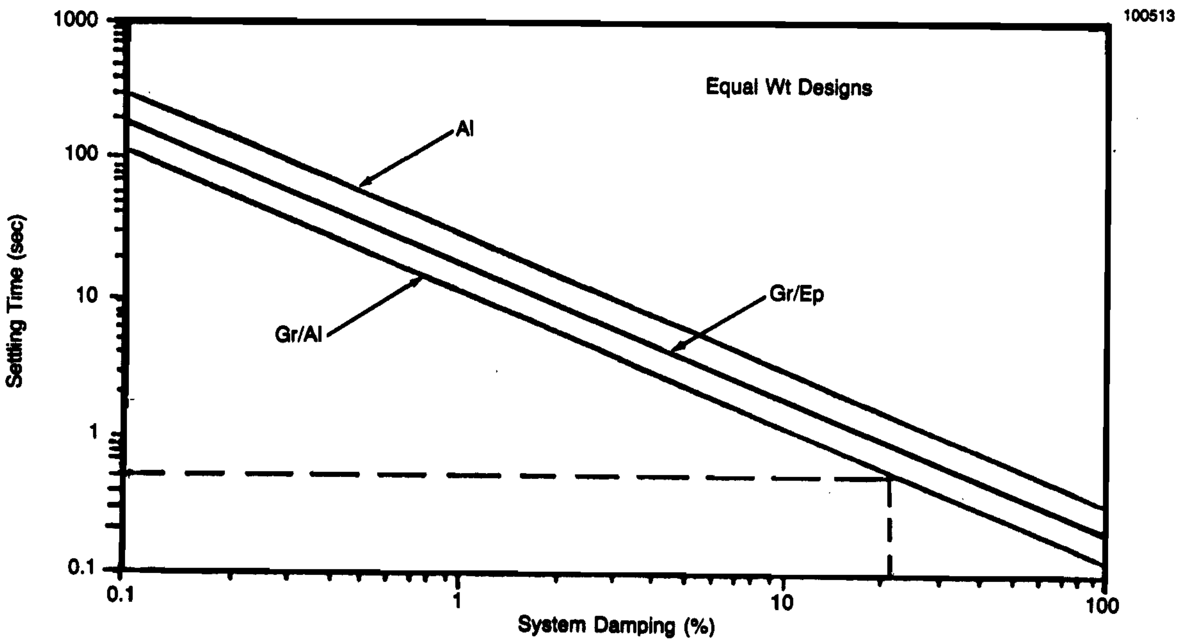


Figure 5. NPB Settling Time Versus Overall System Damping for Various Materials

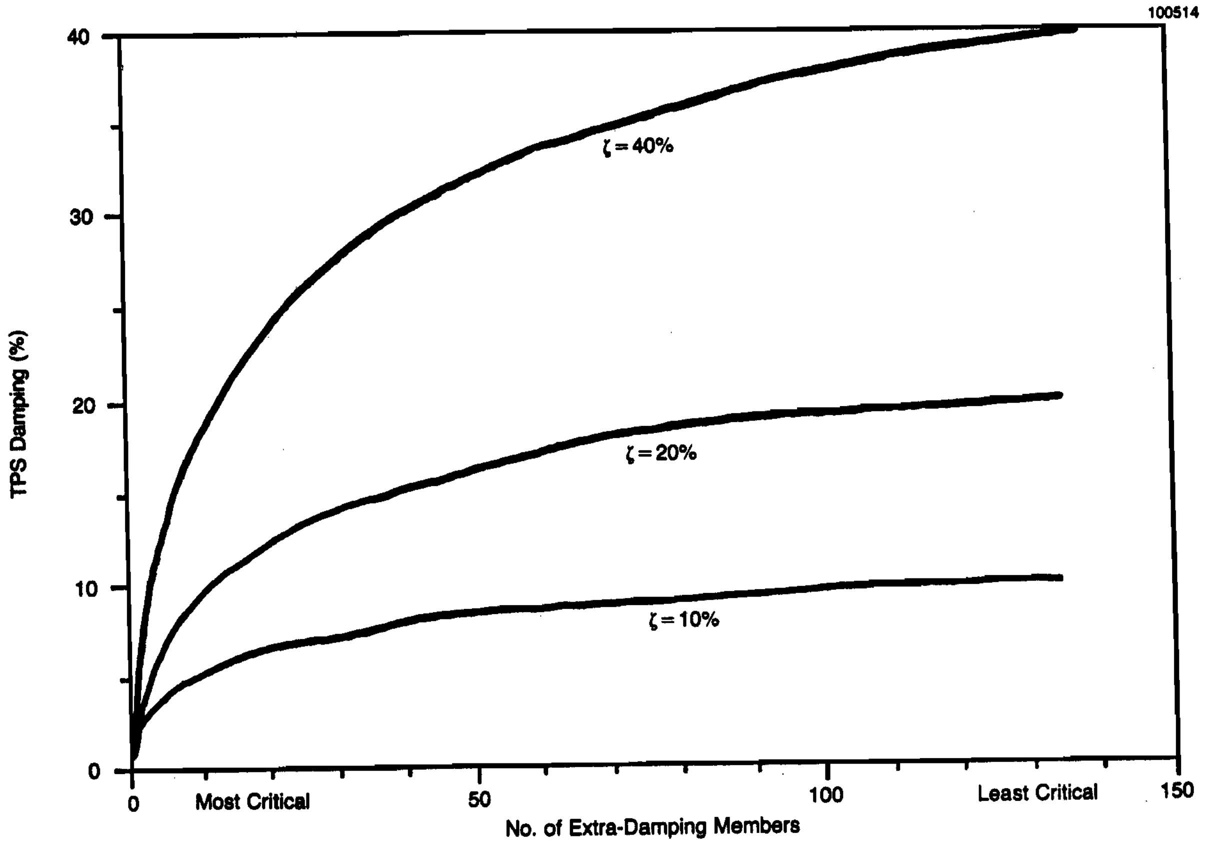
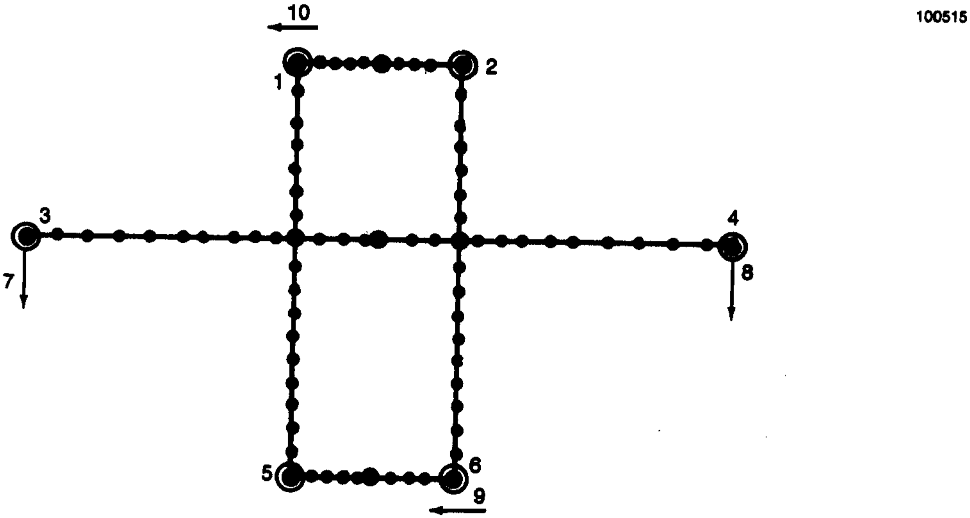


Figure 6. TPS Damping Versus Number of Extra-Damping Members That Replaced Nominal Damping Members

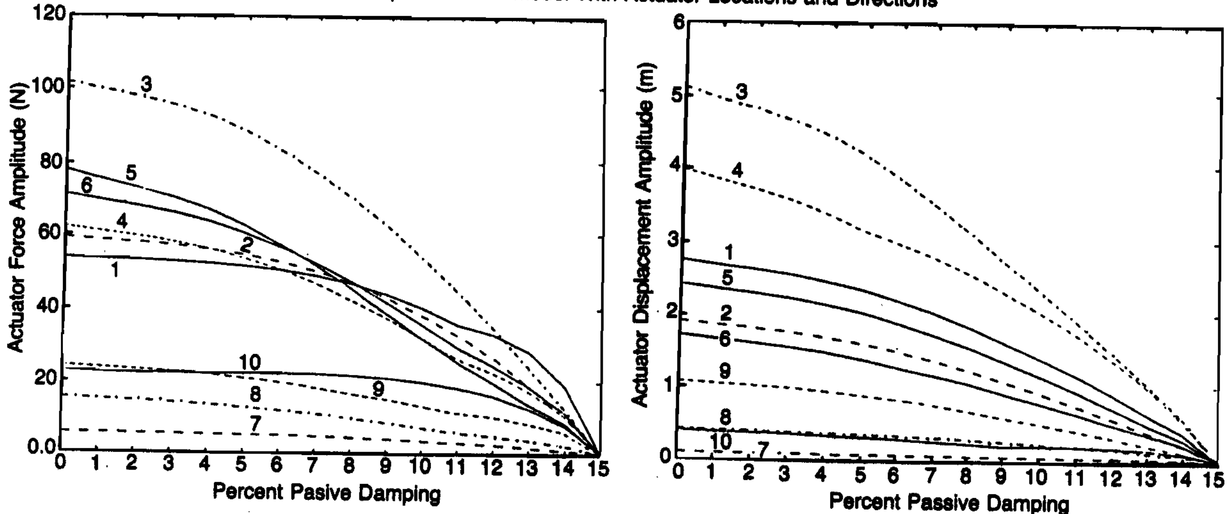
damping ratio of 40 percent then we need only replace 12 of the most critical members out of a total of 134 members to reach an overall structure damping ratio of 20 percent. What the mechanisms are for obtaining members with high damping ratios has not been considered in this study to date. How to obtain these levels of damping (passively, actively, and a mix of the two) in the critical members without significantly degrading the stiffness and increasing the weight of the structure is currently being investigated. The optimum mix of passive and active damping is highly dependent on the spacecraft and mission requirements.

PASSIVE AND ACTIVE DAMPING ROLES

To determine what the roles of passive and active damping should be in the vibration suppression and control of large space platforms a model of the space station was used. This model is shown in Figure 7. The excitation to the structure is representative of a space shuttle hard-docking maneuver at the center of the station. It was desired to investigate how a variation in the passive damping affects the required active control system in terms of actuator forces and displacements and structural displacement at the actuator positions.



a. Space Station Model With Actuator Locations and Directions



b. Actuator Force Amplitudes Versus Passive Damping

c. Actuator Displacement Amplitudes Versus Passive Damping

Figure 7. Effects of Increased Passive Damping on the Actuator Forces and Displacements for the Space Station

The actuators selected for this study were proof-mass actuators with the proof-mass component of the actuator weighing 150 pounds. As shown in Figure 7a, there are 81 candidate actuator locations with 3 directions per location giving a total of 243 candidate actuator positions. A low authority controller (LAC) and 10 actuator-sensor pairs were selected. The requirement of 15 percent damping was set. Based on an optimization routine, 10 actuator positions were chosen so as to give at least 15 percent active damping to the 10 most critical modes when the passive damping is negligible. The critical modes were chosen based on the amplitude of the rotation at certain payload positions due to the given excitation. The results of the simulation are presented in Figures 7b and 7c. The actuator force amplitudes are plotted in Figure 7b versus the amount of passive damping. The sum of passive and active damping is always about 15 percent, which is the requirement set above. As can be seen the actuator force required drops off with increasing passive damping. In Figure 7c the maximum displacement amplitudes of the actuator masses are plotted versus the passive damping. The maximum proof-mass displacement decreases with increasing passive damping. The envisioned design for the space station proof-mass actuators is a 150 pound proof mass running along a truss member. The space station truss longitudinals and battons are 5 meters in length; therefore, if the actuator proof mass is centered before activation, then the maximum it can displace during a control operation is less than 2.5 meters. It can be seen from Figure 7c that if the space station must have at least 15 percent damping ratio and uses proof-mass actuators then either the proof mass of the actuators must increase, the number of sensor-actuator pairs must increase, or the passive damping ratio can be increased to about 11 percent, which would give a proof-mass displacement of about 2 meters.

CONCLUSION

Beginning with the construction and operation of the space station, the large space platforms that are going to be orbited in the next decade will require varying degrees of damping to perform their missions. In some applications little or modest levels of damping will be required that can probably be handled with either passive or active methods of energy dissipation. There will be some applications like NPB, however, where much more damping is required, say more than 10 percent and up to as high as 40 to 50 percent. To achieve these levels of damping performance will require the use of both passive and active damping methods. As was shown above, the two methods can complement each other, the degree to which this occurs depends on the damping required and the system constraints and characteristics.

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