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Coupled vibration isolation/suppression system for space applications: aspects of structural design

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ABSTRACT

Vibrations have long been a source of problems for space systems, with acoustic and aerodynamic excitations causing failures during launch and periodic disturbances degrading performance on-orbit. In exploring new solutions to such problems, research at The Aerospace Corporation has recently considered the applicability of piezoceramic based adaptive structures to space systems. A small-scale testbed has been developed comprised of active mounting brackets that can isolate payloads from disturbances and an active payload platform that can suppress vibrations generated by payload instruments. Various issues related to practical applications have been explored through this representative system, and in this paper the aspects of structural design and structural modeling are explored. Payload capabilities are bounded for realistic launch environments, and the accuracy of structural modeling techniques for the integrated system is considered. Through this effort, the feasibility and potential utility of space structures with integrated piezoceramic transducers is investigated. The paper concludes with a discussion of potential applications for such a system, and examines considerations for the transition to practical space systems.

Keywords: adaptive structures, isolation systems, piezoelectric transducers, finite element models

1. BACKGROUND

Throughout their life, spacecraft components are subject to a wide range of mechanical vibrations. During launch, excessive responses to random and acoustic excitation can lead to failure in components such as electrical circuits. On-orbit, forced responses to disturbances can cause significant performance degradation in instruments such as optical sensors. Typically, the solution is to limit vibrations through the tailoring of mechanical resonances or through passive isolation of components from excitation sources. Such procedures are effective in a wide range of systems, but in some situations attempting to balance widely varying launch and on-orbit requirements can lead to compromises in performance, especially in an environment that emphasizes commonality. Similarly, the current trend toward miniaturization in space systems is leading toward the incorporation of multiple instruments on a single payload, making the isolation of individual instruments difficult. As a result, there is a developing need for a system able to isolate payloads from a range of external disturbances sources while suppressing vibrations internal to the payload.

Such requirements demand an adaptable, broadband vibration isolation system, and suggest the use of an active system. Research in adaptive structures has produced such systems, and the incorporation of piezoceramic sensors and actuators directly in the mounting structure of sensitive instruments or components would seem to be a logical solution. Piezoceramic technology has emerged as one of the most mature adaptive structure concepts, and a wide range of concepts and potential applications have been described in the literature[1-5]. In particular, significant developments have taken place in piezoceramic vibration suppression techniques, and several concepts are being demonstrated on-orbit[6-7]. There is still a perception in the space community, however, that this technology may not be of utility for practical space systems.

Research at The Aerospace Corporation has attempted to investigate the validity of this concern through an assessment of the feasibility of piezoceramic based adaptive structures for the control of vibrations in space systems. A systems point of view was adopted in order to explore various aspects of such systems, but a coupled vibration isolation/suppression concept was explored in detail to address practical issues of adaptive structure design and implementation. Initial development led to a novel isolation concept that was experimentally shown to provide an order of magnitude reduction in transmitted

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vibrations[8]. The concept utilized flexible mounting brackets to filter out high frequency excitations, with low frequency resonant response limited by integrated piezoceramic actuators. Questions remained, however, whether this type of structure could survive the environment experienced by typical space systems. Thus, an effort was initiated to examine structural aspects of such systems including the range of applicability, the effectiveness of standard finite element packages and procedures in design and simulation tasks, and the difficulty inherent in transitioning this technology to practical applications. In this paper, these three issues are explored through the coupled isolation/suppression system.

2. COUPLED ISOLATION/SUPPRESSION SYSTEM

The coupled isolation/suppression system was envisioned for a multiple sensor payload platform that was subject to base excitation as well as internal disturbances. Targeting small, lightweight payloads employing miniature sensors, the payload structure was assumed to consist of a relatively flexible platform supporting three small sensors, one of which had a moving assembly. It's objectives included the isolation of the payload from the spacecraft during launch, six degree of freedom control of the payload platform on-orbit, and suppression of vibrations within the payload in such a way that the relative position of all sensors could be maintained and known during operation. Components were required to be structurally efficient, lightweight, easy to manufacture, and reliable in order to minimize the impact of the active isolation system.

The design investigated for this application utilized active mounting brackets to isolate the payload from spacecraft disturbances, coupled with an active payload platform to suppress vibrations generated by payload instruments, Fig. 1. The brackets are based on a novel approach proposed by Falangas[8] for the isolation of sensitive electronics from broadband excitation. Termed the S-bracket because of its shape, Fig. 2, this concept utilizes soft mounting brackets to filter out high frequency excitation coupled with an adaptive structural design that enables attenuation of low frequency resonant responses. The brackets essentially operate as a two degree of freedom flexure, but through a series of integrated piezoceramic actuators and a digital control system[8], the brackets are able to control vertical and horizontal translation and three rotations of the payload. They are designed to be lightweight, easy and inexpensive to produce, and scaleable. A mockup of this concept was developed and tested using a rigid payload platform, and an order of magnitude reduction in transmitted vibrations was demonstrated[8].

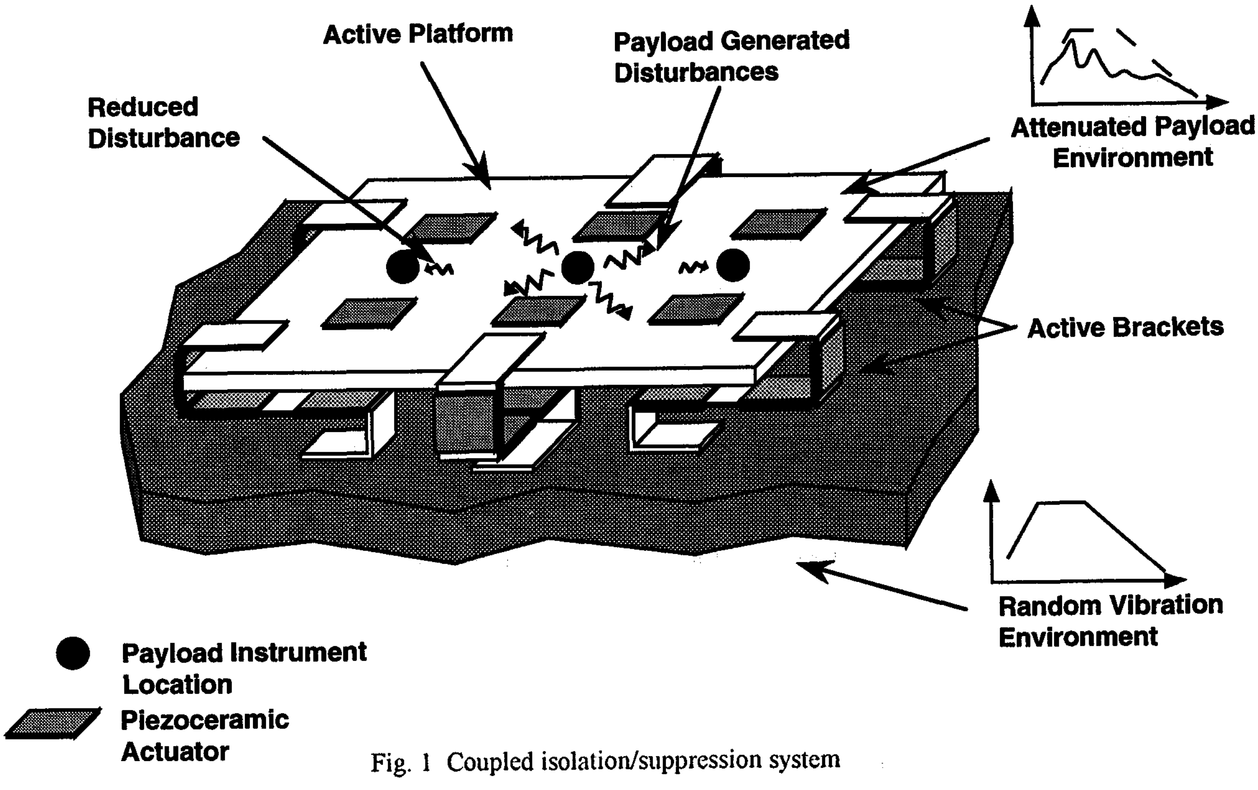

Fig. 1 Coupled isolation/suppression system

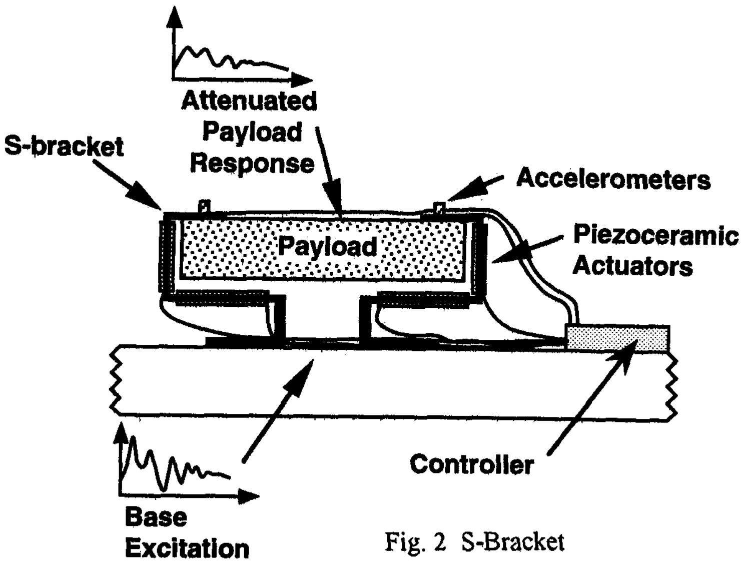

Fig. 2 S-Bracket

The active platform design was also based upon a concept previously shown to be effective in the laboratory[9], and simply involved bonding piezoceramic actuators and sensors on the surface of a plate in regions of high modal strain energy. Although experimental demonstration of the platform utilized simple metal plates, practical applications could employ a variety of designs including layered composites or honeycomb panels. The controller for this system attempts to maintain a zero strain state in the plate, and depends on the brackets to provide the correct orientation. Although this active approach must be traded with simple mechanical solutions for specific applications, such as stiffening the plate, it may provide important benefits. In particular, the tailorability of the active system provides a means to enable a widely applicable, modular design. Based on the experimental data, the combination of the active platform with the S-brackets promises a very stable operational environment for sensitive instruments. Structural issues related to the practical application of such a system, however, have not been fully addressed.

To explore such issues, an experimental mockup of the concept was constructing using simple aluminum stock. Six 6 x 4.5 x 2 in. brackets (40 mils thick) were used to support a 9 x 18 in. platform (30 mils thick) with three simulated payloads. Consistent with the modal strain energy of the assumed three sensor payload configuration, six pairs of 2.5 x 1.5 in piezoceramic actuators (12 mils thick) were bonded to the platform near the sensor mounts, Fig. 1. The piezoceramics were bonded using a conductive adhesive (ECCOBOND 57C) with opposing pairs of actuators configured to apply bending moments to the structure. The brackets were then mounted on a base plate, also composed of aluminum stock, which simulated a spacecraft mounting panel. The plate was clamped on all edges by aluminum bars, supported by four posts, and clamped to the floor. A shaker was installed to drive the base plate and simulate base excitation of the isolation system, Fig. 3.

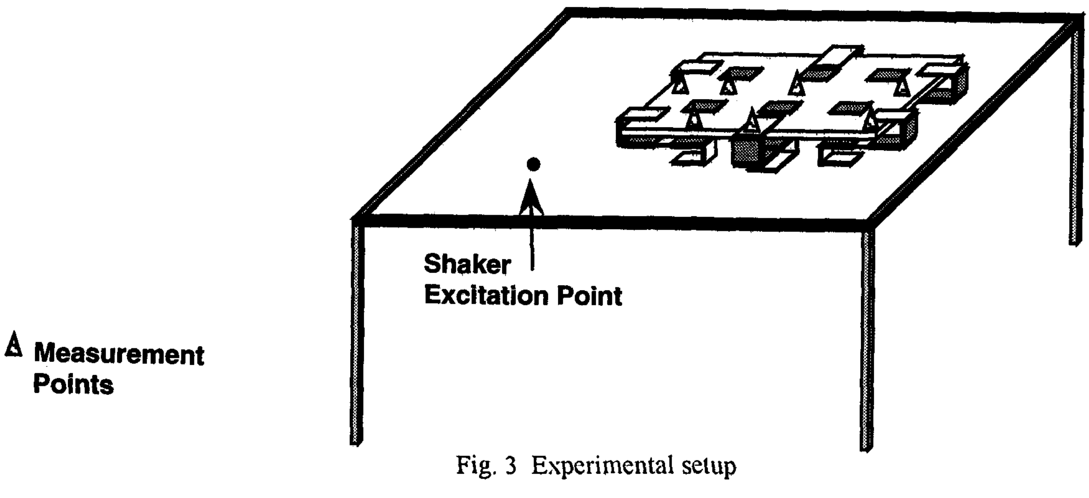

Fig. 3 Experimental setup

3. ASSESSMENT OF CAPABILITIES

Although simple in concept, the structure of the isolation/suppression system has many characteristics that could limit its practical applications. For space application, the driving structural consideration is the survival of static and dynamic launch loads, which have a spectrum with energy in a broad range of frequencies, Fig. 4. For this type of environment, an effective isolation system, at least theoretically, is one with a low fundamental frequency since this allows a filtering of the majority of the energy in the spectrum, Fig. 5. Practically, however, such an isolator is not feasible because low frequency resonances are easily excited by the dynamics of the launch vehicle, leading to large deformations, premature failure, or at least violation of the dynamic envelope of a tightly packed space vehicle. There is also a difficulty in carrying static loads with such a flexible mount. The S-bracket concept attempts to avoid the inherent problems of a low frequency mount by utilizing piezoceramic actuators to limit low frequency, resonant motion. The concern with this configuration, however, is that the piezoceramics will be exposed to significant loads, and may not survive launch or have enough capability to limit large deformations.

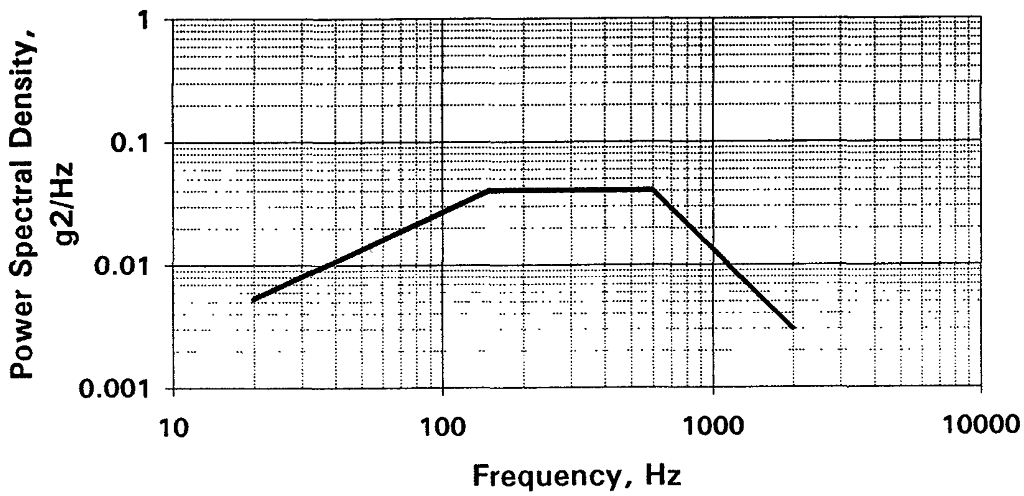

Fig. 4 Typical random vibration environment

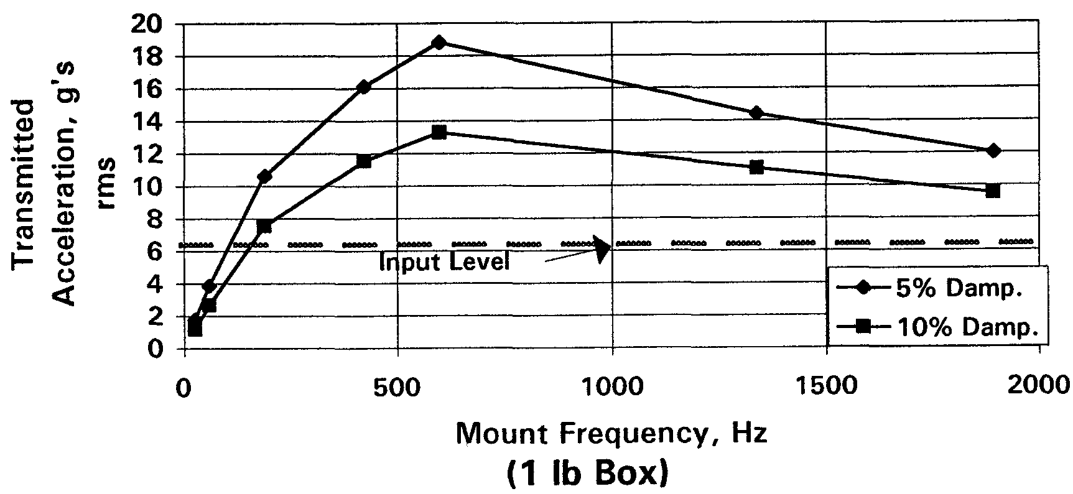

Fig. 5 Transmitted vibrations as a function of mount frequency

To address such concerns, an investigation of the capabilities of the S-bracket design under typical environments for a space system was conducted. The goal of this effort was to bound the potential range of application for the S-brackets. The approach was to conduct first-order analyses of a representative subsystem, consisting of two S-brackets supporting a rigid payload constrained to move within the vertical plane. The overall dimensions of the brackets were selected to match those of the experimental testbed, but a 24 in. wide payload was assumed. Variables included the weight of the payload, the thickness of the brackets, and the thickness of the piezoceramics. For this model, the parameters of interest included the absolute motion of the payload in the vertical direction, the absolute acceleration of the payload in the vertical direction, and the maximum strain in the piezoceramics.

In determining the capability of the brackets, the payload is sized so as to limit responses to static and dynamic accelerations due to ascent, as well as base excitation arising from random and acoustic excitation. Piezoceramics are typically restricted to strains less than 0.001 strain, which for a specified bracket configuration defines the allowable motion of the payload relative to the spacecraft. For example, brackets of the size used in the experimental testbed were limited to a vertical deflection of 0.3 in. To estimate allowable payload masses, a finite element model of the S-bracket pair was subjected to acceleration loads typically used to encompass launch accelerations, Table I, as well as the random vibration environment of Fig. 4. Comparing the sum of the static and peak dynamic responses with the allowable deformation of the brackets, it was determined that brackets of the size used in the experimental testbed would only be able to carry about 2 lb. of payload per bracket. A more realistic bracket design using 80 mil thick brackets, however, could carry about 8 lb. per bracket and still be flexible enough for the piezoceramics to effectively control resonant responses.

Table I. Preliminary structural design criteria

Requirement	Value	Design Factors
Maximum Static Load, Axial	7.1 g	Factors of Safety: 1.25 (yield), 1.4 (ultimate), 1.4 (buckling)
Maximum Static Load, Lateral	2.7 g	Factors of Safety: 1.25 (yield), 1.4 (ultimate), 1.4 (buckling)

Another potential application of the system is control of the angular position of payloads on-orbit. An analysis of brackets with the same dimensions as the experimental brackets indicated that while the brackets could physically survive rotations on the order of a degree, the largest static displacement would be on the order of $\pm$ 0.1° due to the actuation limits of the piezoceramic actuators. Theoretically, this value could be increased by design changes such as lengthening the horizontal sections of the brackets, adding larger piezoceramic actuators, or even using a Z-shaped rather than an S-shaped bracket. Practically, however, such modifications would be limited due to constraints on mounting space and available power. Thus, for position control applications, the bracket design appears to be limited to rotations on the order of a few tenths of a degree.

4. MODELING AND EXPERIMENTAL CORRELATION

Another aspect of interest for the transition of piezoceramic technologies is the ability to accurately predict the behavior and performance of complex systems using standardized design tools and procedures. Modeling provides a visualization tool to understand design drivers, transfer functions and system matrices for initial controller design, a mechanism for optimization, and a tool for demonstration of new designs and testing of potential applications. Validated modeling techniques also allow a reduction in cost through reduction in developmental testing. Various approaches have been adopted for modeling adaptive structures, and many have proven very useful for beam and plate structures. For complex structures, however, their utility can be limited, and numerical methods such as finite elements are used. Although piezoelectric solid elements are currently available in several commercially available packages, their use is not appropriate in system models typically employing the more efficient beam and shell elements. Thus, the simplistic approach of modeling the piezoelectric effect as a thermal distortion was utilized in the current effort. Sections in which piezoceramics are bonded to the structure are modeled using composite shell elements, consisting of either three layers (pzt-aluminum-pzt), if a perfect bond can be assumed, or five layers (pzt-epoxy-aluminum-epoxy-pzt) if bonds are important. Equal and opposite thermal expansion coefficients are defined for the two piezoceramic layers to model the actuation of bending, where the value of the CTE is given by the piezoelectric coefficient d_{31} divided by the thickness of the piezoceramic layer. Temperature changes in the material are then used to simulate voltage actuation. Standard thin shell elements are used for the remainder of the bracket and plate structures. In the current effort, all modeling was completed using the COSMOS/M finite element program in order to explore standardized modeling techniques. A diagram of the model is provided as Fig. 6.

This model was correlated with forced responses of the experimental testbed. The shaker was eccentrically attached to the base of the testbed in order to excite as many modes as possible, and an accelerometer used to measure the response at various locations on the payload platform, Fig. 3. The best frequency response curves were obtained using a burst-chirp excitation, but sine sweeps were also conducted. The experimental data are summarized in Table II. Although not discussed in this paper, preliminary controller design efforts focused on the first six modes of the structure. It can be observed that the first three modes primarily represent deformation of the base plate, with the isolation system following the motion of the base plate. These modes would be the primary targets of the S-brackets in the closed loop system. The next three modes represent a combined response of the base plate and the platform and would require a coordinated effort between the active platform and S-brackets. The modeling correlation effort targeted these modes, but modes seven through ten were also monitored for future effort.

The initial model of the system included several simplifying assumptions. First, a perfect bond was assumed to exist for every piezoceramic element in the structure, and therefore the piezoceramic sections were modeled with the three layer composite shell elements. Second, the brackets were assumed to be fixed over their entire surface to both the upper and lower plates. Finally, the experimental mounting device, consisting of two square beams clamping the edges of the base plate and supported at the four corners by posts clamped to the floor, was modeled explicitly. This model did capture the correct order and shape of the first six modes, but as expected, overpredicted the frequencies of the first six modes by 10-30%, Table II. The model was then simplified by eliminating the four support posts, and replacing the restraining beams with a clamped support along the edge of the base plate. This did not significantly effect the mode shapes or frequencies, demonstrating the experimental implementation of the clamped support was effective. This simpler configuration was used for the remainder of the analyses.

To improve the accuracy of the model, modifications were made to more accurately simulate the joints between the brackets and the plates. On the experimental testbed, the brackets were fastened to the plates using two bolts for each connection. While these bolts do restrain the brackets, they do not provide a perfect bond between the two components. Therefore, a model was created using coincident nodes with a pattern of nodes around the bolt locations constrained to better represent the characteristics of the testbed. This model did provide an improvement in every mode reaffirming the importance of accurate boundary condition definition. Frequencies were still in error by up to 18 %, Table II.

The final alteration that was made involved the epoxy layer between the piezoceramics and the brackets. The bond was included in the model as an additional layer in the composite shell element, and various trades were done on the relative importance of the thickness of the bonding layer and the moduli of the epoxy. The results indicated that there was a counteracting influence of the bonding layer. Although modeling the bonding layer added flexibility to the system, it also increased the moment arm of the piezoceramics. Thus, for modes such as 4 and 6 that had a high modal strain energy in the center of platform where actuator bending is important, the frequencies actually increased. For other modes the frequencies decreased. As a result, the first three modes demonstrated good correlation with the experimental results, differing by 1-3%. The coupled platform/plate modes, 4-6, were not as well correlated differing by as much as 18%. Also of interest is that predictions of the higher modes, primarily involving higher order platform deformations, were more accurate that those for modes 4-6. This indicated that the primary difficulty in modeling the integrated system was capturing the interaction of the base plate with the platform.

The development of this type of model provides significant utility in designing a practical system. The model can be subjected to various base excitations to estimate its open loop behavior for failure analyses. Activating actuators via thermo-structural analyses provides an estimate of their influence, enabling an efficient selection of actuator location and size. The impact of modifications to payload masses and locations can be determined, and optimization of bracket configurations are enabled. For example, simulations have shown that for some applications, a Z-shaped bracket provides better performance than the S-brackets. Augmenting shell elements with electrical degrees of freedom also enables closed loop simulations, and efforts are underway to provide this capability in standardized analysis codes.

Table II. Correlation of models with frequency data.

Mode	Description	Experimental Data	Perfect Bond Model	Bolt Constraints	Bolts and Epoxy Bond
1	Platform rocking, base plate bending w/ peak outside brackets	11.25	12.4	11.6	11.1
2	Platform rocking, base plate bending w/ peak under brackets	12.25	14.0	13.1	12.5
3	Platform rocking about long axis, base plate bending	13.30	16.5	14.4	13.7
4	Platform bending opposite of base plate, brackets extended	24.25	29.3	28.1	28.6
5	Platform 2nd bending, brackets swaying	26.69	33.9	31.5	29.9
6	Platform deformed to saddle, some swaying of brackets	27.88	35.6	32.5	32.7
7		30.06	37.1	33.7	33.9
8		37.00	38.7	35.9	34.4
9		38.10	44.7	37.5	34.8
10		45.87	47.6	44.7	43.5

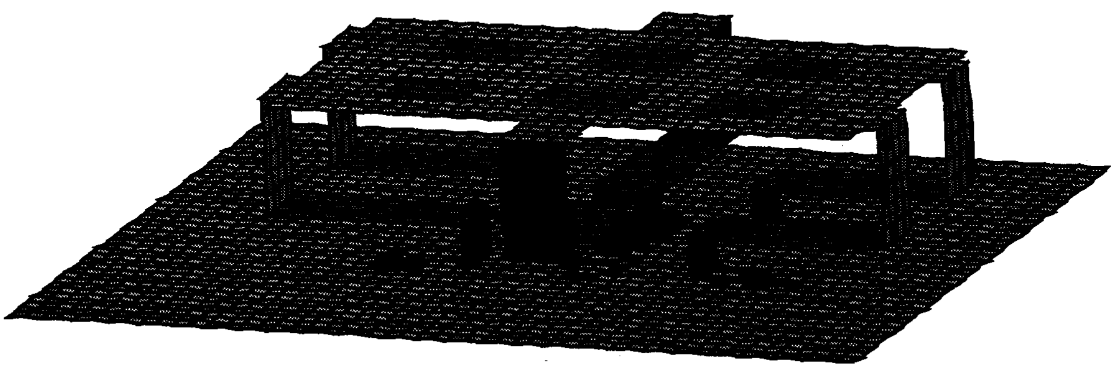

Fig. 6 Finite element model

6. ASSESSMENT OF APPLICATIONS

The coupled isolation/suppression system has been proposed as a low cost, high bandwidth vibration isolation device with additional pointing control capabilities. Current technologies exist, however, to solve most vibration problems due to the launch environment. Passive dampers are simple, proven devices applicable to most frequency ranges, and structural modifications are easily implemented to avoid specific resonances. While the brackets may be able to provide an increase in isolation (this is highly dependent on configuration), they will also introduce additional weight and complexity due to their active components. It is unlikely that such a system would be favored over the simpler technologies for the sole purpose of suppressing vibrations during launch. They could be favored is cases in which the item to be protected is sensitive to a wide range of frequencies, or where significant changes in the vibration environment can occur as the launch progresses. In this case, the adaptability of the active system could offer an advantage over passive systems optimized for a specific range of operation.

Another potential application for the brackets is isolation of vibrations on an operational spacecraft, either the isolation of sensitive instruments, including laser communications and optical sensors, or the isolation of noisy components, such as cryocoolers. For this application, the system is required to satisfy the above requirements during launch, but its critical requirements now become performance requirements during operation. The analysis of capabilities indicated that a system of this type could be developed that can survive a launch, and experimental demonstration of the brackets have indicated an ability to provide significant attenuation from periodic excitations. For spacecraft applications, the isolators also provide some beneficial characteristics. They do not have the contamination and aging concerns of passive damping, and they offer vibration isolation over a much broader frequency range than achievable through conventional mechanical isolation. They could also be made adaptable to respond to varying environments and could be used to simultaneously perform fine position control (on the order of tenths of a degree). As indicated above, S-brackets could be designed to survive launch loads for relatively small payloads (on the order of 50 lb.), although this would likely require having the piezoceramics active during launch to avoid excessive motion. If a stiffer isolator design is used, such as an active strut, it has been estimated that a 1 m^2 adaptive platform could support approximately 180 kg of payload equipment. For this system, it was predicted that the active system required would weigh approximately 15 kg and demand approximately 76 W of power.

7. CONCLUSIONS

In this paper, some aspects of the structural design for a piezoceramic based vibration isolation/suppression system for space applications were investigated. Assuming typical launch requirements, it was determined that an S-bracket based system could feasibly carry a 50 lb. payload while attenuating the transmission of vibrations from the spacecraft into a sensitive payload. A model of an experimental system comprised of six S-brackets supporting three simulated instruments was also discussed. It was found that simple finite element models using standard packages could be used to evaluate actuation capabilities and predict dynamic behavior of the system with reasonable accuracy, with issues such as the bonding layer of the piezoceramic actuators of importance. Potential utility of the S-bracket isolation system was explored indicating that on-orbit vibration isolation/suppression is the most promising application, but that payload capabilities are limited.

The proposed vibration attenuation concept employs an active control system in a flexible mount to provide high frequency vibration isolation with controlled low frequency resonances in a system offering isolation for all six degrees of freedom. From a systems view, the active brackets require support equipment such as power supplies and control hardware that do impose a weight penalty, but the benefits must be traded with this penalty. Although this concept is not viewed as ready for application at present, advances in miniaturization of electronics and power supplies are taking place and will improve the potential. Miniaturization may also increase the number of potential applications as multiple instruments are incorporated on a single payload. A broadband system able to isolate instruments from external disturbances while suppressing vibrations internal to the payload is viewed as a feasible and promising concept.

8. ACKNOWLEDGMENTS

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9. REFERENCES

1. K. Uchino, "Recent Development of Piezoelectric Actuators for Adaptive Structures," *Proc. Third International Conference on Adaptive Structures*, B. K. Wada, M. Natori, E. Breitbach, 245-257, Technomic, San Diego, CA, 1992.
2. J. B. Aldrich, N. W. Hagood, A. von Flotow and D. W. Vos, "Design of passive piezoelectric damping for space structures," *Proc. SPIE Smart Structures and Materials 1993: Smart Structures and Intelligent Systems*, N. W. Hagood, G. J. Knowles, Vol. 1917-2, 692-707, SPIE, Albuquerque, NM, 1993.
3. Z. H. Rahman et. al., "Optical Pathlength Control Experiment on JPL Phase B Testbed," *Proc. 34th Structures, Structural Dynamics and Materials Conference*, Part 6, 3319-3327, AIAA, La Jolla, CA, 1993.
4. M. Rossi, F. Austin and W. VanNostrand, "Active Rib Experiment for Shape Control of an Adaptive Wing," *Proc. 34th Structures, Structural Dynamics and Materials Conference*, Vol. 6, 3485-3489, AIAA, La Jolla, CA, 1993.
5. T. Fujita et. al., "Active 6-DOF Microvibration Control System Using Piezoelectric Actuators ," *Proc. Third International Conference on Adaptive Structures*, B. K. Wada, M. Natori, E. Breitbach, 514-528, Technomic, San Diego, CA, 1992.
6. S. R. Schubert, "ACTEX flight experiment: development issues and lessons learned," *Proc. SPIE Smart Structures and Materials 1993: Smart Structures and Intelligent Systems*, N. W. Hagood, G. J. Knowles, Vol. 1917-1, 510-520, SPIE, Albuquerque, NM, 1993.
7. R. J. Glaser, C.-P. Kuo, J. A. Garba, "Application of smart structure concepts to vibration suppression of a cryocooler coldfinger," *Proc. SPIE Smart Structures and Materials 1993: Smart Structures and Intelligent Systems*, N. W. Hagood, G. J. Knowles, Vol. 1917-1, 555-563, SPIE, Albuquerque, NM, 1993.
8. E. T. Falangas, "A Vibration Isolation System Using Active PZT Brackets," *Proc. of the 1994 American Control Conference*, Baltimore, MD, 1994.
9. E. T. Falangas, J. A. Dworak, and S. Koshigoe, "Methods for Controlling Plate Vibrations using PZT Actuators," *Proc. of the AIAA Guidance, Navigation, and Control Conference*, Monterey, CA, 1993.