DESIGN AND ANALYSIS OF AN ADAPTIVE COMPOSITE PANEL WITH EMBEDDED SENSORS/ACTUATORS FOR ACTIVE VIBRATION SUPPRESSION AND PRECISION POSITIONING

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ABSTRACT

An adaptive composite panel is designed to perform active vibration suppression and precision positioning. Piezoelectric sensors and actuators embedded in the composite panel create a lightweight structure with increased structural efficiency and thermal stability, in addition to the ability to monitor and respond to external stimuli to control shape, properties, and dynamic responses of the structure. The panels are designed to be the mounting surface for an active composite platform on which a thruster is mounted. The thruster and active composite platform is intended for satellite applications. Computer models are generated to predict precision positioning as well as to determine which configuration of the piezoelectric actuators delivers optimum vibration suppression. The optimum configuration of the actuators is determined and different voltage schemes are analyzed.

INTRODUCTION

This present work is part of a larger effort to design, manufacture and test an active composite platform. The platform can be seen in Figure 1(Ghasemi Nejhad and Doherty, 2002a, 2002b). The active composite panel is controlled by three active composite struts, which also feature precision positioning and vibration suppression. The struts are attached 2 cm from the perimeter of the plate and along with the center ball joint, allow the panel to pivot freely. Since the active composite platform is intended for space applications the structure must be lightweight yet have a high strength to handle the loading during firings of the thruster. For this reason nearly the entire structure is made of carbon fiber composite. This includes the active composite panel. The panel has a diameter of 42 cm. Embedded within the panel are six piezoelectric patches. Three of the piezoelectric patches are embedded in the upper half of the panel and the remaining patches are embedded directly below their counterparts in the bottom half of the panel. The piezoelectric patches are able to provide both sensing and actuating by their unique mechanical and electrical properties. A piezoelectric patch produces a voltage when under compression or tension in the longitudinal direction or vice-versa. The configuration of the piezoelectric patches is limited by their size and the size of the active composite panel, as well as the position of the strut and ball joint attachments. Based on these considerations and the fact that a symmetric configuration simplifies the analysis, four different configurations are chosen. The four configurations are: Star, Triangle 1, Triangle 2 and Triangle 3. The schematic of the Star and Triangle 1 configuration can be seen in Figures 2 and 3,

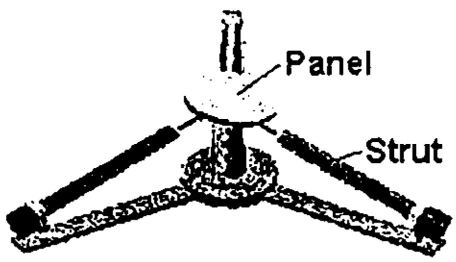

Figure 1: Active Composite Platform (Ghasemi Nejhad and Doherty, 2002a, 2002b)

respectively.

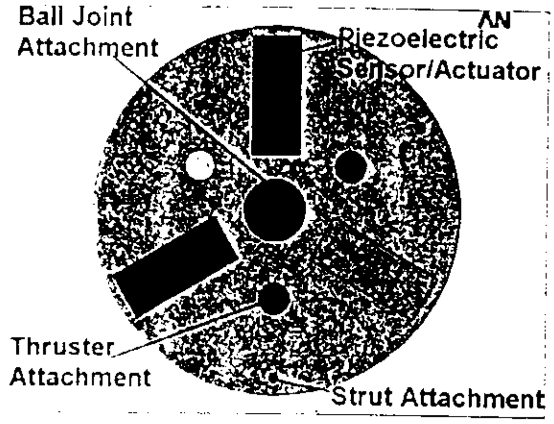

Figure 2: Star Configuration

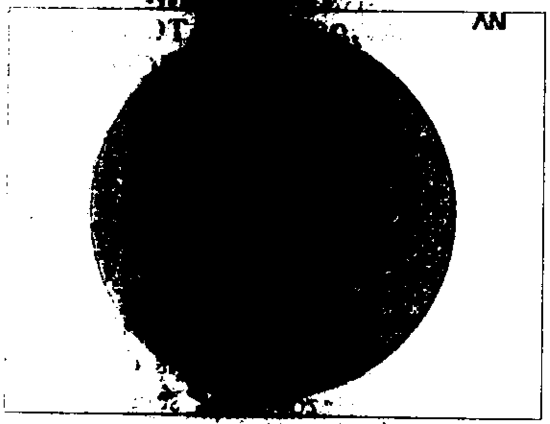

Figure 3: Triangle 1 Configuration

The Triangle 1 configuration places the piezoelectric patches directly in line with strut attachments. The Triangle 2 configuration shifts the piezoelectric patches outwards so that the corner of the patches is 1 cm away from the edge of the panel. This represents the limiting case where the piezoelectric patches are as close to the perimeter of the plate as possible. The Triangle 3 configuration places the piezoelectric patches midway between the Triangle 1 and 2 positions. In order to characterize the vibrational modes and frequencies of the structure, the Finite Element Analysis (FEA) software, ANSYS is employed. FEA is also used to optimize the location and configuration of the piezoelectric actuators to achieve maximum structural damping performance.

METHODS

To begin the analysis the solid modeling of the panels is performed. To reduce computational time, half of the panel is modeled using symmetry. The boundary conditions are applied such that the center ball joint and strut attachments have zero degrees of freedom. Modal analysis is run for each configuration and the first eight vibrational modes and frequencies are determined. The mode shapes are characterized as either bending or torsion modes. Figure 4 shows the first bending mode for the Star and Triangle 1 configuration. The natural frequency for the Star Configuration is 73.0 Hz and the Triangle 1 Configuration is 78.6 Hz. The first bending modes for the remaining configurations are similar to the Star and Triangle 1 configuration. The natural frequencies for the Triangle 2 and 3 configurations are 69.89 Hz and 75.14 Hz, respectively. Once the natural frequencies for the first bending mode are found, harmonic analysis can be performed with the simulated loading of the thruster. The loading is applied to the thruster attachments as shown in Figure 6. Two of the thruster attachments experience an upwards loading while the remaining attachment

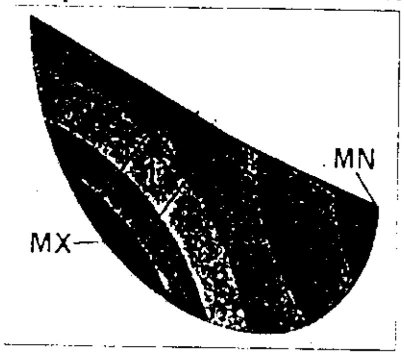

Figure 4: 1st Bending Mode Star, 73.0 Hz

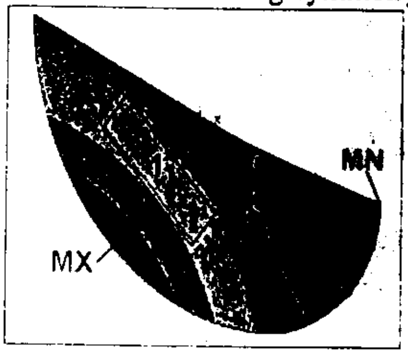

Figure 5: 1st Bending Mode Triangle 1, 78.6 Hz

experiences a downward loading. This loading vibrates the structure about its center. To begin the harmonic analysis, the two points where the maximum and minimum displacement occurs are determined from the modal analysis. A frequency interval of 14 Hz with 8 sub steps is chosen about the first bending natural frequency for each configuration. The harmonic analysis is performed with load only and the displacement of the maximum and minimum points is observed for each of the eight frequency sub steps. The load-only displacement of the minimum and maximum points will be denoted as D_{MN} and D_{MX}, respectively. Next, an arbitrary value of voltage is applied to one of the actuators and the harmonic analysis is run without loading and the displacements are again noted. This step is repeated for the remaining actuator. Since the relationship between displacement and voltage is nearly linear, ratios for voltage to displacement can be calculated. Each configuration has four ratios, that is, for each actuator there are two ratios, one for the maximum point and the other for the minimum point. The ratios are denoted as $r_{1,MN}$, $r_{1,MX}$, $r_{2,MN}$ and $r_{2,MX}$. The ratios are calculated by simply dividing displacement of the point by the input voltage. Then dividing the load-only displacement of the corresponding point by each ratio gives the voltage required for suppression of that particular point. The voltage required for suppression will be denoted as V_1 and V_2 (Ghasemi Nejhad and Russ, 2002a, 2002b, 2002c; Russ and Ghasemi Nejhad, 2002). For each frequency sub step there are four voltage values, two for each of the actuators. These voltage values are the voltage for one piezo only that will deliver complete vibration suppression for one point on the structure at a particular frequency. These voltages can be applied in a number of different voltage schemes to provide vibration suppression to the structure (Ghasemi Nejhad and Russ, 2002a, 2002b, 2002c: Russ and Ghasemi Nejhad, 2002). The first is the Constant Voltage Scheme (Ghasemi Nejhad and Russ, 2002a). The Constant Voltage scheme uses a constant voltage to one or both of the actuators across the frequency interval. The voltage to each of the actuators does not necessarily have to be the same value. The determination of the appropriate value is difficult since the variation of voltages across the frequency range is large and there is no one value that is representative of all the voltages. The second voltage scheme is the Direct Corresponding Voltage Scheme (Ghasemi Nejhad and Russ, 2002b). The Direct Corresponding Voltage Scheme uses one actuator to suppress one point across the frequency range. The Direct Corresponding Voltage Scheme does not use a constant voltage but uses the calculated voltage at each frequency. This method can only suppress either the maximum or minimum point on the structure using one of the actuators. The final voltage scheme is the Direct Corresponding Combination Voltage Scheme. The Combination Scheme uses all the actuators in tandem to suppress both the max and min points. Similar to the Direct Corresponding Voltage Scheme, the Combination Scheme uses the calculated values of voltage for each frequency. The voltages are calculated by solving the following set of linear equations simultaneously at each frequency:

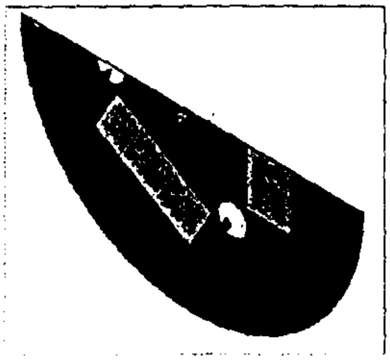

Figure 6: Loading

$$V_1 r_{1,MN} + V_2 r_{2,MN} = -D_{MN} \quad (1)$$

$$V_1 r_{1,MX} + V_2 r_{2,MX} = -D_{MX} \quad (2)$$

In equations (1) and (2), the right-hand-side is negative to provide out-of-phase displacements due to V_1 and V_2. Applying the calculated voltages, V_1 and V_2, at each frequency delivers vibration suppression for both the maximum and minimum points.

RESULTS

The Constant Voltage Scheme delivers varying [illegible] ing on the variation in the magnitude and phase of the voltages across the fr[illegible]. The Star and Triangle 1 Configuration are the only configurations, which h[illegible] that are compatible with the Constant Voltage Scheme. The Triangle 1 co[illegible] vibration suppression of 84.3% for the maximum point and 84.4% for the mi[illegible] with 630V applied to actuator 1. These values are calculated at the natural frequen[illegible] are where the displacements are the greatest. The suppressed displacement at [illegible] quency is 0.9 mm for the maximum point and -1.4 mm for the minimum poi[illegible] configuration yields vibration suppression of 46.9% at the maximum point and [illegible] minimum point with 1648V applied to actuator 1 and 291V applied to actuator 2. T[illegible] displacement at the natural frequency is -1.4 mm for the minimum point and 1.1 [illegible] maximum point. The Direct Corresponding Voltage Scheme uses either actuator [illegible] control either the maximum or minimum point. The Direct Corresponding Voltage S[illegible] applied to all four configurations and the minimum point is suppressed. The minimum [illegible] suppressed by 97.3% or greater across the frequency range for all configurations. The [illegible] the maximum point is dependent on how well the magnitude and phase of the voltage [illegible] actuator matches with the voltage required to suppress the minimum point. Of all the configurations only the Triangle 1 configuration delivers significant suppression across the frequency range for the maximum point. A modified approach to the Direct Corresponding Voltage Scheme incorporates linear interpolation to calculate an improved value of the voltage required for suppression of the minimum point. This approach can reduce the displacement to a negligible value. Finally, the Direct Corresponding Combination Voltage Scheme is applied to each configuration. The combination approach delivers suppression of the minimum point similar to the Direct Corresponding Voltage Scheme. The suppression is 94.1% for the minimum point and 96.4% or greater for the maximum point. The values for the voltages using the Combination approach are listed in the following table:

Triangle 1 Actuator Voltages

Frequency	Actuator1	Actuator2
71	629.01	36.49
73	655.49	29.88
75	683.85	22.50
77	712.40	14.28
79	779.58	3.45
81	796.83	-6.33
83	837.34	-18.45
85	882.98	-32.32

Triangle 2 Actuator Voltages

Frequency	Actuator1	Actuator2
61	-5250.15	-1398.94
63	-3982.50	-1042.80
65	-3179.58	-822.69
67	-2653.62	-672.23
69	-2271.86	-560.93
71	-2005.24	-482.05
73	-1781.83	-414.46
75	-1605.93	-360.22

Triangle 3 Actuator Voltages

Frequency	Actuator1	Actuator2
66	2113.40	-652.58
68	2851.07	-1303.35
70	5085.91	-3541.78
72	-28132.37	32610.74
74	-1754.58	4361.78
76	-64.75	2900.75
78	775.86	2498.60
80	1489.82	2459.59

Star Actuator Voltages

Frequency	Actuator1	Actuator2
62	1596.47	124.17
64	1746.02	197.37
66	1930.58	272.44
68	2162.29	353.17
70	2459.60	444.20
72	2846.70	548.47
74	3431.75	712.74
76	4236.55	905.01

Table 1: Combination Scheme Actuator Voltages

The comparison of the vibration suppression for the Direct Corresponding Voltage (COV) and Direct Corresponding Combination Voltage Schemes for the Triangle 2 configuration can be seen in Figures 7 and 8. It should be mentioned that the vibration suppression for the Triangle 1 configuration is similar to Figures 7 and 8.

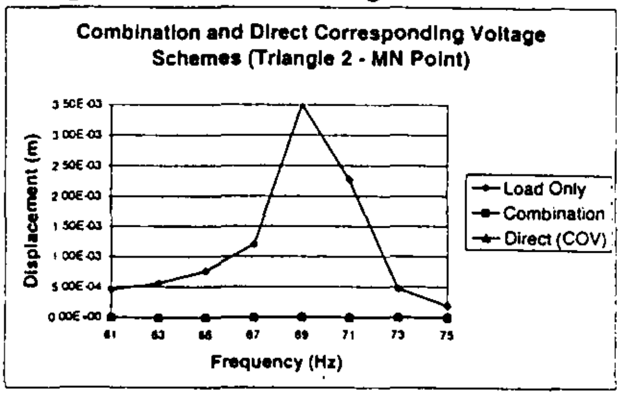

Figure 7: Comparison of Vibration Suppression for Triangle 2 - MN Point

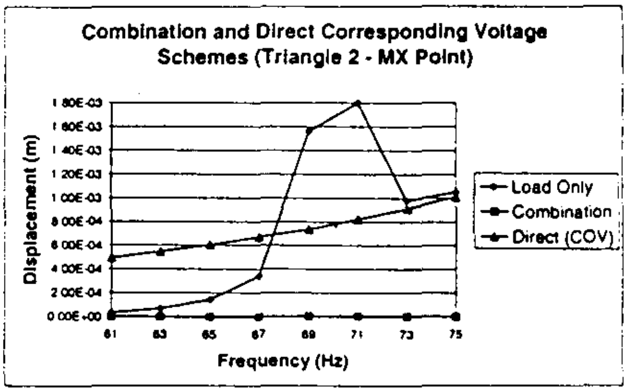

Figure 8: Comparison of Vibration Suppression for Triangle 2 - MX Point

DISCUSSION

The limited variation in the magnitude and phase of the voltage required for the Constant Voltage Scheme is only suitable for the Triangle 1 and Star configurations. The Triangle 1 configuration is an interesting case since only one actuator can suppress both the minimum and maximum points by at least 84.3%. The use of one actuator would reduce power consumption and lessen the complexity of the control system. The Direct Corresponding Voltage Scheme can suppress either the maximum or minimum point across the frequency range. The degree of suppression for the point of interest is much greater than for the Constant Voltage Scheme since the voltages are calculated at each frequency. However, near the natural frequency there is a departure from the linearity between displacement and voltage. This effect can be remedied by applying linear interpolation to get a new value. An improvement over the Direct Corresponding Voltage (COV) Scheme is the Direct Corresponding Combination Scheme. The Combination Scheme can suppress both points since both actuators are used in tandem. The suppression of the maximum point is at least 96.4% whereas for the Direct (COV) Scheme the suppression varies with frequency and even increases the magnitude of displacement at certain frequencies. The determination of the optimum configuration is based on the magnitude of the voltages for the Combination Scheme and the suppressed displacement for the maximum and minimum points. A comparison of the suppressed displacements reveals that the Triangle 1 configuration has the greatest suppressed displacement for the maximum and minimum points at the natural frequency. The suppressed displacement for the Triangle 1 configuration is approximately 5% greater than for the other configurations. However, the average magnitude of the voltage for the Triangle 1 configuration using the Combination Scheme is significantly less than the other configurations. The Triangle 1 configuration requires 78% less voltage than the Star configuration, which has the second lowest voltage requirement. The low voltage required for the Triangle 1 configuration greatly outweighs the higher displacement. Therefore, the Triangle 1 configuration is the optimum configuration.

CONCLUSION[illegible]

Of the various voltage schemes, the Direct Co[illegible]ination Voltage Scheme provides the best overall suppression of the structure. T[illegible]configuration requires the least amount of voltage for the Combination Scheme. T[illegible]Triangle 1 configuration is the optimum configuration. A unique consequence [illegible] 1 configuration is the consistent phase and magnitude for the voltages requ[illegible]ment using the Constant Voltage Scheme. This allows the Triangle 1 confi[illegible]ide vibration suppression across the frequency range for both points using the Con[illegible] Scheme.

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