UNIVERSITY OF HAWAII

FINITE ELEMENT ANALYSIS DESIGN AND OPTIMIZATION OF AN ADAPTIVE CIRCULAR COMPOSITE PANEL FOR VIBRATION SUPPRESSION

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ACNOWLEDGMENT

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ABSTRACT

The objective of this work is to design a circular adaptive composite panel with optimized embedded piezoelectric sensor and actuator patches in terms of their location and configuration for active vibration suppression application. Piezoelectric sensors and actuators embedded in the composite panel create a lightweight smart 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 panel is designed to be the mounting surface for an active composite platform to be used in intelligent thruster vector control applications for satellites. A triangular piece, made of steel, with three circular-shape connections at the three vertices, simulating the base of the thruster, is attached to the circular adaptive composite panel to provide a more realistic boundary condition. The developed finite element model is employed to determine the optimum number of composite layers based on the voltage required to deliver maximum possible vibration suppression for the plate. A direct approach using Control Design Charts is employed for active vibration suppression. The vibration suppression techniques used in this work are the direct Constant Voltage (CV) and direct Corresponding Voltage (COV) schemes.
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CHAPTER 1
INTRODUCTION

The ADPICAS (Active Damping and Positioning using Intelligent Composite Active Structures) project is funded by the Office of Naval Research (ONR) and in collaboration with the Naval Research Laboratory (NRL). The objective of this project is to design a modified Stewart platform for Thrust Vector Control (TVC) to effectively replace the current Reaction Control System (RCS) thrusters. The platform is placed between the satellite body and main thruster and actively isolates the satellite from thruster induced vibrations. The platform also provides precision thruster positioning capabilities for satellite steering and trajectory modification. This work is part of a larger effort to design, analyze, manufacture, and test an active composite platform (see Figure 1.1) with simultaneous vibration suppression and precision positioning capabilities to be used in Thrust Vector Control (TVC) of satellites and spacecrafts (Ghasemi-Nejhad and Doherty, 2002; Doherty and Ghasemi-Nejhad, 2005).

![Active Composite Platform](image)

**Figure 1.1:** *Intelligent Composite Platform.*

The platform shown in Figure 1.1 has three Active Composite Struts (ACSs) that provide
simultaneous precision positioning and vibration suppression (Ma and Ghasemi-Nejhad, 2006a, 2006b, 2005a, 2005b, 2004) for the platform. The ACSs are joined to the top device plate circular Active Composite Panel (ACP) 2 cm from the perimeter of the plate, to allow the panel to pivot freely about its central support. Therefore, the top device plate can pivot about its central support to give two in-plane rotational degrees of freedom (Ma and Ghasemi-Nejhad, 2004). 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 the thruster firings. For this reason, nearly the entire structure is made of carbon/epoxy composite. This includes the active composite panel. Here, there are eight configurations created to simulate the different designs of the circular ACP ANSYS (2004) Finite Element Model (FEM). All eight configurations contain six embedded Active Fiber Composite (AFC) CCC (2002) piezoelectric patches and the diameter varies from 32.5cm to 63.3cm. For the ACP model, 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 in a back-to-back configuration. Initial analysis used three piezoelectric patches on the upper half of the panel as actuators and the three piezoelectric patches on the bottom half of the panel as sensors. To fully utilize the piezoelectric patches, another analysis used all six piezoelectric patches as actuators to suppress vibrations. Ghasemi-Nejhad et al. (2005) introduced three techniques to embed piezoelectric patches into composites. The piezoelectric patches are able to provide both sensing and actuation by their unique mechanical and electrical properties. A piezoelectric patch produces a voltage (a charge) when under tension/compression in a direct effect as a sensor, or vice-versa extends/contracts when a
voltage is applied in a converse effect as an actuator (Doherty and Ghasemi-Nejhad, 2005).

Basically, the thruster induced satellite vibration can be suppressed (i.e., vibration suppression) with minimum transmissibility from thruster to satellite using the piezoelectric stack, within the ACSs of the platform, while the top plate with embedded sensors and actuators can be used for precision stabilization of the thruster. It should be noted that the ACSs are also equipped with precision motors to perform precision positioning of the main thruster.

Here, the primary objectives of this work are to determine if the piezoelectric patches embedded in the top adaptive circular composite plate are capable of performing both thruster precision stabilization (by suppressing the vibration of the thruster) and satellite vibration suppression (by preventing the vibration to transmit from the thruster to the satellite), and finally to determine the level of vibration suppression, control voltage, and effectiveness of the actuator patches of the top plate for each case of precision stabilization and vibration suppression.
CHAPTER 2
HALF PANEL METHODS

The half panel model utilized the Triangle 1 configuration of the piezoelectric patches, which was shown to have the best performance in previous analyses (Ghasemi-Nejhad and Soon, 2003). The half panel model also made use of a symmetry to reduce computational time and was rigidly constrained at three locations, the central support and two ball joint locations for the top strut connections (see Figure 2.1). With the use of ANSYS Finite Element Analysis (FEA) software, the vibration modes and frequencies of the structure were characterized. The results from this new analysis were compared with the previous results (Ghasemi-Nejhad and Soon, 2003) to verify the model before continuing to the full panel model.

Figure 2.1: Half panel model showing the location of the central support and ball joints.

Modal analysis is run to determine the first eight vibration modes. 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 2.2. The combined lateral (normal to plate) dynamic
loading on the half panel model is assumed to be five pounds of force (the symmetric boundary conditions make the total loading on the full panel ten pounds). The axial static thrust force is assumed to be 100 lbs here. The axial dynamic component of it is about 1% which gives a 1 lb axial dynamic force. The lateral (normal to plate) dynamic force is about 10% of the axial dynamic force which gives a 0.1 lb lateral (normal to plate) dynamic force. Here, we start with 10 lbs of lateral (normal to plate) dynamic force for higher load applications and later will consider both 1 lb and 0.1 lbs of lateral (normal to plate) dynamic force.

![Half panel model showing the direction of loading applied to the thruster attachments.](image)

**Figure 2.2:** Half panel model showing the direction of loading applied to the thruster attachments.

Due to symmetry, two of the thruster attachments experience a downward loading while the remaining attachment experiences an upward loading. This dynamic lateral (normal to plate) loading vibrates the structure about its center. To begin the harmonic analysis, the two points where the maximum and minimum displacements occur are determined from the modal analysis. A frequency interval of 10 Hz with five sub-steps is chosen about the first bending natural frequency (which is 87Hz). Then harmonic analysis is performed with load only and the displacements of the maximum and minimum points are observed for each of the five frequency sub-steps. The load-only displacement
of the minimum and maximum points are 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 actuators. Since the relationship between displacement and voltage is assumed to be linear, ratios for voltage to displacement can be calculated. The 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 $V_2$ (Russ and Ghasemi-Nejad, 2002; Doherty and Ghasemi-Nejad, 2005; Ghasemi-Nejad et al., 2006). These voltage values are the voltage for one piezoelectric patch 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; namely, Constant Voltage (CV), Optimum Voltage (OV), Corresponding Voltage (COV), and Truncated Corresponding Voltage (TCOV) (Russ and Ghasemi-Nejad, 2002; Doherty and Ghasemi-Nejad, 2005; Ghasemi-Nejad et al., 2006). The Constant Voltage (CV) scheme uses a constant peak voltage applied to each actuator across the frequency range of interest. The Optimum Voltage (OV) scheme uses the CV scheme for three zones of before, around, and after natural frequency within the range of interest. The Corresponding Voltage (COV) scheme applies a constant
voltage to each actuator at each frequency. The Truncated Corresponding Voltage (TCOV) scheme uses COV and OV outside and inside the natural frequency zones (defined in the OV scheme), respectively. The scheme selected for this analysis was the Constant Voltage (CV) scheme. The Constant Voltage (CV) scheme was used because it is the quickest to calculate for and we are only interested in the general values and trends to obtain the results quickly and compare them efficiently. In the case of the CV scheme, the voltages are calculated by solving the following set of linear equations simultaneously at each frequency:

\[ V_1 r_{1, MN} + V_2 r_{2, MN} = -D_{MN} \quad (2.1) \]
\[ V_1 r_{1, MX} + V_2 r_{2, MX} = -D_{MX} \quad (2.2) \]

In Equations (2.1) and (2.2), the right-hand-side is negative to provide 180° out-of-phase displacements for \( V_1 \) and \( V_2 \) compared to the external disturbance (Russ and Ghasemi-Nejhad, 2002; Doherty and Ghasemi-Nejhad, 2005; Ghasemi-Nejhad et al., 2006). Applying the calculated voltages, \( V_1 \) and \( V_2 \), at each frequency delivers vibration suppression for both the maximum and minimum points. The purpose of this analysis is to verify the accuracy of the model and replicate the earlier work performed on the circular top panel in the Intelligent and Composite Materials Laboratory, ICML, (Ghasemi-Nejahd and Soon, 2003).

The next step utilizes the upper and bottom layer of piezoelectric patches in tandem to reduce the overall control voltage required for vibration suppression. This is achieved by applying the voltage in a plus/minus fashion which means the upper layer is applied a
positive voltage and expands while the lower layer is applied a negative voltage and contracts or vice versa.

2.1: HALF PANEL RESULTS

Previous works have been conducted in this area by former ICML students, Cory Soon and Karl Santa (Santa, 2003). The current work is compared to the control voltage obtained using the Constant Voltage scheme from Karl Santa's analysis and is shown in Table 2.1. The values of $V_1$ and $V_2$ are the calculated control voltages from Equations (2.1) and (2.2) required to obtain vibration suppression at the frequency of interest.

Table 2.1: Comparison of the control voltage (volts) obtained from the Constant Voltage scheme for the new and previous (Santa's) half panel model using the upper layer of piezoelectric patches for vibration suppression.

<table>
<thead>
<tr>
<th>New Results</th>
<th>Santa's Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>voltage</td>
</tr>
<tr>
<td>$V_1$</td>
<td>781.17</td>
</tr>
<tr>
<td>$V_2$</td>
<td>-134.36</td>
</tr>
</tbody>
</table>

The new results differ by five to ten percent from the old results. The differences in the results are due to the fact that the new analysis is conducted on a newer version of ANSYS, since the models are the same.

The results from the analysis utilizing the upper and bottom layer of piezoelectric patches in tandem are shown in Table 2.2 and compared with the results utilizing only the upper layer of piezoelectric patches (upper). The values of $V_1$ and $V_2$ are the calculated
control voltages from Equations (2.1) and (2.2) required to obtain vibration suppression at the frequency of interest.

*Table 2.2: Comparison of the control voltage (volts) obtained from the Constant Voltage scheme for the half panel model when utilizing the upper layer of piezoelectric patches and the upper and bottom layer of piezoelectric patches in tandem for vibration suppression.*

<table>
<thead>
<tr>
<th>Upper Results</th>
<th>Tandem Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>voltage</td>
<td>voltage</td>
</tr>
<tr>
<td>$V_1$</td>
<td>$V_1$</td>
</tr>
<tr>
<td>781.17</td>
<td>388.73</td>
</tr>
<tr>
<td>$V_2$</td>
<td>$V_2$</td>
</tr>
<tr>
<td>-134.36</td>
<td>-70.76</td>
</tr>
</tbody>
</table>

The tandem results are approximately fifty percent of the results from using only the piezoelectric patches in the upper half as actuators, as one would expect.
CHAPTER 3
FULL PANEL METHODS

The full panel model contains six piezoelectric patches and utilized the same Triangle 1 configuration of the piezoelectric patches as employed in the half panel model. The full panel model was used to determine if the half panel model could be used for further analyses or if it would be necessary to utilize a full panel model for future analyses. The full panel model removed the symmetric boundary condition constraint used in the half panel model and thus increased the computational time. The full panel was rigidly constrained at four locations, i.e., the central support and three ACS ball joint locations (see Figure 3.1). With the use of ANSYS Finite Element Analysis (FEA) software, the vibration modes and frequencies of the structure were characterized. The results from the full panel six-patch modal analysis were compared with the results from the half panel modal analysis to verify the model before continuing to harmonic analysis.

![Figure 3.1: Full panel model showing the location of the central support and ball joints.](image)

Modal analysis is run to determine the first eight vibration modes. Once the natural frequencies for the bending modes 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 3.2. The combined loading on the full panel model is ten pounds of force, as explained earlier, and applied in the same way as the half panel model when considering the symmetric boundary conditions.

![Figure 3.2. Full panel model showing the direction of loading applied to the thruster attachments.](image)

Two of the thruster attachments experience a downward loading while the remaining attachment experiences an upward loading. This dynamic loading laterally vibrates the structure about its center. To begin harmonic analysis, the two points where the maximum and minimum displacements occur are determined from the modal analysis. A frequency interval of 10 Hz with five sub steps is chosen about the same natural frequency as the half panel (which is 87 Hz). The same process used in the half panel methods is followed with the only exception being the application of an arbitrary value of voltage to two of the actuators, based on the symmetric loading conditions used. The solution is determined with Equations (2.1) and (2.2) and the results from this analysis were compared to the results from the half panel model. The voltage was first applied to the piezoelectric patches in the upper layer and then the upper and bottom layer were used in tandem for comparison to the half panel.
3.1: FULL PANEL RESULTS

The results for the comparison of the first eight natural frequencies obtained from the modal analysis for the half panel and full panel models are given in Table 3.1 for 6 and 24 total woven composite layers. It should be noted that the piezoelectric patches are always placed one layer underneath the top and bottom surface layers.

<table>
<thead>
<tr>
<th>6 Total Layers</th>
<th>24 Total Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Full Panel</strong></td>
<td><strong>Half Panel</strong></td>
</tr>
<tr>
<td>85.07</td>
<td>-</td>
</tr>
<tr>
<td>87.73</td>
<td>86.91</td>
</tr>
<tr>
<td>92.28</td>
<td>91.54</td>
</tr>
<tr>
<td>203.82</td>
<td>-</td>
</tr>
<tr>
<td>207.49</td>
<td>-</td>
</tr>
<tr>
<td>210.04</td>
<td>208.78</td>
</tr>
<tr>
<td>235.85</td>
<td>238.57</td>
</tr>
<tr>
<td>279.62</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td><strong>Full Panel</strong></td>
</tr>
<tr>
<td></td>
<td>248.29</td>
</tr>
<tr>
<td></td>
<td>263.38</td>
</tr>
<tr>
<td></td>
<td>321.74</td>
</tr>
<tr>
<td></td>
<td>590.32</td>
</tr>
<tr>
<td></td>
<td>690.38</td>
</tr>
<tr>
<td></td>
<td>698.92</td>
</tr>
<tr>
<td></td>
<td>906.98</td>
</tr>
<tr>
<td></td>
<td>998.66</td>
</tr>
<tr>
<td></td>
<td><strong>Half Panel</strong></td>
</tr>
<tr>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>263.00</td>
</tr>
<tr>
<td></td>
<td>319.77</td>
</tr>
<tr>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>695.50</td>
</tr>
<tr>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

This comparison reveals that the half panel model does not see some of the vibration modes. The reason that the half panel model misses these vibration modes is due to the fact that the missing vibration modes are non-symmetric. Figures 3.3 and 3.4 show a non-symmetric and a symmetric vibration mode, respectively.
Figure 3.3: The first vibration mode (non-symmetric), at 85.07Hz, of the full panel model with six total layers of composite.
Figure 3.4: The second vibration mode (symmetric), at 87.73Hz, of the full panel model with six total layers of composite.

Since the first mode of the full panel model was non-symmetric (see Figure 3.3), the second vibration mode (see Figure 3.4) was used for the comparisons of the Constant Voltage scheme results from the half panel analysis. The results obtained from the full panel six-patch model are shown in Table 3.2. The values of $V_1$ and $V_2$ are the calculated control voltages from Equations (2.1) and (2.2) required to obtain vibration suppression at the frequency of interest.
Table 3.2: Comparison of the control voltage (volts) obtained from the Constant Voltage scheme for the half and full panel model using only the upper layer piezoelectric patches as actuators for vibration suppression.

<table>
<thead>
<tr>
<th>Half Panel Results</th>
<th>Full Panel Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>voltage</td>
<td>voltage</td>
</tr>
<tr>
<td>$V_1$</td>
<td>$V_1$</td>
</tr>
<tr>
<td>781.17</td>
<td>739.92</td>
</tr>
<tr>
<td>$V_2$</td>
<td>$V_2$</td>
</tr>
<tr>
<td>-134.36</td>
<td>-180.38</td>
</tr>
</tbody>
</table>

The results from the half and full panel six-patch model are reasonably close to each other when using the upper layer piezoelectric patches. The results are also similar when using the upper and bottom layers of piezoelectric patches in tandem (see Table 3.3). The variations in the results can be attributed to the selection of points not being in exactly the same location for the full and half panel models. Another contribution in the error is the different mesh generated from switching to a full panel model from a half panel model. The values of $V_1$ and $V_2$ are the calculated control voltages from Equations (2.1) and (2.2) required to obtain vibration suppression at the frequency of interest.

Table 3.3: Comparison of the control voltage (volts) obtained from the Constant Voltage scheme for the half and full panel model using both the upper and bottom layers of piezoelectric patches in tandem for vibration suppression.

<table>
<thead>
<tr>
<th>Half Panel Results</th>
<th>Full Panel Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>voltage</td>
<td>voltage</td>
</tr>
<tr>
<td>$V_1$</td>
<td>$V_1$</td>
</tr>
<tr>
<td>388.73</td>
<td>370.35</td>
</tr>
<tr>
<td>$V_2$</td>
<td>$V_2$</td>
</tr>
<tr>
<td>-70.76</td>
<td>-92.57</td>
</tr>
</tbody>
</table>
CHAPTER 4
FULL PANEL WITH EIGHT CONFIGURATIONS

The full panel model was modified to include central support and ACS joints modeled as aluminum brackets and underwent a change in the boundary conditions (BCs) that would better represent the conditions that exist in practice. Figure 4.1 shows the model with the addition of the aluminum brackets to represent the central support and ACS ball joints.

Therefore, the other changes to the model involved the rigid boundary conditions on the central support and ACS ball joints. The rigid boundary conditions was replaced with a simple support BC by selecting a single node on the bottom of the central support bracket instead of selecting the entire area and applying a constraint. The rigid boundary conditions on the ACS ball joints was replaced with a roller boundary condition by selecting a single node on the bottom of the ACS ball joint bracket and constraining the movement in the Z-direction, the same direction that pressure is being applied.
The changes in the design and constraints of the model required the ACP to be retested to see if the current Triangle 1 configuration was still the optimum configuration (Ghasemi-Nejhad and Soon, 2003). The eight different configurations consisted of three star configurations and five triangle configurations. The diameter of the ACP was increased to 63.6 cm due to the second star configuration, i.e., Star 2, which required the piezoelectric patches to be in-line with the thruster attachments and the ACS ball joint. The first configuration, i.e., Star 1 shown in Figure 4.2, has the embedded piezoelectric patches arrayed in a similar design as the Star 2 configuration, but rotated to be off-line with the thruster attachments and ACS ball joints. The second configuration is Star 2, shown in Figure 4.3, which has the piezoelectric patches rotated to be in-line with the thruster attachments. Three Triangle configurations follow Triangle 1, shown in Figure 4.4, that has the embedded piezoelectric patches located the closest to the center of the circular ACP. For Triangle 2, shown in Figure 4.5, the orientation of the piezoelectric patches is the same as Triangle 1, but the patches are the furthest away from the center of the circular ACP as possible. Triangle 3, shown in Figure 4.6, has the same orientation of embedded piezoelectric patches as Triangle 1 with the patches located in between the locations of Triangle 1 and Triangle 2. These five configurations (Star 1, Star 2, Triangle 1, Triangle 2 and Triangle 3) were selected because they were the original configurations studied when the ACP used rigid constraints. The next two cases are the optimized cases for the Star and Triangle configurations. Star Optimized, shown in Figure 4.7, has the same configuration of embedded piezoelectric patches as the Star 2 configuration and removes as much composite material as possible to make the panel lighter (basically removing the composites in between the piezoelectric patches, leaving more of a star
shape rather than a circle). Triangle Optimized, shown in Figure 4.8, has the same configuration of embedded piezoelectric patches as Triangle 1 and removes as much composite material as possible to make the panel lighter (basically removing all around the panel, and hence making the ACP the smallest circle possible). Therefore, the diameter of Triangle Optimized becomes 32.5 cm. The optimized cases represented new work to create the lightest panel possible for each configuration of Star and Triangle. The last configuration is Triangle Current, shown in Figure 4.9, which is the same as Triangle 1 configuration of embedded piezoelectric patches that has been used in all previous analyses. Triangle Current was the optimized configuration based on previous analyses and used to determine if this configuration remained the best possible case. Figures 4.2 to 4.9 are drawn to scale with respect to one another for size comparisons of each configuration.

*Figure 4.2: Star 1 Configuration (63.3 cm in diameter).*

*Figure 4.3: Star 2 Configuration (63.3 cm in diameter).*

*Figure 4.4: Triangle 1 Configuration (63.3 cm in diameter).*

*Figure 4.5: Triangle 2 Configuration (63.3 cm in diameter).*
There were two objectives in the harmonic analysis studies for the eight different configurations. The first was to perform precision stabilization (PS) of the rocket thruster by selecting three nodes on the thruster attachment (see Figure 4.10) and suppressing the resultant vibration in the Z-direction.

The three pairs of piezoelectric patches were used independently to fully suppress
vibrations at those three locations which represent the connecting points of the thruster to the circular panel. For this analysis, four frequencies (25Hz, 50Hz, 75Hz, and 100Hz) were selected to conduct the harmonic analysis. These frequencies were selected because the actual operational frequency is 0 to 100Hz. In addition, it is shown and explained later in this work that the natural frequency of the final design plate is greater than 100Hz. The next step is performed with load only and the displacements of the three points are observed for each frequency. The load-only displacements of these three points are denoted as $D_{p1}$, $D_{p2}$, and $D_{p3}$. Next, an arbitrary value of voltage is applied to one pair of actuators and harmonic analysis is run without loading and the displacements of those three points are noted. This step is repeated for the two remaining pairs of actuators. Since the relationship between displacement and voltage is assumed to be linear, ratios for voltage to displacement can be calculated. The configuration has nine ratios, that is, for each pair of actuators there are three ratios, one for point one, one for point two, and one for point three. The ratios are denoted as $r_{1,p1}$, $r_{1,p2}$, $r_{1,p3}$, $r_{2,p1}$, $r_{2,p2}$, $r_{2,p3}$, $r_{3,p1}$, $r_{3,p2}$, and $r_{3,p3}$. The ratios are calculated by simply dividing the 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 are denoted as $V_1$, $V_2$, and $V_3$. These voltages can be applied in a number of different voltage schemes to provide vibration suppression to the structure (Russ and Ghasemi-Nejhad, 2002; Doherty and Ghasemi-Nejhad, 2005; Ghasemi-Nejhad et al., 2006); however, the scheme used for this analysis is the Corresponding Voltage (COV) scheme. The Corresponding Voltage
scheme was selected because the Constant Voltage (CV) scheme would only suppress a percentage of the vibrations across the frequency interval whereas the Corresponding Voltage (COV) scheme would suppress the vibrations for each frequency substep on the interval studied and has less intensive calculations compared to the Truncated Corresponding Voltage scheme (TCOV). The Corresponding Voltage scheme applies the control voltage to the actuators for each frequency substep. The control 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 voltages are calculated by solving the following set of linear equations simultaneously at each frequency:

\[
\begin{bmatrix}
    r_{1,p1} & r_{2,p1} & r_{3,p1} \\
    r_{1,p2} & r_{2,p2} & r_{3,p2} \\
    r_{1,p3} & r_{2,p3} & r_{3,p3}
\end{bmatrix}
\begin{bmatrix}
    V_1 \\
    V_2 \\
    V_3
\end{bmatrix}
=
\begin{bmatrix}
    -D_{p1} \\
    -D_{p2} \\
    -D_{p3}
\end{bmatrix}
\] (4.1)

In Equation (4.1), the right-hand-side is negative to provide 180° out-of-phase displacements for \( V_1 \), \( V_2 \), and \( V_3 \) compared to the external disturbance (Russ and Ghasemi-Nejhad, 2002; Doherty and Ghasemi-Nejhad, 2005; Ghasemi-Nejhad et al., 2006). Applying the calculated voltages, \( V_1 \), \( V_2 \), and \( V_3 \), at each frequency delivers vibration suppression for all three points. This analysis was carried out for the eight different configurations.

The second was to perform vibration suppression (VS) at the ACS ball joints, which will
eliminate the transmission of the vibration from the thruster to the satellite. This was achieved by using the three nodes that are simply supported (see Figure 4.11) and suppressing their resultant force in the Z-direction.

![Simply Support locations](image)

*Figure 4.11: Full panel model with brackets showing the location where the simply support constraints on the ACS ball joints are located.*

The three pairs of piezoelectric patches were used independently to fully suppress the force resultant at those three locations that are simply supported, which represent the connecting points of the circular panel to the ACS struts. Harmonic analysis is performed at 25Hz, 50Hz, 75Hz, and 100Hz with load only and the force resultant at the ACS ball joints is observed. These frequencies were selected because the actual operational frequency is 0 to 100Hz. In addition, it is shown and explained later in this work that the natural frequency of the final design plate is greater than 100Hz. The force resultants of the ball joints are denoted as $F_{p1}$, $F_{p2}$, and $F_{p3}$. Next, an arbitrary value of voltage is applied to one pair of actuators and the harmonic analysis is run without external loading and the force resultants at the three ACS ball joints are noted. This step is repeated for the two remaining pairs of actuators. Since the relationship between force resultant and voltage is assumed to be linear, ratios for voltage to force resultant can...
be calculated. The configuration has nine ratios, that is, for each actuator there are three ratios, one for point one, one for point two, and one for point three. The ratios are denoted as $r_{1,P1}$, $r_{1,P2}$, $r_{1,P3}$, $r_{2,P1}$, $r_{2,P2}$, $r_{2,P3}$, $r_{3,P1}$, $r_{3,P2}$, and $r_{3,P3}$. The ratios are calculated by simply dividing force resultant of the point by the input voltage. Then dividing the load-only force resultant of the corresponding point by each ratio gives the voltage required for suppression of that particular point. The voltage required for suppression are denoted as $V_1$, $V_2$, and $V_3$. These voltages can be applied in a number of different voltage schemes to provide vibration suppression to the structure (Russ and Ghasemi-Nejhad, 2002; Doherty and Ghasemi-Nejhad, 2005; Ghasemi-Nejhad et al., 2006). The Corresponding Voltage scheme was selected because the Constant Voltage (CV) scheme would only suppress a percentage of the vibrations across the frequency interval whereas the Corresponding Voltage (COV) scheme would suppress the vibrations for each frequency substep on the interval studied and has less intensive calculations compared to the Truncated Corresponding Voltage scheme (TCOV). The Corresponding Voltage scheme applies a control voltage to the actuators for each frequency substep. The control voltage to each of the actuators does not necessarily have to be the same value and are calculated by simultaneously solving the set of linear equations given by Equation (4.2) at each frequency.

$$
\begin{bmatrix}
  r_{1,P1} & r_{2,P1} & r_{3,P1} \\
  r_{1,P2} & r_{2,P2} & r_{3,P2} \\
  r_{1,P3} & r_{2,P3} & r_{3,P3}
\end{bmatrix}
\begin{bmatrix}
  V_1 \\
  V_2 \\
  V_3
\end{bmatrix}
=
\begin{bmatrix}
  -F_{P1} \\
  -F_{P2} \\
  -F_{P3}
\end{bmatrix}
$$

(4.2)

In Equation (4.2), the right-hand-side is negative to provide $180^\circ$ out-of-phase force resultants for $V_1$, $V_2$, and $V_3$ compared to the external disturbance (Russ and
Applying the calculated voltages, $V_1$, $V_2$, and $V_3$, at each frequency delivers vibration suppression for all three points. This analysis was carried out for the eight different configurations.

**4.1: FULL PANEL WITH EIGHT CONFIGURATIONS RESULTS**

The results from the analyses are plotted in Figures 4.12 and 4.13 with the numerical results tabled in Tables 4.1 and 4.2. Figure 4.12 has a bar graph that contains the maximum control voltage required to conduct VS for each configuration. Figure 4.13 has a bar graph that contains the maximum control voltage to conduct PS for each configuration. The maximum control voltages are taken from the voltage curves shown in Appendix B.
Figure 4.12: Maximum control voltage required to conduct VS for each configuration.
Table 4.1: Numerical results for the maximum control voltage (volts) required to conduct VS for each configuration.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star 1</td>
<td>12350.24</td>
</tr>
<tr>
<td>Star 2</td>
<td>3814.89</td>
</tr>
<tr>
<td>Δ 1</td>
<td>2418.57</td>
</tr>
<tr>
<td>Δ 2</td>
<td>6911.79</td>
</tr>
<tr>
<td>Δ 3</td>
<td>7136.17</td>
</tr>
<tr>
<td>Star Opt</td>
<td>4886.44</td>
</tr>
<tr>
<td>Δ Opt</td>
<td>562369.25</td>
</tr>
<tr>
<td>Δ Cur</td>
<td>68367.42</td>
</tr>
</tbody>
</table>

In the case of VS using the force resultant, the worst case is the Triangle Optimized configuration and the best case is the Triangle 1 configuration.

Figure 4.13: Maximum control voltage required to conduct PS for each configuration.
Table 4.2: Numerical results for the maximum control voltage (volts) required to conduct PS for each configuration.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star 1</td>
<td>4344.79</td>
</tr>
<tr>
<td>Star 2</td>
<td>21892.72</td>
</tr>
<tr>
<td>Δ 1</td>
<td>21913.95</td>
</tr>
<tr>
<td>Δ 2</td>
<td>72966.68</td>
</tr>
<tr>
<td>Δ 3</td>
<td>14468.68</td>
</tr>
<tr>
<td>Star Opt</td>
<td>3796.64</td>
</tr>
<tr>
<td>Δ Opt</td>
<td>1842.57</td>
</tr>
<tr>
<td>Δ Cur</td>
<td>3923.33</td>
</tr>
</tbody>
</table>

In the case of thruster steering, the worst case is the Triangle 2 configuration and the best case is the Triangle Optimized configuration. The Star Optimized configuration gives us the best flexibility between the two operations of vibration suppression or precision stabilization.
CHAPTER 5
FULL PANEL WITH EIGHT CONFIGURATIONS AND STRUCTURAL DAMPING

Since in real life, the structure will have some damping, the next step in the analysis considers all eight configurations with a damping ratio of 1% added to the entire structure since the plate is very stiff and we are interested in active damping portion of testing, not passive damping. This allows us to find the optimum voltage and phase required for vibration suppression or precision stabilization.

The first analysis which is precision stabilization of the rocket thruster is performed by selecting one point within each of the three circular sections of the thruster attachment, denoted as $D_{p1}$, $D_{p2}$, and $D_{p3}$ (see Figure 4.10). Next, an arbitrary value of voltage is applied to one pair of the actuators and the harmonic analysis is run without external loading and the displacements of those three points are noted, both the magnitude and phase. This step is repeated for the two remaining pairs of actuators. The phase of the displacement is accounted for by using the equation of $D_P x e^{i\phi_d}$, where $D_P$ is the magnitude of the displacement for point $x$, $\phi_d$ is the phase of the displacement, and $i = \sqrt{-1}$. This complex number is used with the assumption that the relationship between the displacement and control voltage is assumed to be linear, to obtain the voltage to displacement ratios. Each configuration has nine ratios, that is, for each actuator there
are three ratios, one for point one, one for point two, and one for point three. The ratios are denoted as \( r_{1,1}e^{\phi_1}, r_{1,2}e^{\phi_2}, r_{1,3}e^{\phi_3}, r_{2,1}e^{\phi_1}, r_{2,2}e^{\phi_2}, r_{2,3}e^{\phi_3}, r_{3,1}e^{\phi_1}, r_{3,2}e^{\phi_2}, r_{3,3}e^{\phi_3} \). The ratios are calculated by simply dividing the 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 control voltage required for suppression is denoted as \( V_1e^{\phi_1}, V_2e^{\phi_2}, \) and \( V_3e^{\phi_3} \); where \( V_x \) is the magnitude of the control voltage required for the suppression of point \( x \), \( \phi_x \) is the phase of the voltage, and \( i = \sqrt{-1} \).

\[
\begin{bmatrix}
  r_{1,1}e^{\phi_1} & r_{1,2}e^{\phi_2} & r_{1,3}e^{\phi_3} \\
  r_{2,1}e^{\phi_1} & r_{2,2}e^{\phi_2} & r_{2,3}e^{\phi_3} \\
  r_{3,1}e^{\phi_1} & r_{3,2}e^{\phi_2} & r_{3,3}e^{\phi_3}
\end{bmatrix}
\begin{bmatrix}
  V_1e^{\phi_1} \\
  V_2e^{\phi_2} \\
  V_3e^{\phi_3}
\end{bmatrix} =
\begin{bmatrix}
  -D_{1,1}e^{\phi_1} \\
  -D_{2,2}e^{\phi_2} \\
  -D_{3,3}e^{\phi_3}
\end{bmatrix} \tag{5.1}
\]

In Equation (5.1), the right-hand-side is negative to provide out-of-phase displacements for \( V_1, V_2, \) and \( V_3 \) compared to the external disturbance (Russ and Ghasemi-Nejhad, 2002; Doherty and Ghasemi-Nejhad, 2005; Ghasemi-Nejhad et al., 2006). Applying the calculated control voltages, \( V_1e^{\phi_1}, V_2e^{\phi_2}, \) and \( V_3e^{\phi_3} \), at each frequency delivers precision stabilization (i.e., PS) for all three points.

The three nodes that are simply supported (see Figure 4.11) are used to achieve the second objective, i.e., the vibration suppression at the ACS ball joints. Similar procedures as explained earlier can be applied to arrive at an equation for VS similar to Equation (5.1) for PS. The changes to the right-hand-side of Equation (5.1) would be: \( D \)
should be replaced by $F$ and obviously $\phi_d$ by $\phi_f$ as shown in Equation (5.2).

\[
\begin{bmatrix}
 r_{1,p1}e^{\phi_{f1}} & r_{2,p1}e^{\phi_{f1}} & r_{3,p1}e^{\phi_{f1}} \\
r_{1,p2}e^{\phi_{f2}} & r_{2,p2}e^{\phi_{f2}} & r_{3,p2}e^{\phi_{f2}} \\
r_{1,p3}e^{\phi_{f3}} & r_{2,p3}e^{\phi_{f3}} & r_{3,p3}e^{\phi_{f3}}
\end{bmatrix}
\begin{bmatrix}
 V_{e}e^{\phi_{f1}} \\
 V_{2}e^{\phi_{f2}} \\
 V_{3}e^{\phi_{f3}}
\end{bmatrix}
= \begin{bmatrix}
 -F_{p1}e^{\phi_{f1}} \\
 -F_{p2}e^{\phi_{f2}} \\
 -F_{p3}e^{\phi_{f3}}
\end{bmatrix} \tag{5.2}
\]

Equation (5.2) solves for the control voltages required for vibration suppression (i.e., $V_S$) at the ACS ball joints.

5.1: FULL PANEL WITH EIGHT CONFIGURATIONS AND STRUCTURAL DAMPING RESULTS

The results from the analysis are plotted in Figures 5.1 and 5.2 with the numerical results tabled in Tables 5.1 and 5.2. Figure 5.1 has a bar graph that contains the maximum control voltage required to conduct $V_S$ for each configuration with a damping ratio of one percent. Figure 5.2 has a bar graph that contains the maximum control voltage to conduct $P_S$ for each configuration with a damping ratio of one percent. The maximum control voltage was taken from the control voltage curves shown in Appendix C. Also contained in Appendix C is the plots of the phase angles.
Figure 5.1: Maximum control voltage required to conduct VS for each configuration with a damping ratio of one percent.

Table 5.1: Maximum control voltage (volts) required to conduct VS for each configuration with a damping ratio of one percent.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star 1</td>
<td>12184.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Star 2</td>
<td>3817.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δ 1</td>
<td>2421.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δ 2</td>
<td>6895.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δ 3</td>
<td>7140.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Star Opt</td>
<td>4887.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δ Opt</td>
<td>562504.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δ Cur</td>
<td>68387.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the case of VS using the force resultant, the worst case is the Triangle Optimized configuration and the best case is the Triangle 1 configuration.
**Figure 5.2:** Maximum control voltage required to conduct PS for each configuration with a damping ratio of one percent.

**Table 5.2:** Maximum control voltage (volts) required to conduct PS for each configuration with a damping ratio of one percent.

<table>
<thead>
<tr>
<th></th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star 1</td>
<td>4341.95</td>
</tr>
<tr>
<td>Star 2</td>
<td>19931.49</td>
</tr>
<tr>
<td>Δ 1</td>
<td>3093.64</td>
</tr>
<tr>
<td>Δ 2</td>
<td>69285.53</td>
</tr>
<tr>
<td>Δ 3</td>
<td>14348.62</td>
</tr>
<tr>
<td>Star Opt</td>
<td>3796.75</td>
</tr>
<tr>
<td>Δ Opt</td>
<td>1840.34</td>
</tr>
<tr>
<td>Δ Cur</td>
<td>3926.98</td>
</tr>
</tbody>
</table>

In the case of thruster steering, the worst case is the Triangle 2 configuration and the best case is the Triangle Optimized configuration. The Triangle 1 and Star Optimized configuration gives us the best flexibility between the two operations of vibration suppression or precision stabilization with a damping ratio of one percent.
The comparison of the results with and without a damping ratio of one percent is shown below in Figures 5.3 and 5.4 and Tables 5.3 and 5.4.

![Voltage vs Configuration](image)

**Figure 5.3:** Maximum control voltage required to conduct VS for each configuration without damping (solid) and with a damping ratio of one percent (striped).

**Table 5.3:** Maximum control voltage (volts) required to conduct VS for each configuration without damping and with a damping ratio of one percent, as well as the percent change in maximum voltage.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>w/o Damping</th>
<th>w/ Damping</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star 1</td>
<td>12350.24</td>
<td>12184.68</td>
<td>1.34%</td>
</tr>
<tr>
<td>Star 2</td>
<td>3814.89</td>
<td>3817.44</td>
<td>-0.07%</td>
</tr>
<tr>
<td>Δ 1</td>
<td>2418.57</td>
<td>2421.87</td>
<td>-0.14%</td>
</tr>
<tr>
<td>Δ 2</td>
<td>6911.79</td>
<td>6895.12</td>
<td>0.24%</td>
</tr>
<tr>
<td>Δ 3</td>
<td>7136.17</td>
<td>7140.30</td>
<td>-0.06%</td>
</tr>
<tr>
<td>Star Opt</td>
<td>4886.44</td>
<td>4887.14</td>
<td>-0.01%</td>
</tr>
<tr>
<td>Δ Opt</td>
<td>562369.25</td>
<td>562504.48</td>
<td>-0.02%</td>
</tr>
<tr>
<td>Δ Cur</td>
<td>68367.42</td>
<td>68387.01</td>
<td>-0.03%</td>
</tr>
</tbody>
</table>

The application of a damping ratio of one percent to the structure had very minimal impact on the magnitude of voltage required for vibration suppression (i.e., VS) and remained relatively unchanged.
Figure 5.4: Maximum control voltage required to conduct PS for each configuration without damping (solid) and with a damping ratio of one percent (striped).

Table 5.4: Maximum control voltage (volts) required to conduct PS for each configuration without damping and with a damping ratio of one percent, as well as the percent change in maximum voltage.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>w/o Damping</th>
<th>w/ Damping</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star 1</td>
<td>4344.79</td>
<td>4341.95</td>
<td>0.07%</td>
</tr>
<tr>
<td>Star 2</td>
<td>21892.72</td>
<td>19931.49</td>
<td>8.96%</td>
</tr>
<tr>
<td>Δ 1</td>
<td>21913.95</td>
<td>3093.64</td>
<td>85.88%</td>
</tr>
<tr>
<td>Δ 2</td>
<td>72966.68</td>
<td>69285.53</td>
<td>5.04%</td>
</tr>
<tr>
<td>Δ 3</td>
<td>14468.68</td>
<td>14348.62</td>
<td>0.83%</td>
</tr>
<tr>
<td>Star Opt</td>
<td>3796.64</td>
<td>3796.75</td>
<td>0.00%</td>
</tr>
<tr>
<td>Δ Opt</td>
<td>1842.57</td>
<td>1840.34</td>
<td>0.12%</td>
</tr>
<tr>
<td>Δ Cur</td>
<td>3923.33</td>
<td>3926.98</td>
<td>-0.09%</td>
</tr>
</tbody>
</table>

The application of a damping ratio of one percent to the structure had a significant impact on conducting precision stabilization (i.e., PS) for three cases when compared to vibration suppression (i.e., VS). The largest impact came with the Triangle 1 configuration where the magnitude of the control voltage required for precision stabilization was 86% lower.
These results showed that the Star Optimized configuration provided the most flexibility for conducting vibration suppression or precision stabilization without structural damping present and with a damping ratio of one percent both the Triangle 1 and Star Optimized configurations provided the most flexibility for conducting VS or PS. Due to dimensional constraints the Triangle Current configuration was selected for manufacturing. This analysis shows that the Triangle Current configuration of the ACP is more effective for precision stabilization (i.e., PS) because the voltages for vibration suppression (i.e., VS) are much greater than those for PS; and if the lateral (normal to plate) dynamic load is 10 lbs, then the Triangle Current configuration VS control voltages are much greater than the capabilities of the current piezoelectric active fiber composite actuators available on the market.
CHAPTER 6
TRIANGLE CURRENT THICKNESS
OPTIMIZATION METHODS

With the configuration selected, thickness optimization was performed by changing the middle layer thickness and running harmonic analysis with the simulated loading of the thruster at 25, 50, 75, and 100Hz since the actual operational frequency is 0 to 100Hz. In addition, it is shown and explained later in this work that the natural frequency of the final design plate is greater than 100Hz. The loading is applied to the thruster attachments as shown previously in Figure 3.2. The combined lateral (normal to plate) dynamic loading on the full panel with brackets model is assumed to be ten pounds of force, as explained earlier. Equation (4.1) was used to solve for the control voltage required for precision stabilization at each frequency substep and thickness change.

The different thicknesses studied were six, eight, ten, twelve, fourteen, sixteen, eighteen, twenty, twenty two, and twenty four total composite layers. The location of the piezoelectric patches remained the same, being just one layer above the bottom layer and one layer below the upper layer of composite. The change of the thickness resulted from changing the number of layers sandwiched between the piezoelectric patches. The optimum thickness was selected by accounting for the maximum allowable voltage of the piezoelectric patches which is ±500 volts.
6.1: TRIANGLE CURRENT THICKNESS OPTIMIZATION RESULTS

The maximum control voltage for precision stabilization (i.e., PS) versus total plate thickness is shown in Figure 6.1. The horizontal line at 500 volts represents the maximum control voltage that can be applied to the piezoelectric patches.

![Voltage vs Plate Thickness](image)

*Figure 6.1: Maximum control voltage versus total plate thickness for precision stabilization of Triangle Current configuration.*

It was decided to manufacture the ACP top plate with a quasi-isotropic stacking sequence of \([0/30/60]_s\) employing plain weave composite prepreg. This meant the top place could only be manufactured by multiples of six layers, i.e., 6, 12, 18, 24 total layers of composite. Since 24 total layers was determined to be too thick for the piezoelectric patches to have any effect, the ACP was manufactured with eighteen total layers of composite.
CHAPTER 7  
FEA VOLTAGE VERSUS ACTUAL VOLTAGE  

The control voltage results from this FEA analysis, \( V_{FEA} \), are smaller when compared to actual needed control voltages (\( V_{actual} \)), since there are three conversion factors that should be applied to the results from ANSYS to obtain the actual control voltage. The three conversion factors are for the (a) effective area, (b) volume fraction, and (c) voltage.  

(a) The effective area conversion factor (\( CF_{EA} \)) is 0.75 and this factor is provided by the piezoelectric manufacturer (CCC, 2002), and it implies that the actual effective AFC area within each patch is 75%.  
(b) The volume fraction conversion factor (\( CF_{VF} \)) is 0.55 which is due to the fact that the active piezoelectric fibers in the AFC patch only make up 55% of the actual area/volume of the AFC patch effective area/volume (CCC, 2002).  
(c) The voltage conversion factor (\( CF_{Volt} \)) is 0.60 and is found from the comparison of the voltage versus free expansion experimental data supplied by the manufacturer and those obtained from the finite element model taking the effective area and fiber volume fractions also into account, and it was found to be 60%.  

Applied conversion factors to the FEA voltages to obtain the actual voltages, which is justified due to linearity assumption made in here. Therefore, Equation (7.1) given below gives the actual Voltage Conversion Equation.

\[
V_{FEA} = V_{actual} \times CF_{EA} \times CF_{VF} \times CF_{Volt} \quad (7.1)
\]
7.1: FEA VOLTAGE VERSUS ACTUAL VOLTAGE RESULTS

The maximum control voltage ($V_{\text{actual}}$) for precision stabilization (i.e., PS) versus total plate thickness is shown in Figure 7.2. The horizontal line at 500 volts represents the maximum control voltage that can be applied to the piezoelectric patches.

![Voltage vs Plate Thickness](image)

Figure 7.2: Maximum control voltage ($V_{\text{actual}}$) versus total plate thickness for precision stabilization of Triangle Current configuration.

The results show that the required control voltages for complete precision stabilization...
are beyond the capabilities of the piezoelectric patches, if the lateral (normal to plate) dynamic force is 10 lbs.
The piezoelectric patches require 2500 volts to fully suppress the vibrations of the thruster for precision stabilization (if the lateral (normal to plate) dynamic force is 10 lbs) and the capabilities of the piezoelectric AFC patches used here are ±500 volts. This means that we need to determine how much vibration we can suppress while keeping within the operating limits of the piezoelectric patches (for 10 lbs of lateral (normal to plate) dynamic force). There are two methods used for applying control voltages to the ACP, these methods were truncated and scaled. The “truncated method” uses the maximum operation limit of the piezoelectric patches as the cutoff voltage. Any control scheme that requires a control voltage higher than the capabilities of the piezoelectric patches will be changed to the cutoff voltage and anything below the cutoff voltage is used as determined. The “scaled method” takes the maximum control voltage for the control scheme and reduces it to the cutoff voltage level and scales all other voltage values accordingly. The cutoff voltages used in this analysis were ±500 volts representing the current capabilities of the CCC piezoelectric AFC patches and ±1500 volts representing the new piezoelectric patches that we are going to obtain.
8.1: VIBRATION SUPPRESSION WITH ACTUAL VOLTAGE IN FEA RESULTS

The result from applying ±500 volts to the piezoelectric actuators for the truncated and scaled method is shown in Figures 8.1 and 8.2. Points 1, 2 and 3 are the points selected (see Figure 4.10) to conduct precision stabilization of the ACP.

Figure 8.1: Percentage of vibration suppressed using the truncated method with a maximum operating voltage of ±500 volts (for a lateral (normal to plate) dynamic force of 10 lbs).
Figure 8.2: Percentage of vibration suppressed using the scaled method with a maximum operating voltage of ±500 volts (for a lateral (normal to plate) dynamic load of 10 lbs).

By applying the truncated method to the piezoelectric patches with a maximum control voltage of ±500 volts we can achieve a suppression of 30% to 40%, and by applying the scaled method to the piezoelectric patches with a maximum control voltage of ±500 volts we can achieve a suppression of 20% to 25% within the frequency range considered here.

The results from applying ±1500 volts to the piezoelectric actuators for the truncated and scaled method are shown in Figures 8.3 and 8.4. Points 1, 2 and 3 are the points selected (see Figure 4.10) to conduct precision stabilization of the ACP.
Figure 8.3: Percentage of vibration suppressed using the truncated method with a maximum operating voltage of ±1500 volts (for a lateral (normal to plate) dynamic force of 10 lbs).
Figure 8.4: Percentage of vibration suppressed using the scaled method with a maximum operating voltage of ±1500 volts (for a lateral (normal to plate) dynamic force of 10 lbs).

By applying the truncated method to the piezoelectric patches with a maximum control voltage of ±1500 volts we can achieve a suppression of 60% to 95%, and by applying the scaled method to the piezoelectric patches with a maximum control voltage of ±1500 volts we can achieve a suppression of 55% to 75% within the frequency range considered here.
CHAPTER 9
ACTIVE VIBRATION SUPPRESSION WITH REDUCED LATERAL DYNAMIC FORCE

The previous chapters contained results for a higher loading application of 10 lbs lateral (normal to plate) dynamic force. In consideration of lower loading applications, the lateral (normal to plate) dynamic force was reduced from 10 lbs to 1 lb and 0.1 lbs. The loading is applied to the thruster attachments as shown previously in Figure 3.2 with the only difference being the reduction of lateral (normal to plate) dynamic force. Equations (4.1) and (4.2) were used to solve for the control voltage required for precision stabilization and vibration suppression at each frequency substep (25, 50, 75, and 100Hz).

9.1: PRECISION STABILIZATION WITH REDUCED LATERAL DYNAMIC FORCE RESULTS

The results of control voltage \( V_{\text{actual}} \) for precision stabilization (i.e., PS) versus frequency for 1 lb of lateral (normal to plate) dynamic force is shown in Figure 9.1 with the numerical results shown in Table 9.1. The values of \( V_1 \), \( V_2 \), and \( V_3 \) are the calculated control voltages from Equation (4.1) required to obtain vibration suppression at the frequency of interest.
Figure 9.1: Control voltage versus frequency to perform precision stabilization for a lateral (normal to plate) dynamic force of 1 lb.

Table 9.1: Control voltage (volts) required to perform precision stabilization for a lateral (normal to plate) dynamic force of 1 lb.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>V1</th>
<th>V2</th>
<th>V3</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>-239.76</td>
<td>87.30</td>
<td>91.82</td>
</tr>
<tr>
<td>50</td>
<td>-244.56</td>
<td>90.26</td>
<td>97.86</td>
</tr>
<tr>
<td>75</td>
<td>-254.74</td>
<td>133.57</td>
<td>74.82</td>
</tr>
<tr>
<td>100</td>
<td>-257.90</td>
<td>138.43</td>
<td>134.50</td>
</tr>
</tbody>
</table>

The results of control voltage ($V_{actual}$) for precision stabilization (i.e., PS) versus frequency for 0.1lb of lateral (normal to plate) dynamic force is shown in Figure 9.2 with the numerical results shown in Table 9.2. The values of $V_1$, $V_2$ and $V_3$ are the calculated control voltages from Equation (4.1) required to obtain vibration suppression at the frequency of interest.
**Figure 9.2:** Control voltage versus frequency to perform precision stabilization for a lateral (normal to plate) dynamic force of 0.1 lbs.

**Table 9.2:** Control voltage (volts) required to perform precision stabilization for a lateral (normal to plate) dynamic force of 0.1 lbs.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>V1</th>
<th>V2</th>
<th>V3</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>-23.98</td>
<td>8.73</td>
<td>9.18</td>
</tr>
<tr>
<td>50</td>
<td>-24.46</td>
<td>9.03</td>
<td>9.79</td>
</tr>
<tr>
<td>75</td>
<td>-25.47</td>
<td>13.36</td>
<td>7.48</td>
</tr>
<tr>
<td>100</td>
<td>-25.79</td>
<td>13.84</td>
<td>13.45</td>
</tr>
</tbody>
</table>

The results of control voltage ($V_{actual}$) required for precision stabilization (i.e., PS) versus frequency for 0.1lb of lateral (normal to plate) dynamic force (see Figure 9.2) is 10% of that for 1 lb of lateral (normal to plate) dynamic force, as one would expect due to the linearity of the system.
9.2: VIBRATION SUPPRESSION WITH REDUCED LATERAL DYNAMIC FORCE RESULTS

The results of control voltage ($V_{actual}$) for vibration suppression (i.e., VS) versus frequency for 1 lb of lateral (normal to plate) dynamic force is shown in Figure 9.3 with the numerical results shown in Table 9.3. The values of $V_1$, $V_2$ and $V_3$ are the calculated control voltages from Equation (4.2) required to obtain vibration suppression at the frequency of interest.

![Control Voltage vs. Frequency](image)

*Figure 9.3: Control voltage versus frequency to perform vibration suppression for a lateral (normal to plate) dynamic force of 1 lb.*
Table 9.3: Control voltage (volts) required to perform vibration suppression for a lateral (normal to plate) dynamic force of 1 lb.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>V1</th>
<th>V2</th>
<th>V3</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>50349.60</td>
<td>24829.32</td>
<td>24565.79</td>
</tr>
<tr>
<td>50</td>
<td>12856.04</td>
<td>6338.89</td>
<td>6277.73</td>
</tr>
<tr>
<td>75</td>
<td>5992.69</td>
<td>2951.24</td>
<td>2926.81</td>
</tr>
<tr>
<td>100</td>
<td>3758.77</td>
<td>1842.64</td>
<td>1830.14</td>
</tr>
</tbody>
</table>

The results of control voltage ($V_{act}$) for vibration suppression (i.e., VS) versus frequency for 0.1 lb of lateral (normal to plate) dynamic force is shown in Figure 9.4 with the numerical results shown in Table 9.4. The values of $V_1$, $V_2$ and $V_3$ are the calculated control voltages from Equation (4.2) required to obtain vibration suppression at the frequency of interest.
Figure 9.4: Control voltage versus frequency to perform vibration suppression for a lateral (normal to plate) dynamic force of 0.1 lbs.

Table 9.4: Control voltage (volts) required to perform vibration suppression for a lateral (normal to plate) dynamic force of 0.1 lbs.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>V1</th>
<th>V2</th>
<th>V3</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>5034.96</td>
<td>2482.93</td>
<td>2456.58</td>
</tr>
<tr>
<td>50</td>
<td>1285.60</td>
<td>633.89</td>
<td>627.77</td>
</tr>
<tr>
<td>75</td>
<td>599.27</td>
<td>295.12</td>
<td>292.68</td>
</tr>
<tr>
<td>100</td>
<td>375.88</td>
<td>184.26</td>
<td>183.01</td>
</tr>
</tbody>
</table>

The results of control voltage ($V_{actual}$) required for vibration suppression (i.e., VS) versus frequency for 0.1 lb of lateral (normal to plate) dynamic force (see Figure 9.4) is 10% of that for 1 lb of lateral (normal to plate) dynamic force, as one would expect due to the linearity of the system. The results also show that the control voltages required ($V_{actual}$) for complete VS are beyond the capabilities of the piezoelectric patches for a lateral...
(normal to plate) dynamic force of 1 lb and 0.1 lbs.

9.3: TRUNCATED AND SCALED RESULTS FOR VS WITH REDUCED LATERAL DYNAMIC FORCE

Using the truncated and scaled methods explained in Chapter 8, the results obtained from applying ±500 volts to the piezoelectric actuators for 1 lb of lateral (normal to plate) dynamic force are shown in Figures 9.5 and 9.6, respectively. In the case of truncated, there is negative vibration suppression which means the vibrations in the top plate are increase when compared to the initial free vibrations of the structure. Points 1, 2 and 3 are the points selected (see Figure 4.11) to conduct vibration suppression of the ACP.
Figure 9.5: Percentage of vibration suppressed using the truncated method with a maximum operating voltage of ±500 volts (for a lateral (normal to plate) dynamic force of 1 lb).
Figure 9.6: Percentage of vibration suppressed using the scaled method with a maximum operating voltage of ±500 volts (for a lateral (normal to plate) dynamic force of 1 lb).

By applying the truncated method to the piezoelectric patches with a maximum control voltage of ±500 volts for a lateral (normal to plate) dynamic force of 1 lb we cannot practically conduct vibration suppression, and by applying the scaled method to the piezoelectric patches with a maximum control voltage of ±500 volts we can achieve a suppression of 1% to 12% within the frequency range considered here. The results from applying ±1500 volts to the piezoelectric actuators for 1 lb of lateral (normal to plate) dynamic force for truncated and scaled methods are shown in Figures 9.7 and 9.8, respectively. Points 1, 2 and 3 are the points selected (see Figure 4.11) to conduct vibration suppression of the ACP.
Figure 9.7: Percentage of vibration suppressed using the truncated method with a maximum operating voltage of ±1500 volts (for a lateral (normal to plate) dynamic force of 1 lb).
By applying the truncated method to the piezoelectric patches with a maximum control voltage of ±1500 volts for a lateral (normal to plate) dynamic force of 1 lb we cannot achieve vibration suppression, and by applying the scaled method to the piezoelectric patches with a maximum control voltage of ±1500 volts we can achieve a suppression of 3% to 40% for the frequency range considered here. The results obtained from applying ±500 volts to the piezoelectric actuators for 0.1 lbs of lateral (normal to plate) dynamic force for truncated and scaled methods are shown in Figures 9.9 and 9.10, respectively. Points 1, 2 and 3 are the points selected (see Figure 4.11) to conduct vibration suppression of the ACP.

*Figure 9.8: Percentage of vibration suppressed using the scaled method with a maximum operating voltage of ±1500 volts (for a lateral (normal to plate) dynamic force of 1 lb).*
Figure 9.9: Percentage of vibration suppressed using the truncated method with a maximum operating voltage of ±500 volts (for a lateral (normal to plate) dynamic force of 0.1 lbs).
Figure 9.10: Percentage of vibration suppressed using the scaled method with a maximum operating voltage of ±500 volts (for a lateral (normal to plate) dynamic force of 0.1 lbs).

By applying the truncated method to the piezoelectric patches with a maximum control voltage of ±500 volts for a lateral (normal to plate) dynamic force of 0.1 lbs we can only achieve 100% vibration suppression near 100 Hz, and by applying the scaled method to the piezoelectric patches with a maximum control voltage of ±500 volts we can achieve a suppression of 10% to 100% within the frequency range considered here. The results obtained from applying ±1500 volts to the piezoelectric actuators for 0.1 lbs of lateral (normal to plate) dynamic force for truncated and scaled methods are shown in Figures 9.11 and 9.12, respectively. Points 1, 2 and 3 are the points selected (see Figure 4.11) to conduct vibration suppression of the ACP.
Figure 9.11: Percentage of vibration suppressed using the truncated method with a maximum operating voltage of ±1500 volts (for a lateral (normal to plate) dynamic force of 0.1 lbs).
Figure 9.12: Percentage of vibration suppressed using the scaled method with a maximum operating voltage of ±1500 volts (for a lateral (normal to plate) dynamic force of 0.1 lbs).

By applying the truncated method to the piezoelectric patches with a maximum control voltage of ±1500 volts for a lateral (normal to plate) dynamic force of 0.1 lbs we can basically achieve vibration suppression at frequencies greater than 50Hz, and by applying the scaled method to the piezoelectric patches with a maximum control voltage of ±1500 volts we can achieve a suppression of 30% to 100% within the frequency range considered here.
CHAPTER 10
CONCLUSIONS

Due to varying constraints on the design of the adaptive circular composite plate, the current triangle configuration was selected for manufacturing with eighteen total woven composite carbon/epoxy prepreg layers. The amount of suppression we can achieve to perform precision stabilization, with a lateral (normal to plate) dynamic force of ten pounds for the actuator voltage limits of ±500 is 30 and 20 percent employing the “truncated” and “scaled” methods introduced here. It should be noted that for this case of 10 lbs, “vibration suppression” of the satellite is not possible due to excessive actual actuator control voltage requirements. The control voltage is linearly related to the lateral (normal to plate) dynamic force being applied to the structure. Therefore, with the current AFC piezoelectric patches of ±500 voltage limits, we can conduct “precision stabilization” of the thruster for a lateral (normal to plate) dynamic load of up to 2 lbs, as demonstrated in this work. Finally, we can also perform “vibration suppression” of the satellite with the current AFC piezoelectric patches of ±500 voltage limits, for a lateral (normal to plate) dynamic load of 0.01 lbs.
APPENDIX A

MODAL RESULTS FOR FULL PANEL WITH EIGHT CONFIGURATIONS

Table A.1: The natural frequency results (in Hertz) for the eight different configurations of the full panel model with six total layers of prepreg within the operational frequency range of 0 to 100Hz.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Star 1</th>
<th>Star 2</th>
<th>Δ 1</th>
<th>Δ 2</th>
<th>Δ 3</th>
<th>Star Optimized</th>
<th>Δ Optimized</th>
<th>Δ Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>15.15</td>
<td>15.58</td>
<td>15.30</td>
<td>14.80</td>
<td>15.32</td>
<td>15.33</td>
<td>114.79</td>
<td>51.41</td>
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<tr>
<td>3</td>
<td>22.00</td>
<td>22.45</td>
<td>22.52</td>
<td>21.44</td>
<td>22.32</td>
<td>22.36</td>
<td>37.36</td>
<td>64.15</td>
</tr>
<tr>
<td>4</td>
<td>35.17</td>
<td>36.02</td>
<td>35.71</td>
<td>33.67</td>
<td>35.64</td>
<td>109.10</td>
<td>86.24</td>
<td>86.16</td>
</tr>
<tr>
<td>5</td>
<td>54.69</td>
<td>54.96</td>
<td>54.70</td>
<td>54.30</td>
<td>54.61</td>
<td></td>
<td></td>
<td>129.76</td>
</tr>
<tr>
<td>6</td>
<td>61.69</td>
<td>60.05</td>
<td>60.53</td>
<td>61.45</td>
<td>61.51</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>64.89</td>
<td>63.13</td>
<td>63.82</td>
<td>64.75</td>
<td>64.48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>84.93</td>
<td>83.64</td>
<td>83.32</td>
<td>84.09</td>
<td>84.63</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>86.08</td>
<td>85.16</td>
<td>85.04</td>
<td>84.72</td>
<td>86.16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>126.20</td>
<td>129.48</td>
<td>128.84</td>
<td>124.24</td>
<td>127.83</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table A.2: The natural frequency results (in Hertz) for the Triangle Current configuration with eighteen total layers of composite prepreg within the operational frequency range of 0 to 100Hz.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Δ Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>100.41</td>
</tr>
</tbody>
</table>
APPENDIX B
INDIVIDUAL RESULTS FOR FULL PANEL WITH EIGHT CONFIGURATIONS

Figure B.1: Control voltage versus frequency to conduct VS for the Star 1 configuration.

Figure B.2: Control voltage versus frequency to conduct PS for the Star 1 configuration.
Figure B.3: Control voltage versus frequency to conduct VS for the Star 2 configuration.

Figure B.4: Control voltage versus frequency to conduct PS for the Star 2 configuration.
Figure B.5: Control voltage versus frequency to conduct VS for the Triangle 1 configuration.

Figure B.6: Control voltage versus frequency to conduct PS for the Triangle 1 configuration.
Figure B.7: Control voltage versus frequency to conduct VS for the Triangle 2 configuration.

Figure B.8: Control voltage versus frequency to conduct PS for the Triangle 2 configuration.
Figure B.9: Control voltage versus frequency to conduct VS for the Triangle 3 configuration.

Figure B.10: Control voltage versus frequency to conduct PS for the Triangle 3 configuration.
Figure B.11: Control voltage versus frequency to conduct VS for the Star Optimized configuration.

Figure B.12: Control voltage versus frequency to conduct PS for the Star Optimized configuration.
Figure B.13: Control voltage versus frequency to conduct VS for the Triangle Optimized configuration.

Figure B.14: Control voltage versus frequency to conduct PS for the Triangle Optimized configuration.
Figure B.15: Control voltage versus frequency to conduct VS for the Triangle Current configuration.

Figure B.16: Control voltage versus frequency to conduct PS for the Triangle Current configuration.
APPENDIX C

INDIVIDUAL RESULTS FOR FULL PANEL WITH EIGHT CONFIGURATIONS AND STRUCTURAL DAMPING

Figure C.1: Control voltage (top) and phase angle (bottom) versus frequency to conduct VS for the Star 1 configuration.

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Figure C.2: Control voltage (top) and phase angle (bottom) versus frequency to conduct PS for the Star 1 configuration.
Figure C.3: Control voltage (top) and phase angle (bottom) versus frequency to conduct VS for the Star 2 configuration.
Figure C.4: Control voltage (top) and phase angle (bottom) versus frequency to conduct PS for the Star 2 configuration.
Figure C.5: Control voltage (top) and phase angle (bottom) versus frequency to conduct VS for the Triangle 1 configuration.
Figure C.6: Control voltage (top) and phase angle (bottom) versus frequency to conduct PS for the Triangle 1 configuration.
Figure C.7: Control voltage (top) and phase angle (bottom) versus frequency to conduct VS for the Triangle 2 configuration.
Figure C.8: Control voltage (top) and phase angle (bottom) versus frequency to conduct PS for the Triangle 2 configuration.
Figure C.9: Control voltage (top) and phase angle (bottom) versus frequency to conduct VS for the Triangle 3 configuration.
Figure C.10: Control voltage (top) and phase angle (bottom) versus frequency to conduct PS for the Triangle 3 configuration.
Figure C.11: Control voltage (top) and phase angle (bottom) versus frequency to conduct VS for the Star Optimized configuration.
Figure C.12: Control voltage (top) and phase angle (bottom) versus frequency to conduct PS for the Star Optimized configuration.
Figure C.13: Control voltage (top) and phase angle (bottom) versus frequency to conduct VS for the Triangle Optimized configuration.
Figure C.14: Control voltage (top) and phase angle (bottom) versus frequency to conduct PS for the Triangle Optimized configuration.
Figure C.15: Control voltage (top) and phase angle (bottom) versus frequency to conduct VS for the Triangle Current configuration.
Figure C.16: Control voltage (top) and phase angle (bottom) versus frequency to conduct PS for the Triangle Current configuration.
APPENDIX D
INDIVIDUAL RESULTS FOR TRIANGLE CURRENT THICKNESS OPTIMIZATION

![Graph](image1)

**Figure D.1:** Control voltage versus frequency to conduct PS for six total layers of composite.

![Graph](image2)

**Figure D.2:** Control voltage versus frequency to conduct PS for eight total layers of composite.
Figure D.3: Control voltage versus frequency to conduct PS for ten total layers of composite.

Figure D.4: Control voltage versus frequency to conduct PS for twelve total layers of composite.
Figure D.5: Control voltage versus frequency to conduct PS for fourteen total layers of composite.

Figure D.6: Control voltage versus frequency to conduct PS for sixteen total layers of composite.
Figure D.7: Control voltage versus frequency to conduct PS for eighteen total layers of composite.

Figure D.8: Control voltage versus frequency to conduct PS for twenty total layers of composite.
Figure D.9: Control voltage versus frequency to conduct PS for twenty two total layers of composite.

Figure D.10: Control voltage versus frequency to conduct PS for twenty four total layers of composite.
REFERENCES


