Vibration Control of Tensioned Precision Structures

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Abstract

This summer I worked primarily on the Tensioned Precision Structures (TPS) project within the AFRL RV Integrated Structural Systems/Deployables group.

TPS is developing and testing a design intended to provide an effective and advantageous alternative to traditional truss-based spacecraft structures. The sensitive project testing requires high precision, and thus involves motion capture technology using specialized infrared cameras. I helped perform a series of static observation tests on the TPS test article in preparation for later dynamic vibration testing. My tasks have included optimizing the motion capture system, performing tests and recording data, and conducting subsequent data post-processing.

The results of the experimentation and analysis indicate that the necessary precision is achieved by using the motion capture system; however, positional accuracy remains a problem, particularly with regard to inaccuracies from the motion capture system.

Introduction

The goal of the Tensioned Precision Structures project is to develop alternatives to traditional three-dimensional truss structures, which can suffer from various disadvantages, including metrology and control issues, and complications resulting from thermal deformation and expansion in very large structures. Research in TPS aims to mitigate these issues though the use of tensioned structures – structures established by tensioning construction materials, as in, for example a large tent structure or a suspension bridge – and the removal of structural depth. Tensioned stiffening allows for the structural rigidity usually provided by truss structures while simplifying the structure’s metrology; and the removal of structural depth helps to minimize precision issues associated with thermal expansion effects. Further advantages of TPS methods include scalability and conservation of mass efficiency while other potential advantages are affordability, foldability, stability, and compactness.

The TPS project’s research and goals are important for their potential to provide beneficial alternatives for spacecraft structures other than the traditional truss structures that are generally used today. An alternative to these traditional truss structures is needed, because in large truss structures, thermal deformations can lead to serious complications for spacecraft, especially when structural precision is necessary. Current solutions to thermal deformation issues can be
prohibitively expensive. For the Air Force, TPS research outcomes could improve structural design standards for future space missions. The current Air Force target application for TPS is a phased array for use in spacecraft. Development of phased array technologies is of interest to the Air Force for such applications as communication and tracking.

A test article based on TPS concepts has been designed and fabricated, and a gravity offload system has been successfully implemented. The test article is a tensioned thin, foldable, membrane array structure. The structure folds along hinged lines at the boundaries between triangular membrane panels, which constitute the array. As a result of the effort to remove structural depth, the structure is virtually two-dimensional. See the current test bed in Figure 1.

![Figure 1: TPS test bed featuring (a) the tensioned deployable test structure, (b) catenary tensioning system, and (c) gravity offload system.](image)

This summer, TPS research objectives focused on performing a series of tests to understand and characterize how the test structure responds to dynamic excitation through vibration testing. Prior to performing these vibration tests, it was necessary to examine the structure’s static shape. Consequently static testing and subsequent data post-processing took place.

**Experiment**

To characterize and verify the mechanics of the TPS test article design, high-precision data capture was required for both static and dynamic conditions. To achieve the precision necessary,
a motion capture system was used. A motion capture system tracks objects by using specialized cameras and retro-reflective materials, which reflect light back along its incident direction to the source of the light. The use of Vicon motion capture cameras and software allows tracking of structural positions via retro-reflective markers, as seen in Figure 2.

Using the motion capture system, a series of tests was performed in which different modifications to the shape and tensioning of the test article were made. These tests included observations of the nominal structure shape (the shape of the article with an even distribution of tensioning) and four different perturbed shapes with offset boundaries. Repetition of the testing procedure is of high importance for TPS testing in order to minimize variability in human error throughout the test series.

The static series of tests was performed in five stages. The first stage involved data capture with the structure at nominal shape; three sets of data were taken, first at 100% tensioning (with about 45 pounds of force at each of the four catenary corners), then with the structure 80% tensioned and 60% tensioned. The following four data capture sets were performed with the structure in four different perturbed shapes. The first perturbed shape set the structure at 80% operational tension with positional offsets in the lower left and lower right corners. The second perturbed
Data/Results

For each data capture set, a file of data is recorded containing about 500 frames of unlabeled x, y, and z positions for each marker. The resulting data files are fairly large and require post-processing. Table 1 on the following page gives average values for the position error resulting from the Vicon motion capture system and the standard deviation for the x, y, and z positions for each data set. The Vicon position error was calculated by averaging the position data per marker across all the data sets for one group and then averaging the differences between each data set and the averaged position information. The Vicon motion capture system can allow precision down to about one tenth of a millimeter, and the current accuracy goal for TPS testing is one millimeter. Accuracy calculations tell how closely the Vicon system records the structural marker positions compared to their actual positions, and while the system has high precision, its accuracy is dependent on a variety of factors (e.g.: thermal or physical disturbances, calibration accuracy, time since calibration) and can vary between data captures. The one millimeter accuracy goal was achieved in one third of the data sets from the first series of static tests, indicating that more work needs to be done to improve the Vicon data capturing and post-processing. The high standard deviations seen in the z position data across all the data sets further imply inexactness in the motion capture system, which can have a low depth accuracy (for the TPS test bed, the Vicon systems “look” in the z direction).
Table 1: Results from analysis of data from the first static series of tests

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Vicon Position Error (mm)</th>
<th>X Position Standard Deviation (mm)</th>
<th>Y Position Standard Deviation (mm)</th>
<th>Z Position Standard Deviation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static 100%-1</td>
<td>0.81771</td>
<td>0.26518</td>
<td>0.40841</td>
<td>2.2915</td>
</tr>
<tr>
<td>Static 100%-2</td>
<td>3.4774</td>
<td>0.31049</td>
<td>0.23408</td>
<td>1.2015</td>
</tr>
<tr>
<td>Static 100%-3</td>
<td>11.947</td>
<td>0.20127</td>
<td>0.15673</td>
<td>1.6513</td>
</tr>
<tr>
<td>Static 80%</td>
<td>0.40446</td>
<td>0.19205</td>
<td>0.23629</td>
<td>1.1033</td>
</tr>
<tr>
<td>Static 60%</td>
<td>4.3404</td>
<td>0.36750</td>
<td>0.28413</td>
<td>1.1209</td>
</tr>
<tr>
<td>Perturbation 1</td>
<td>0.47320</td>
<td>0.24588</td>
<td>0.20110</td>
<td>1.3670</td>
</tr>
<tr>
<td>Perturbation 2</td>
<td>2.9106</td>
<td>0.24117</td>
<td>0.21589</td>
<td>1.3659</td>
</tr>
<tr>
<td>Perturbation 3</td>
<td>3.0721</td>
<td>0.25692</td>
<td>0.41570</td>
<td>1.4102</td>
</tr>
<tr>
<td>Perturbation 4</td>
<td>4.3333</td>
<td>0.20519</td>
<td>0.25185</td>
<td>1.2782</td>
</tr>
</tbody>
</table>

Figure 3 below shows the position data for nine data captures at 100% tensioning. The magnified window in the plot displays data for one marker with nine data captures clustered into three groups showing 1 millimeter precision between different calibration sets and approximately 0.1 millimeter precision within a calibration. Furthermore Figure 4 shows the standard deviation values for each marker plotted over the marker positions. Figure 5 is a quiver plot of the positional displacement over the capture period for the Perturbation 2 test. For TPS analysis, quiver plots can be useful in observing and analyzing dynamic behavior that occurs in the structure.
Figure 3: Position data for nine data captures at 100% tensioning

Figure 4: Standard deviation values plotted over marker positions
Figure 5: Quiver plot showing positional displacement over the capture period

Discussion/Conclusion

The wide variations of computed position errors and relatively high z position standard deviations likely indicate issues in data capture and processing, so improvements in the Vicon system and data post-processing may minimize error and increase confidence in observations of the test article. The discrepancy in position error observed between calibrations indicates that accuracy is lost when the system is recalibrated; this loss can be caused by various factors like thermal changes between calibrations, motion, or simply inaccuracies inherent to the Vicon system. The standard deviation heatmap and the quiver plot both indicate greater variation in data near the right tower; these kinds of results can help identify issues in data precision for a particular region. If it is determined that particular regions do have higher rates of error, the source of the difference in error should be explored and remedied, whether the issue is related to the settings or positions of the Vicon cameras and system or if there is a problem with the structure itself.

While positional errors below 1 millimeter have been observed, further improvements in precision and confidence of the data capture system stand to be made and should be explored. Further testing through the summer will incorporate motor control of the test article to allow for observation of the structure’s dynamic behavior. Future work on TPS will likely progress from qualification testing to environmental testing before flight system integration.
References
