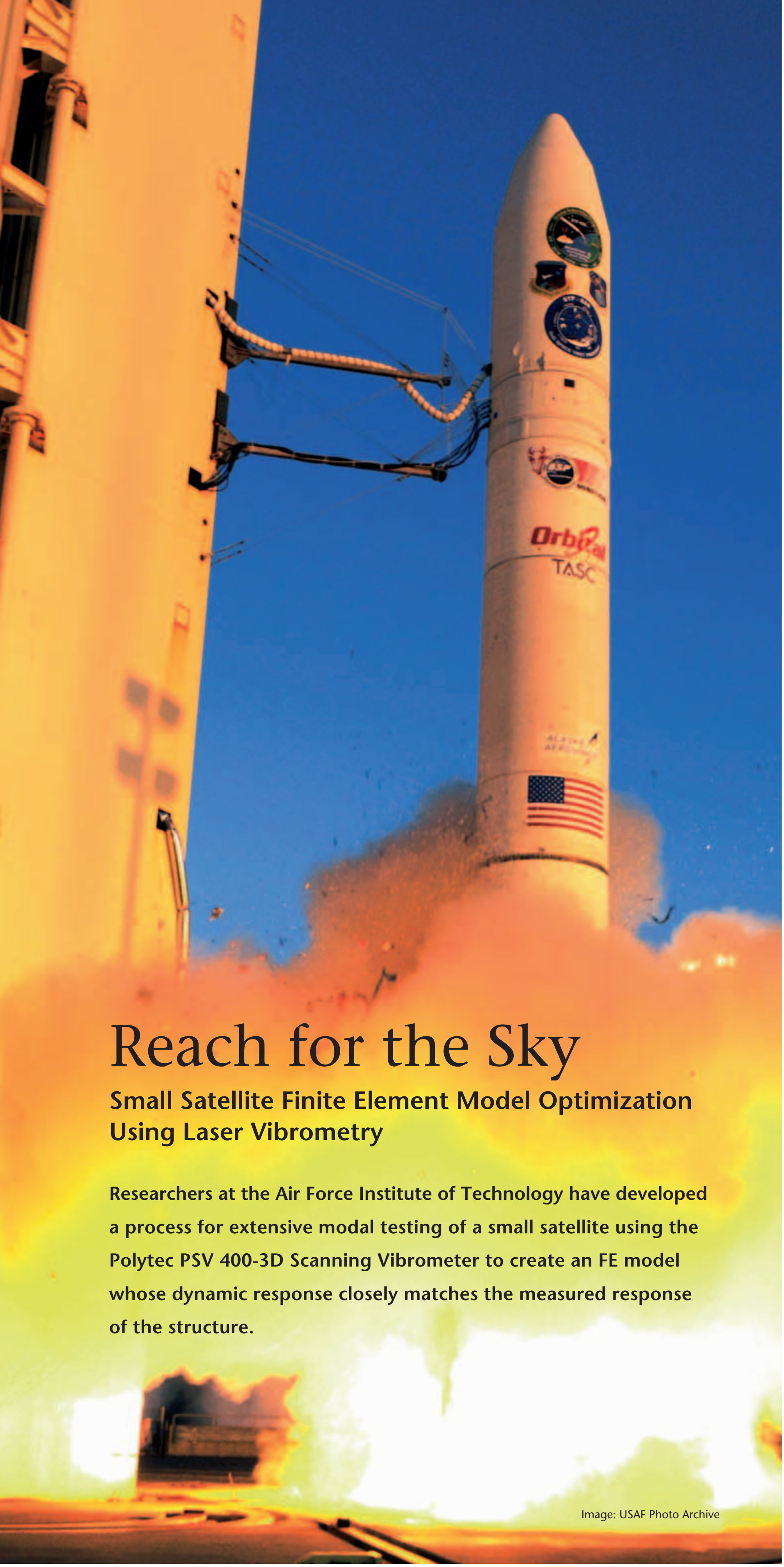


Image: USAF Photo Archive

Reach for the Sky

Small Satellite Finite Element Model Optimization Using Laser Vibrometry

Researchers at the Air Force Institute of Technology have developed a process for extensive modal testing of a small satellite using the Polytec PSV 400-3D Scanning Vibrometer to create an FE model whose dynamic response closely matches the measured response of the structure.

Polytec

Introduction

One of the senior capstone design courses offered at the United States Air Force Academy is the Department of Astronautics FalconSAT program. It is a student-run, faculty led program to design, build, test, and eventually launch a small satellite.

FalconSAT-5 is the latest in the series of FalconSAT satellites from the US Air Force Academy (USAFA). The second of FalconSAT-5 structural engineering models (FS-5 SEM II, Fig. 1) was constructed in spring 2008 to validate design modifications resulting from a change in customer/payload requirements. In the meantime, the satellite has been launched on November 19, 2010 onboard a Minotaur IV launch system (large image).

Accurate predictions of the dynamic responses of space launch payloads (Fig. 2) are required by launch vehicle integrators, but not achieved easily. The finite element (FE) method has proven to be the best approach in creating accurate dynamic models of complex structures. Previous research efforts used measured vibration data from only a few locations on the surface of the satellite to validate the first three predicted modes of the FE model. However, given the capability to collect dense vibration data over thousands of grid points presents an opportunity to develop a more accurate FE model.

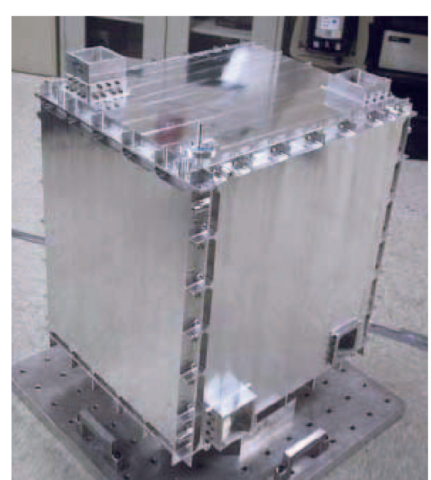


Fig. 1: FS-5 SEM II satellite.

Fig. 2: USAFA cadet and faculty member integrating the payload onto FS-5.

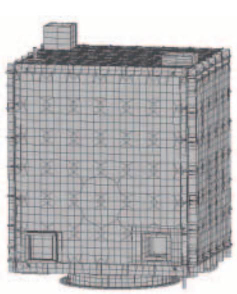
Fig. 4: FS-5 SEM II with Polytec PSV-400-3D.

Researchers at the Air Force Institute of Technology have developed a process for extensive modal testing using the Polytec PSV 400-3D Scanning Vibrometer to create an FE model whose dynamic response closely matches the measured response of FS-5.

Model Tuning

The first step in the tuning process is generating the untuned FE model (Fig. 3). Since the primary structure of the FS-5 SEM II is comprised of relatively thin panels, bilinear plate elements are predominantly used in the FE modeling approach. The second step in the tuning process is hand-tuning or adjusting the mass of each component of the FE model to match the measured mass. Measuring the mass of each structural component and carefully modeling the components results in very accurate FE mass matrices. The third step in the tuning process is measuring and extracting modal data from each panel and tuning the corresponding panel FE models by adjusting the Young's modulus of the panel materials. The vibrometer scans a grid of points spaced approximately one inch apart over the surface of each panel, collecting the operating deflection shapes through 1000 Hz as they are excited with an automated impact hammer. With each panel accurately modeled, a full satellite FE model is assimilated, leaving only connections between the panels, modeled by three columns of 6 degree-of-freedom (DOF) springs along each edge, as the design variable to tune. The fourth step in the tuning process is measuring modal data from the integrated satellite and tuning the corresponding FE model by adjusting 6 DOF spring constants and Young's moduli of the adapter ring material, which represents the launch vehicle mating and ejection rings.

Fig. 3: Model of the FS-5 SEM II.



Experimental Setup

For panel testing, a harness which imparts the smallest amount of strain in the panel is desirable to simulate free vibration. To accomplish this, a horizontal test harness was built which uses a mesh of bungee cords to suspend the panels above the floor. The frame is adjustable in height to allow the excitation source to fit underneath. Excitation is provided via an electromagnetic shaker programmed to impart periodic impulses with an arbitrary waveform generator and amplifier.

A force cell located between the stinger and the impact plate allows the Polytec vibrometer software to accurately estimate frequency response functions (FRFs). This approach also provides a much better coherence than other methods. With the panels supported and excited, data is

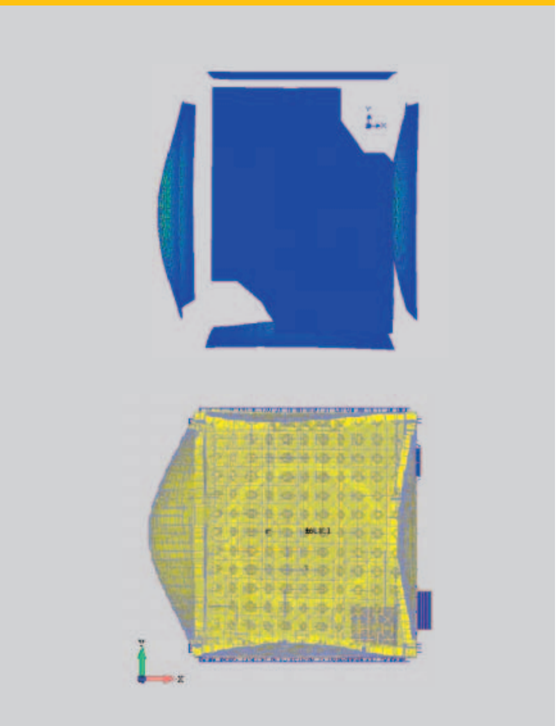


Fig. 5: Measured mode 5 (top) vs tuned FEM – asymmetrical X panel breathing.

collected on the dynamic response over the frequency range 0 to 1 kHz. Given the size of the SEM II panels, noise levels as low as those generated by people talking, can impart erroneous inputs or overrange the lasers, so care was taken to only collect data at night when noise levels were lower. Overall, eight modes were recorded for the side panels, six modes for the top panel, and five modes for the base panel.

Setup for testing the full SEM II (Fig. 4) begins with bolting the satellite stand plate to the floor to provide rigid boundary conditions. The same automated electromagnetic ping hammer that is used in panel testing is positioned at a 45 degree angle to the satellite horizontal in order to excite the greatest number of modes possible while maintaining excellent coherence. Aliasing and leakage are issues which can be remedied with sampling rate and window functions. Unlike the panel data, three translational velocities are measured at each measurement point resulting in three FRFs for each measurement point. A best practice is to keep all scan points within 10 to 12 degrees of the field of vision for each head. In order to meet this restriction with the side panels, only one panel is tested at a time with the heads positioned directly facing the panel.

With data collected, complex-valued modal data is extracted from the raw data using curve-fitting software then converted to real-values for use in tuning. With a set of spatially dense real-valued data, optimization may begin. Optimization software algorithms vary the design variables (stiffness for panels and spring constants for the full satellite) while attempting to minimize a cost function based on differences between measured and analytical eigenvalues and eigenvectors. In order to keep the model parameters from departing too far from the nominal values, constraints are specified in the optimization input which keep the design variables within desired bounds. The end result is a tuned FE model which closely matches the modal measured data in the frequency range of interest.

Results

The laser vibrometer collection process for the panels yields modal data (Fig. 5) for the first eight modes of the side panels, six modes of the top panel, and five modes for the base panel in the frequency range from 0 to 1 kHz. Over 400 locations were scanned on each panel in order to collect this data. Over 6500 FRFs were collected on the full satellite from approximately 2200 measurement points on the five visible surfaces. Every panel's FE model was successfully tuned to match the measured data up to at least 600 Hz.

Cost function reduction is shown in Fig. 6. Overall, the tuned panel eigenvalues matching the squared measured natural frequencies to within 2% and the general decreases in the cost functions indicate successful panel tuning. The tuning process reduces the cost function for full satellite model tuning as well, though generally the value of the cost function increases with increasing numbers of modes tuned. The process allowed tuning up to the first five modes. Overall,

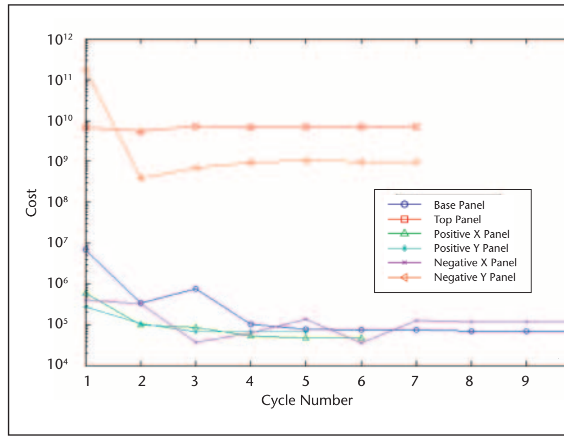


Fig. 6: Panel cost function reductions.

the tuned FE model eigenvectors for modes 4 and 5 yield modal assurance criterion (MAC) values which are improved by 31% and 33% over the untuned FE model respectively and natural frequency accuracy improved by an average of 7% when tuning the first five modes.

Conclusions

A Polytec 3-D Scanning Vibrometer was successfully used to develop and improve a FE model for FalconSAT-5. Several approaches used during creation of the tuning process were critical to its success. First, creating nodes on the untuned FE model directly from the structure geometry files allows the panel models to predict modal data that closely matches the measured values before adjusting design variables. Next, collecting vibration data using the Polytec laser vibrometer only at night is a large reason the measured FRF data has very low noise content. During the tuning stages of the process, the quality of the results and the ability of the software to converge are most sensitive to the desired allowable eigenvalue deviation.

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