Sail away

Laser vibrometry helps to validate Gossamer space structures

NASA is pursuing the development of large ultra-lightweight structures commonly referred to as Gossamer space structures. These structures have large areas and small aerial densities, which complicates ground testing significantly as the ground operations interfaces and gravity loading can become cumbersome. Laser vibrometry has proven to be a critical sensing technology for validating the dynamical characteristics of these Gossamer structures, due to its precision, range, and non-contacting (zero mass loading) nature.

NASA has been developing Gossamer space structures for many years to reduce launch costs and to exploit the unique capabilities of particular concepts. For instance, dish antennas (Figure 1) are currently being pursued because they can be inflated in space to sizes as large as 30 meters and then rigidized to enable high data rate communica-tions. Another example of a Gossamer structure is a solar sail that provides a cost effective source of propellantless propulsion. Solar sails span very large areas to capture momentum energy from photons and to use it to propel a spacecraft. The thrust of a solar sail, though small, is continuous and acts for the life of the mission without the need for propellant. Recent advances in materials and ultra-lightweight Gossamer structures have enabled a host of useful space exploration missions utilizing solar sail propulsion.

The team of ATK Space Systems, SRS Technologies, and NASA Langley Research Center, under the direction of the NASA In-Space Propulsion Office (ISP), has developed and evaluated a scalable solar sail configuration (Figure 2) to address NASA's future space propulsion needs. Testing of solar sails on the ground presented engineers with three major challenges:

- Measurements on large area surfaces thinner than paper
- Air mass loading under ambient conditions was significant thus requiring in-vacuum tests
- High modal density required partitioning of the surface into manageable areas.

This article will focus on the unique challenges with vacuum chamber, dynamic testing of a 20-meter solar sail concept at the NASA Glenn Plum Brook Facility (Figure 3).

In-vacuum setup

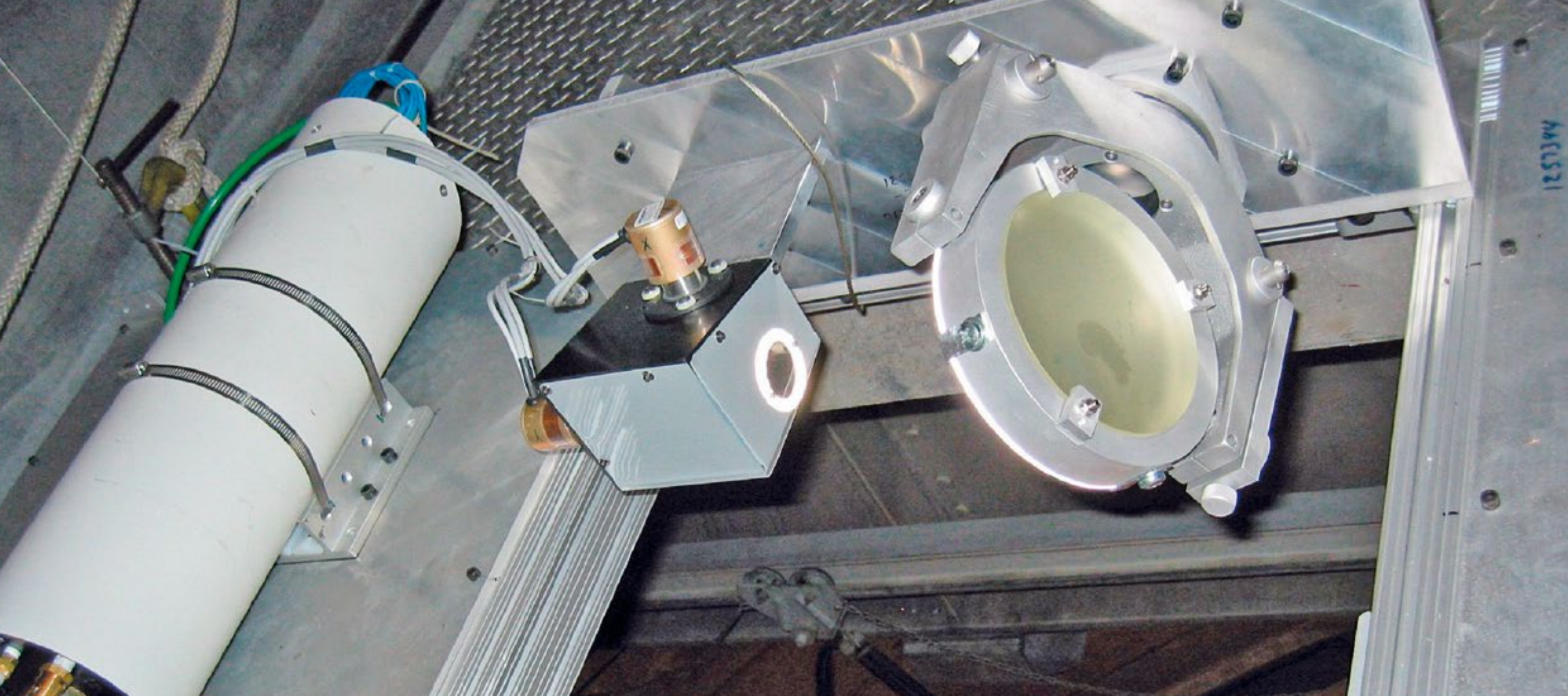
A Polytec Scanning Laser Vibrometer system was the main instrument used to measure the vibration modes. The laser scan head was placed inside a pressurized canister to protect it from the vacuum environment (Figure 4). The canister had a window port from which the laser exited, and a forced air cooling system prevented overheating. A Scanning Mirror System (SMS) was developed and implemented, that allowed full-field measurements of the sail from distances in excess of 60 meters within the vacuum chamber.

1
Inflatable 4x6-meter communications antenna concept

2
Deployed 20-meter solar sail on vacuum chamber floor

3
Vacuum chamber facility

4
PSV Scanning Vibrometer in pressurized canister



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Scanning mirror system inside vacuum chamber

The SMS (Figure 5) was mounted near the top of the vacuum chamber facility and centered over the test article, while the vibrometer head was mounted above the door frame of one of the large chamber doors. The SMS contained a stationary mirror that reflected the Polytec laser beam to a system of two orthogonal active mirrors.

These mirrors were used to scan the surface of the sail to find retro-reflective targets previously attached to the sail surface. These targets were essential to getting a good return signal and overcoming the specular nature of the reflective sail surface.

Fully automated test procedure

A specially developed target tracking algorithm enabled automatic centering of the laser beam on each retro-reflective target. The initial laser system alignment, target tracking process, and entire data acquisition procedure was automated using the Microsoft Visual Basic (VB) programming language. Polytec's VB Engine and PolyFileAccess allowed the program to control all the functional capability of the Polytec system. The alignment of the vibrometer laser to the SMS steering mirrors was accomplished by software that used the vibrometer scan mirrors to trace out a square grid across a retroreflective target ring on the SMS. The strength of the laser return signal was measured during the scan. The software finds the angular location of the center of the target by calculating the centroid of this array of signal strength values and the corresponding mirror angles.

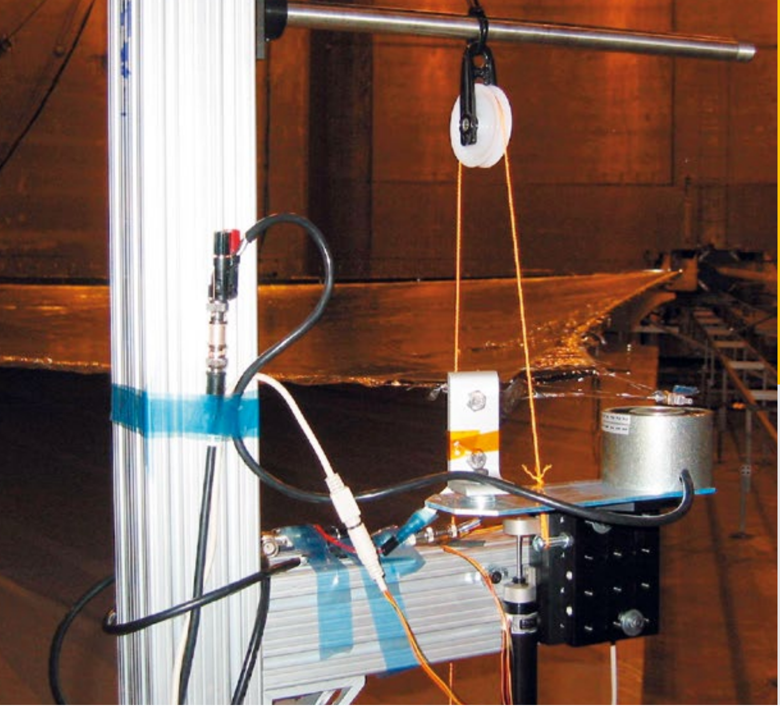
Once the laser was aligned to the SMS, a second program aligned the laser to the targets on the solar sail using the SMS steering mirrors. When all the targets were aligned and identified, then a third program incrementally read the target locations from a file and ran the entire data acquisition and storage process.

For each target, the program would re-scan and center the laser prior to acquisition to ensure the highest quality dataset. This fully automated test procedure was considered critical, since many tests could take over 5 hours to run. Prior to the test, the vibrometer and SMS were certified for an 85-meter standoff distance (although larger distances are possible), well beyond the required distance of 60 meters for this test configuration.

Excitation of sail motion

The baseline excitation method for the solar sail dynamics test used an electro-magnet mounted at each sail membrane quadrant corner near themast tip (2 magnets per sail quadrant), for a total of 8 magnets. A side view of the mounting fixture is shown in Figure 6. The magnet is mounted on a vertical translation stage with a linear actuator for precise, remote in-vacuum positioning of the magnet. The magnet needs to be positioned within 5 mm of the sail to work properly, so small cameras were positioned next to each magnet and carefully aligned to ensure that the proper gap size was achieved. To reduce sail motion during vacuum pump down, the mast tips were secured with an electro-magnet that prevented vertical and lateral motion. Once at vacuum the voltage to the electro-magnet was removed, allowing a spring to pull the magnet away from the test article. The mast tips were then free to move with a soft suspension system gravity off-loader.

Most of the dynamics testing effort was focused on getting the best quality data possible on a single quadrant invacuum. The quadrant that had the most pristine sail membrane surface with few flaws was selected. The quadrant test used only the magnets on the quadrant of interest for stimulating the dynamics. The quadrant test was followed by a full sail system test, in which one corner magnet on each quadrant is driven simultaneously.



6
Magnetic exciter system configuration

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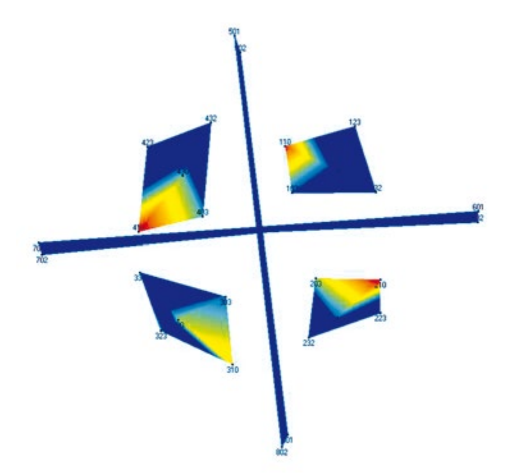
This technique allowed for adequate excitation of the entire sail system and for the identification of major system level vibration modes. To reduce test time, the full sail system test only measured 5 sail membrane locations per uadrant and two mast tip measurements per mast. Since the test article configuration did not change from the quadrant tests to full sail system tests, the high spatial resolution quadrant test results with 44 measurements per quadrant could be compared with the lower spatial resolution system test results with only 5 measurements per quadrant.

Solar sail dynamics

The 1st fundamental system mode of the solar sail identified was a "Pin Wheel Mode" with all quadrants rocking in-phase (Figure 7) at a frequency of 0.5 Hz. In this mode all the mast tips are twisting in-phase and the quadrants follow the motion by rocking and pivoting about the quadrant centerline. The 1st sail membrane mode, that has low mast participation, is a breathing mode (Figure 8) at 0.69 Hz. In this mode, the sail quadrant undergoes 1st bending through its centerline. Other higher order sail dominant modes were also found in which the long edge of the quadrant is in 1st bending, but the centerline undergoes either 2nd or 3rd order bending. These test results are important for updating structural analytical models that can be used to predict the on-orbit performance of the solar sail, free of gravity, to aid in further design iterations.

Conclusions

Laser vibrometry was successfully used to identify the fundamental solar sail system modes for structural model correlation. Also, higher order sail membrane modes were identified through a combination of many tests on each quadrant. The methodology described in this article is being further utilized for other Gossamer test programs, such as the antenna technology development program to validate large space based communication antennas. We would like to thank NASA for granting permission to publish this article.



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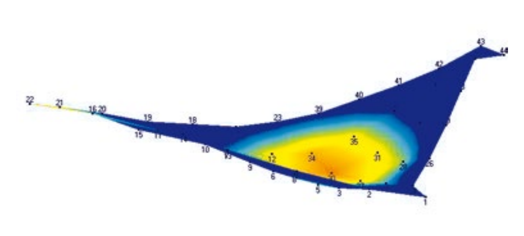
1st fundamental solar sail system mode (0.5 Hz)



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1st sail membrane mode (0.69 Hz)