Strain Monitoring of Flexible Structures

Draft Paper – Submitted on 6/6/16 for Structures Technical Forum, AIAA SciTech 2017

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I. Introduction

One of the biggest challenges facing NASA's deep space exploration goals is structural mass. A long duration transit vehicle on a journey to Mars, for example, requires a large internal volume for cargo, supplies and crew support. As with all space structures, a large pressure vessel is not enough. The vehicle also requires thermal, micro-meteoroid, and radiation protection, a navigation and control system, a propulsion system, and a power system, etc. As vehicles get larger, their associated systems also get larger and more complex. These vehicles require larger lift capacities and force the mission to become extremely costly. In order to build large volume habitable vehicles, with only minimal increases in launch volume and mass, NASA is developing lightweight structures.

Lightweight structures are made from non-metallic materials including graphite composites and high strength fabrics and could provide similar or better structural capability than metals, but with significant launch volume and mass savings. Fabric structures specifically, have been worked by NASA off and on since its inception, but most notably in the 1990's with the TransHAB program. These TransHAB developed structures use a layered material approach to form a pressure vessel with integrated thermal and micro-meteoroid and orbital debris (MMOD) protection. The flexible fabrics allow the vessel to be packed in a small volume during launch and expand into a much larger volume once in orbit. NASA and Bigelow Aerospace recently installed the first human-rated inflatable module on the International Space Station (ISS), known as the Bigelow Expandable Activity Module (BEAM) in May of 2016. The module provides a similar internal volume to that of an Orbital ATK Cygnus cargo vehicle, but with a 77% launch volume savings.

As lightweight structures are developed, testing methods are vital to understanding their behavior and validating analytical models. Common techniques can be applied to fabric materials, such as tensile testing, fatigue testing, and shear testing, but common measurement techniques cannot be used on fabric. Measuring strain in a material and during a test is a critical parameter for an engineer to monitor the structure during the test and correlate to an analytical model. The ability to measure strain in fabric structures is a challenge for NASA. Foil strain gauges, for example, are commonplace on metallic structures testing, but are extremely difficult to interface with a fabric substrate. New strain measuring techniques need to be developed for use with fabric structures. This paper investigates options for measuring strain in fabric structures for both ground testing and in-space structural health monitoring. It evaluates current commercially available options and outlines development work underway to build custom measurement solutions for NASA's fabric structures.

II. Current State of the Art

NASA's current fabric structures are used as pressure vessels made from a layered composition of high strength materials. The two primary layers of all fabric pressure vessels are the bladder layer, which holds the internal air and pressure, and the restraint layer, which is the structural layer that takes the loads from the internal pressure and any attached systems. The restraint layer is the most important from a structures standpoint and is the critical loading path where strain is measured. Depending on the vehicle geometry and mission, the restraint layer is composed of a single broadcloth, a weave of flat straps, a pattern of cylindrical cordage, or a combination of two or all three. The broadcloth configuration is typically made of a woven fabric that carries load in multiple directions, much like an orthotropic composite layup. The flat strap and cylindrical cordage, however, carry load uniaxially through the length of the material. To create a successful flexible strain gauge, then, measuring loads in all three configurations: broadcloth, flat straps, and cylindrical cordage will be considered and evaluated.

Current ground testing of NASA's inflatable structures use non-contact videography systems, known as photogrammetry, to measure strain and deflection of the fabric surfaces. This technique produces very accurate results and very high resolutions. This method has been used on both a flat strap surface and a broadcloth surface with good

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results. The technique is very dependent on lighting conditions and works well in a controlled test setting, but is difficult to complete outdoors with sun movements throughout the day. Photogrammetry is also challenging to use on a large scale pressure vessel. The resolution of the camera system is fixed, so moving the camera closer or father from the test article will result in a change in resolution of strain data. For a large test article, then, multiple photo systems are necessary to full encompass the structure. While this system does work well on the ground, it cannot be used effectively in space without additional hardware to hold and fix multiple camera locations. Alternate methods that are embedded or integrated into the structure are preferred for on-orbit strain measuring systems.

The NASA Hypersonic Inflatable Aerodynamic Decelerator (HIAD) is a fabric structure made of concentric inflatable tubes that form a heat shield for Mars deceleration. It is made of similar high strength materials as the pressure vessels explained above, with both broadcloth and flat straps making up the structural components. The HIAD team has tested the system in ground testing and high altitude deployment testing. In order to measure the strain and load in the fabric components, they have used a series of devices, including a high elongation foil strain gauge. The foil gauges are adhered directly to an epoxy substrate that is first installed on the broadcloth fabric. The epoxy forms a composite with the broadcloth and creates a surface for the strain gauge to be bonded. The gauges are then bonded to the composite surface and are connected to a data acquisition system. The team has also used seat belt tensioning gauges on the flat straps to measure the load in the straps. These devices attach around a strap and utilize a three-point bending mechanism that correlates the amount of bending in the device to the tension in the strap. Both the tension gauge and the foil strain gauges proved to provide accurate and reliable structural data in both ground and flight testing. Because of their effective results, these devices are included in the evaluation for fabric structure measurements described in this paper.

III. Gage Descriptions

Fabric materials are very flexible and have higher moduli of elasticity than metals. They produce high-elongation strains that can range between 5-50%, depending on their material stiffness and the applied load. A strain gauge for a fabric needs to be in intimate contact with the material and have a higher modulus than the substrate so that strain can be transferred to the measuring device without any stiffening effects from the device onto the substrate material. It should be integrated on a material or sub-component level to minimize any snagging hazards or interference with other components. The device also needs to withstand the same folding and packing conditions that the fabric structure will see prior to launch and deployment. The deployment phase is a dynamic event and will induce strains on the fabric that need to be captured. The strain measuring device, then, needs to be able to withstand and measuring peak dynamic loads. Once deployed, the strain gauge will be measuring material strain for the remainder of its life. To be used as a structural health monitoring system, it should be capable of measuring a constant strain over an extended period of time, potentially years, without any loss of signal or resolution.

The most common type of device for strain measurement is based on a change in resistive properties. A conductive material has a known resistance in its free state and that resistance changes when the material is stretched. Applying an input excitation voltage into the resistor, we can measure the output voltage and correlate the change in resistance to a change in length and thus a strain. A Wheatstone bridge is also used to clean and amplify the results. A typical foil strain gauge operates on the same principle. Another type of device, a capacitance based sensor, works in a similar way, but instead of a changing resistance, it measures a changing capacitance that can be correlated to stretch and strain.

We have identified commercially available “stretch” gauges and a number of available conductive materials that can be used as strain sensors. We are also working on unique, custom gauges that better fit our project requirements. A list of the current gauges and materials under review is shown in Table 1 below and described as: 1) The High Elongation Foil Strain Gauge is a typical metallic gauge, but uses a substrate that allows for greater elongations up to 10%. Using the techniques derived from the HIAD project, we will adhere the gauges directly to a broadcloth and strap to get strain measurements. 2) A Clip Strain Gauge is an alternate method to get high elongations using standard foil gauges. A metallic clip is adhered to the broadcloth or strap and the strain gauge measures the bending of the ends of the clip and indirectly measures the strain in the substrate. 3) A Conductive Paint or RTV changes resistance based on surface area and volume. We can paint the conductive material directly onto the surface of the broadcloth and measure the change in resistance as it is pulled in tension. 4) A Conductive Thread Coverstitch is a collaborative device developed at the University of Minnesota as a stretch sensor for smart clothing. The conductive thread is stitched in a way that changes the resistance as it is stretched. The device can be sewn into the broadcloth material directly. 5) The Conductive Polymer Cord is used in robotics as a stretch sensor and acts like a rubber band that changes resistance as it is stretched and released. It can be adhered or sewn at its ends directly into the material. 6) The StretchSense Fabric Sensor is a capacitive based stretch sensor made by StretchSense Ltd. from New Zealand.

The sensor is commercially available and has an integrated battery, circuit board and Bluetooth module for data logging on a Bluetooth enabled device. It is made of fabric and can be directly stitched into the broadcloth. 7) NanoSonic Metal Rubber is made by NanoSonic Inc. from Virginia. It is a highly elastic conductive material that can be adhered or sewn into a substrate and changes resistance as it is stretched. 8) The Novatech Seat Belt Tension Gauge is typically used in the automobile industry to measure seat belt loads. It uses a metallic fixture of three beams that bend when the strap is tensioned. Internal strain gauges measure the bending and correlate that to a strap tension. They have been used successfully in the HIAD project with high accuracy and high reliability. 9) An In-Line Load Cell has traditionally been used for crane operations to measure the weight or mass of lifting objects. It can be placed in-line of a high strength cord to measure the tension in the cord. The load cell has to be placed in-line however, so the cord has to be split and terminated at the ends to interface with the load cell. 10) A custom tension measuring device is under development that can measure the in-line tension of a cord without having to split the cord. It is still under development, but will be included in this evaluation test program.

Table 1. List of Devices Being Evaluated.

#	Gauge Name	Application
1	High Elongation Foil Strain Gauge	Broadcloth, Strap
2	Clip Strain Gauge	Broadcloth, Strap
3	Conductive Paint/RTV	Broadcloth, Strap
4	Conductive Tread Coverstitch	Broadcloth, Strap
5	Conductive Polymer Cord	Broadcloth, Strap, Cord
6	StretchSense Fabric Sensor	Broadcloth, Strap
7	NanoSonic Metal Rubber	Broadcloth, Strap, Cord
8	Novatech Seat Belt Tension Gauge	Strap, Cord
9	In-Line Load Cell	Cord
10	Custom Tension C-Gauge	Cord

IV. Test Program

The candidate gauge devices will be evaluated in a series of mechanical tests to compare their performance. The tests include: 1) low-rate tensile tests to evaluate their sensitivity to small changes in length, 2) long-term creep tests to record any loss of signal under a sustained load, 3) cyclic tests to identify any hysteresis or timing issues of the resistivity changes over cyclic loading, 4) dynamic tensile loading tests to track the device behavior in high-rate deployment scenarios. Beside these four main tests, additional testing will be completed to evaluate the device’s sensitivity to packaging and adhesion with the substrate material. Additional considerations such as electrical resources needs will be evaluated in future phases of this investigation.

V. Preliminary Results

The test program described is currently in work, but some preliminary results are available. The Conductive Paint/RTV device has been tested with a flat strap test specimen. It showed a good correlation in a low-rate tensile test, but exhibited hysteresis during cyclic testing. The resistance value also progressively lowered over time during the sustained load test and does not appear to be a good candidate for fabric structure health monitoring. The Conductive Polymer Cord behaved similarly with greater hysteresis on a sustained load test than the paint or RTV. It is suspected that this is due to the polymeric nature of the material. As the load is held, the polymer chains align and the internal resistance decreases. The Conductive Thread Coverstitch device showed only slight hysteresis, but very noisy data. This was due to the quality of stitches installed on the flat strap. A refined stitching method is in work with positive results. The StretchSense Fabric Sensor showed excellent results in the low-rate tensile and cyclic tests. It also shows little to no hysteresis in the creep test. The Novatech Seat Belt Tension Gauge and the In-Line Load Cell were very reliable gauges during all of our tests. However, these tests were only done with single cords and no interaction of other materials. The design of the fabric structures, however, offers some interaction between the cord and the broadcloth and may cause issues with these types of devices. The Custom Tension C-Gauge is still under development and the Foil Strain Gauges have yet to be tested.

VI. Forward Work

The remaining work for this test program is on schedule to be completed by August 2016. At the conclusion of the test program, a complete report will be made on the results and conclusions. After this phase, the candidate devices will be down-selected and further testing will be completed on the top performers. Future full scale pressurized testing of fabric structures will be completed using these devices for evaluation. They will be compared directly to the current state of the art photogrammetry systems. With those results, the last project phase is to scale the devices into a network to be installed and provide full coverage as a structural health monitoring system for a fabric structures. This type of system will ensure that future fabric structures stay safe during their operational life and work successfully as designed.