Space Habitat Restraint Layer Strain Measurements

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***Abstract*— NASA is exploring the use of woven straps for restraint layers in inflatable structures. This initial work investigates the use of microwaves to measure the strain in a woven restraint layer strap during loading. Microwaves are transmitted through a section of the Vectran strap under load from one Vivaldi antenna to another Vivaldi antenna, and the data is fitted to measured displacement, load, and strain data. The results for the three measurements and the antenna data from are presented.**

Keywords*— *Microwave, Electromagnetic, Inflatable, Woven Straps, Strain, Space

I. Introduction

NASA has investigated inflatable structures since Dr. Wernher von Braun proposed an inflatable space station in 1952 [1]. NASA has tested several structures in space including an inflatable satellite, ECHO 1, which was launched in August 12 1960 [2], an inflatable module called BEAM which was installed on the International Space Station (ISS) in April of 2016 [3], and an inflatable reentry structure the Hypersonic Inflatable Aerodynamic Decelerator (HIAD) [3] which was flown in 2009.

This work seeks to address risk mitigation for inflatable structures by investigating the use of microwaves to detect load/strain changes in woven straps used for the restraint layer. "The restraint layer is the most important from a structures standpoint and is the critical loading path where strain is measured" [4]. Previously, NASA investigated six methods to measure strain in inflatable structures: a high elongation foil strain gauge, a conductive paint, a conductive thread cover stich, a conductive polymer cord, Nano Sonic Metal Rubber, and a capacitive StretchSense fabric sensor [4]. Although each sensor has its strengths and weaknesses, two were selected to be used in future missions: the Foil Strain Gauge and the StretchSense Fabric Sensor. In addition, other research in the area of instrumenting Kevlar straps for softgoods structures includes aerosol-jet-printed capacitive strain gauges [5], instrumentation of stratospheric balloon straps with optical fibers for temperature and strain monitoring [6], a stitch-based strain sensor for woven lashing straps [7], and a highly elastic strain gauge for low modulus materials [8]. However, these methods require wires for the sensors. Wires are at risk of breaking due to flexure during the folding of the deflated structures and unfolding during inflation. The proposed technique uses the response of microwaves transmitted from a Vivaldi antenna through the Vectran strap to a second Vivaldi antenna. The transmitted microwaves are affected by and correlate to the mechanical deformation,

Fig. 1. Inflatable Damage Tolerance Test (DTT) Article [9].

presumably due to changes in the dielectric constant (the real component of electrical permittivity) and a change in the distance between the antennas. The wires for the antenna can be located at the top and bottom of the inflatable structure/strap where minimal folding, if any, occurs. For structures with metallic end caps supporting strap attachment through clevises, the wires do not require folding as they travel between the end cap electrical penetrations to the clevises. Therefore, this effort investigates potential interrogation techniques compatible with end cap to end cap microwave measurements.

This microwave sensing technique relies in part on the change in the overall relative permittivity (effective dielectric constant) of the strap as the loading is changed. It has been found in prior work that mechanical deformation of woven textiles changes the relative permittivity [10]. For the work presented here, the fibers that compose the strap become closer together as the load is increased, which will affect the permittivity of the straps. The change in the permittivity causes both an amplitude change and a shift in the frequency response (spectral shift) of the S21 data. Spectral shifts and amplitude changes of the S21 data are also caused by changes in the distance between the antennas as the strap deforms (stretches) under loading conditions. A post processing method that can reduce the dimensionality and yield useful strain or load information is necessary. Spectral centroiding (SC) [11], cross-correlation (XC) [12], and principal component analysis (PCA) [13] have been demonstrated in previous microwave sensing applications. This work explored the results of applying all three post-processing methodologies to both the raw S_{21} (transmission coefficient) data and the phase of the S_{21} data of the restraint layer straps for inflatable structures. The PCA method yielded the best data of the three techniques. Due to page limitation, only the results from the PCA method are presented here.

II. Test Setup

The test setup consists of a 50 kip load frame with split-capstan grips on which a Vectran 12K (lbs.) strap is attached (Fig. 2). Two Vivaldi antennas are clamped to the strap, 76.2 mm apart. The antennas are placed on the front and back side of the strap, so that the microwaves must pass through the length of the strap from the transmitter to the receiver. The antennas are connected to a Fieldfox network analyzer. A laptop connected to the network analyzer and the load frame records antenna response, load, and displacement via LabVIEW. A separate strain measurement was achieved from a digital image correlation photogrammetry system.

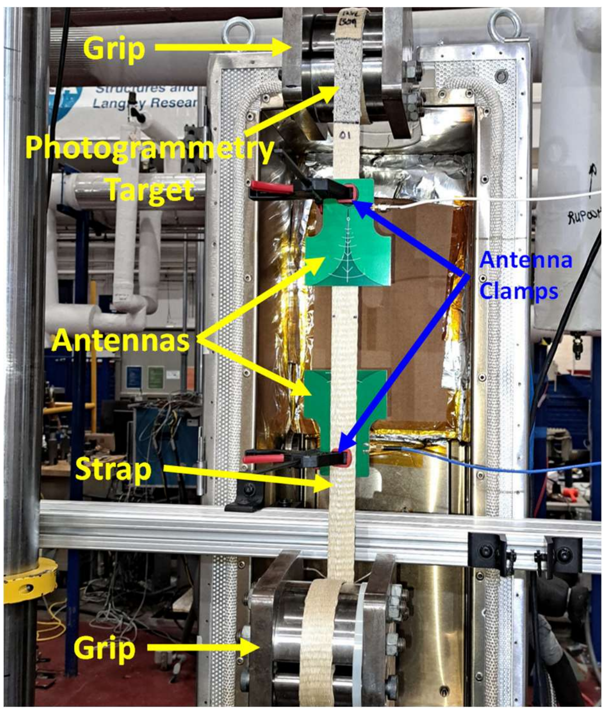

Fig. 2. Load frame test setup, showing the grips, photogrammetry target, Vectran strap, and the Vivaldi antennas.

III. Results

The test run starts by loading the specimen up to 500 lbs. The specimen is then ramped up sequentially to 1K, 2K, 4K, 6K and 8K lbs., then back down to 500 lbs. with 70 second dwell periods in between. Throughout the run the network analyzer takes a dataset of 1601 points of S_{21} frequency response data (magnitude and phase) from 1 to 10 GHz, every 2 seconds. The entire sequence of 554 sets of 1601 points of raw S_{21} magnitude data shows changes but not a clear trend that would correspond to a useful measurement (Fig. 3). Therefore, further post

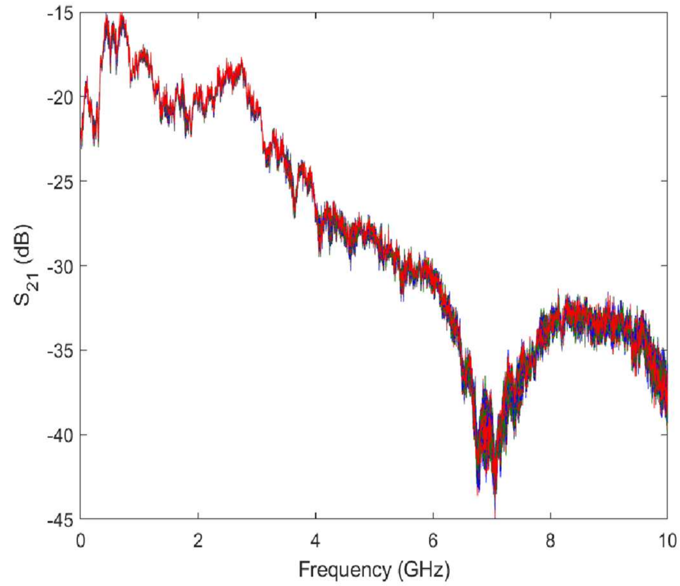

Fig. 3. Plot of the full sequence of raw S_{21} response, 554 sets of 1601 points of frequency data from 1 to 10 GHz, for a full load sequence from 500 lbs to 1K, 2K, 4K, 6K, 8K lbs, then back down to 500 lbs.

processing is needed to reduce the large number of points per dataset. This necessitates some form of dimensionality reduction to produce a single measurement value from each dataset. As mentioned earlier, the PCA method worked best for dimensionality reduction. The PCA of the S_{21} amplitude can be fitted using:

$$fit = -1.525e{-17}\, x^2 + -1.034e{-8}\, x + 1.107\,, \quad (1)$$

where x is the first PCA coefficient of the S_{21} amplitude data.

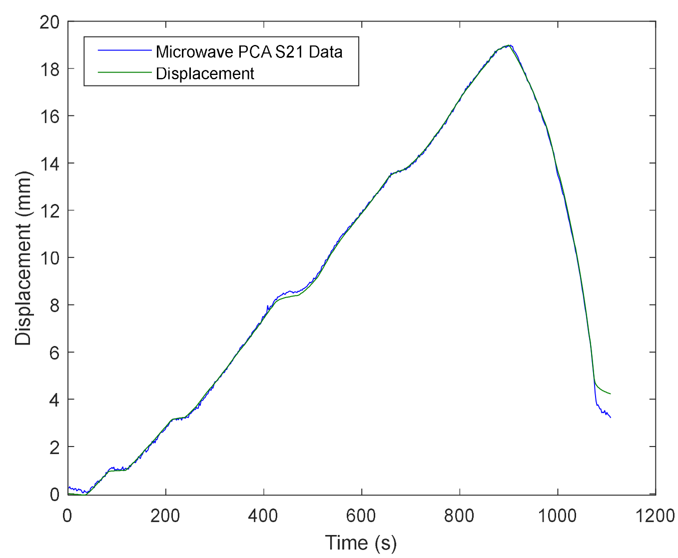

Fig. 4. Plot of the fitted PCA S_{21} data to the measured displacement. Note that the displacment is zeroed out initially when the starting load is at 500lbs.

The amplitude changes from the PCA of the S_{21} data match the closest to the displacement (Fig. 4). However, there are discrepancies at the beginning, and hysteresis at the end of the run.

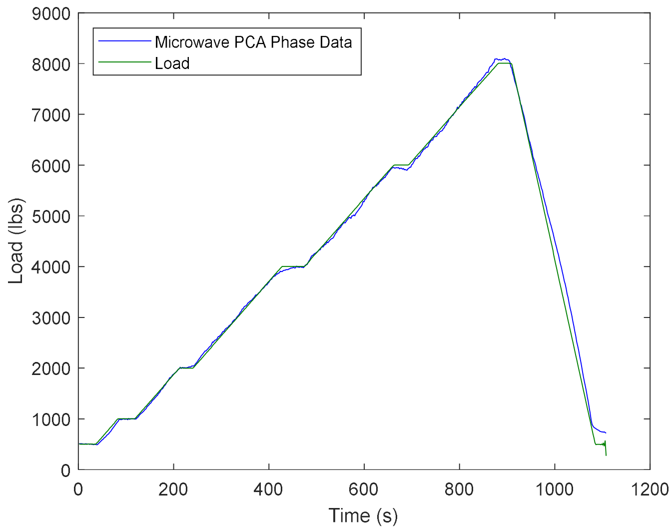

Fig. 5. Plot of the fitted PCA phase data to the measured load.

Meanwhile, the PCA of the S_{21} phase data was fitted to the load measurements using:

$$fit = 11.5x^2 + 411.8x + 3667 \,. \quad (2)$$

The results of the fit to the load match well, except for hysteresis at the end of the run (Fig. 5). Next the PCA of the S_{21} phase data was fitted to the strain measurements using:

$$fit = 9.049\text{e-}7\, x^3 + 9.509\text{e-}6\, x^2 + 0.0008318x + 0.007127. \quad (3)$$

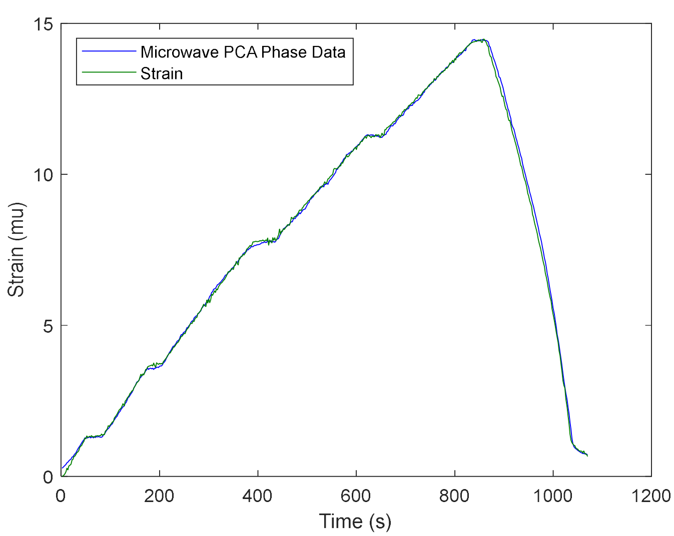

Fig. 6. Plot of the fitted PCA phase data to the measured strain. Note that the strain is zeroed out initially when the starting load is at 500lbs.

The results of the fit to the strain match the best, with only a small discrepancy at the beginning of the run, and no hysteresis at the end of the run (Fig. 6).

IV. Conclusions

It was demonstrated that measurements which correlate well with displacement, load, and strain can be performed by transmitting microwaves longitudinally through the straps. More specifically, fitted results from microwave S_{21} data taken during loading of the Vectran strap matched well to the displacement, load and strain. When the PCA method was applied to the phase of the S_{21} data, the results showed a closer match to the strain and load compared to the same method being applied to the amplitude of the S_{21} data. Since the goal is to monitor straps down their entire length, future work will include further testing to determine the maximum transmission distance between the antennas. In addition, the technique will be evaluated/tested with the antennas and straps surrounded by conducting layers of a realistic layup.

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