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STRAIN AND DYNAMIC MEASUREMENTS USING FIBER OPTIC SENSORS EMBEDDED INTO GRAPHITE/EPOXY TUBES

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1. INTRODUCTION:

Smart is defined by The American Heritage Dictionary as, "Of, relating to, or being a device that imitates human intelligence."[1] The concept of smart structures meets this definition.

Several planned United States Air Force (USAF) and National Aeronautics and Space Administration (NASA) space systems such as Space Based Radar (SBR), Space Based Laser (SBL), and Space Station, pose serious vibration and control issues., See figure 1. Their low system mass combined with their large size, extreme precision pointing/shape control and rapid retargeting requirements will result in an unprecedented degree of interaction between the system controller and the modes of vibration of the structure. The resulting structural vibrations and/or those caused by foreign objects impacting the space structure could seriously degrade system performance, making it virtually impossible for passive structural systems to perform their missions. There resides a need for creating an active vibration control system which will sense these natural and spurious vibrations, evaluate them and then dampen them out. This active vibration control system must be impervious to the space environment and electromagnetic interference, have very low weight, and in essence become part of the structure itself. The concept of smart structures also meets these criteria. Smart structures is defined as the embedment of sensors, actuators, and possibly microprocessors in the material which forms the structure, particularly advanced composites. These sensors, actuators, and microprocessors will work interactively to sense, evaluate, and dampen those vibrations which pose a threat to large flexible space systems (LSS). The sensors will also be capable of sensing any degradation to the structure. (Fig. 1.)

CORPORATE FED ARRAY / PHASED ARRAY
TYPICAL SPACECRAFT CONFIGURATION

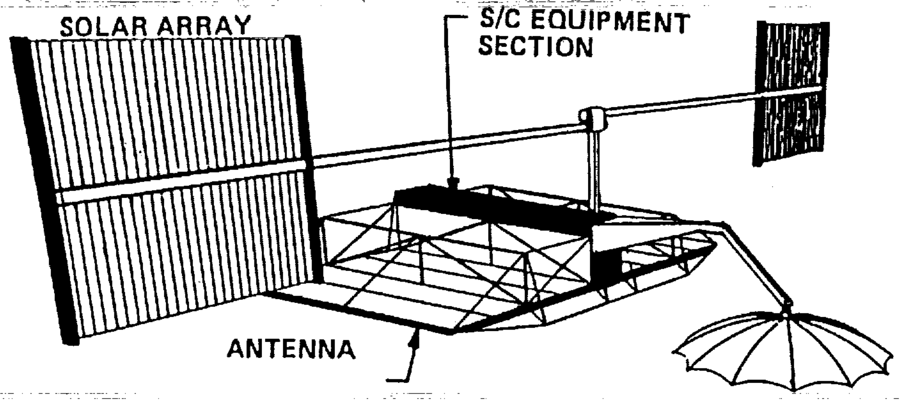


Figure 1

In conjunction with this problem, the Air Force Astronautics Laboratory (AFAL) and NASA Langley Research Center (NASA LaRC) have initiated a program to design, fabricate, and experimentally test composite struts and panels with embedded sensors, actuators, and microprocessors that can be used for dynamic sensing and controlling vibrations and motions in space structures. The sensors will also be able to monitor the health of space structures. This program is divided into four tasks. Task one is acquiring equipment necessary for embedding sensors and actuators into composite material. Baseline structures of aluminum and composite materials will be fabricated (coupons, flat panels, struts) to demonstrate concept feasibility. The baseline structures will be tested for stiffness, strength, and vibration for comparison with data from the structures that have embedded components. Task two will include the processing science studies required to process the composite components. Task three will include the fabrication of the selected composite struts with embedded components. Both sub-scale and full-scale struts will be fabricated. Task four will include non-destructive evaluation, mechanical testing, and vibration damping testing of the Task three components with the embedded control system for overall concept performance, endurance, reliability and response.[2] See figure 2.

SMART SPACE STRUCTURES PROJECT (IN-HOUSE)

I. Task one encompasses acquiring equipment necessary for embedding sensors and actuators into composite materials. Baseline structures of aluminum and composite material will be fabricated.

II. Task two will run parallel to Task I and will encompass studies of fabrication and processing technologies.

III. Task three will encompass the fabrication of subscale and fullscale composite structures with embedded sensors and actuators.

IV. Task four will encompass experimentation on the fabricated components. Such experiments will include non-destructive evaluation, mechanical testing, and vibration testing within a ground dynamic test facility.

Figure 2

The AFAL has been working in the area of dynamics and control of LSS for the past five years. They have had numerous programs, both contractual and in-house, to develop sensors and actuators for controlling LSS. Presently the AFAL is developing a large scale laboratory, called Advanced Space Structures Technology Research Experiments (ASTREX), which will have the capacity of performing large angle rapid retargeting maneuvers and vibration analysis on LSS. Also they have been fabricating advanced composite materials for the last four years. However, most of the composite components that were fabricated were rocket components such as: nozzles, payload shrouds, exit cones, and nose cones. For the last two years though, the AFAL has been fabricating composite space components such as trusses, tubes, beams and flat panels. Research on fiber optic sensors at NASA LaRC dates back to 1979. Recently an optical phase locked loop (OPLL) system has been developed that uses fiber optics for sensing. See figure 3. Static and dynamic strain measurements have been demonstrated using this device.[3]

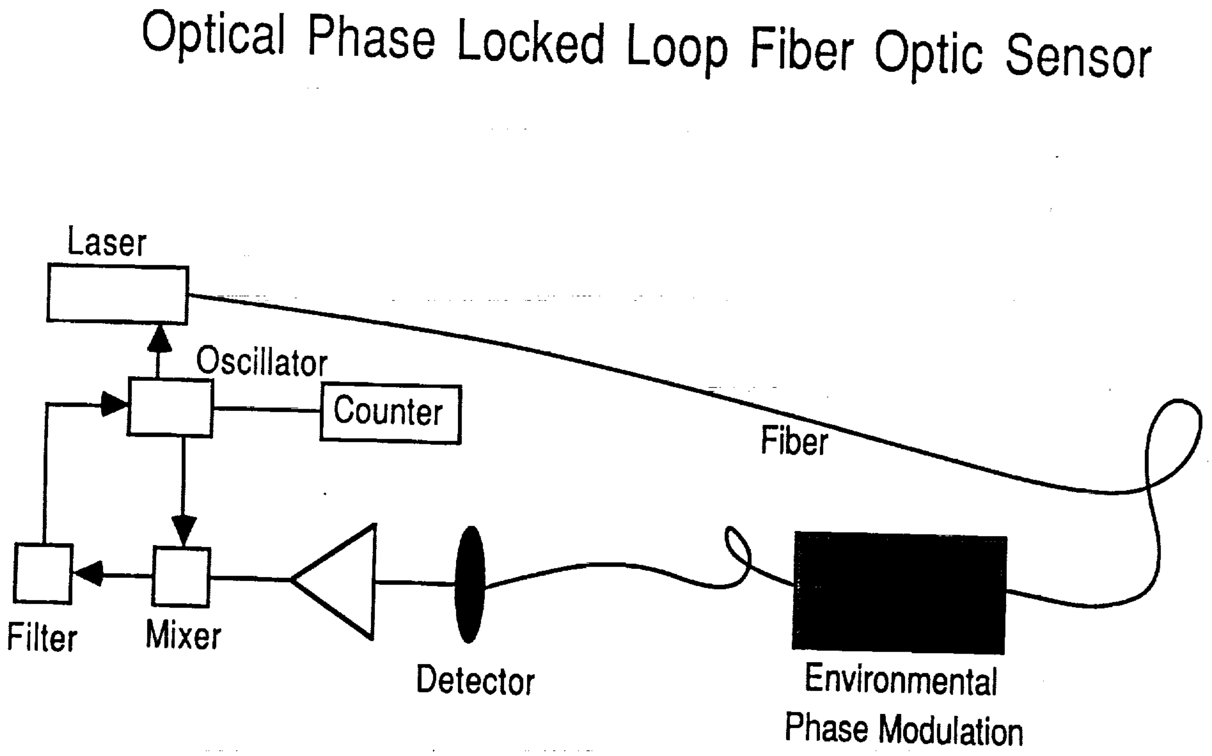


Figure 3

2. FABRICATION OF EXPERIMENTAL STRUTS

The first goal of the program is to demonstrate the feasibility of smart structures. A simple composite tube structure with a circular cross section was fabricated with a fiber-optic sensor embedded into it. The tube was chosen because it is a key structural element in most space truss systems. Optical fibers were chosen as the sensing element because of the demonstrated capability of the OPLL developed at NASA LaRC. To date, a total of three tubes fabricated at the AFAL have been tested at NASA LaRC. The results of two of these tubes are presented in this paper. All three tubes were fabricated in a similar manner, by filament winding on an En-Tec computer filament winding machine. The first two tubes were wound as one single tube on the same steel mandrel and then cut into two. The composite material used was graphite epoxy prepreg roving from Fiberite composed of medium strength G-40 graphite fibers from Union Carbide and 5245 epoxy resin. The single tube prior to cutting was approximately five and one half feet in length, with an inside diameter of one and one half inches. The single tube consisted of one layer of 90 degree fiber; two layers of +/- 45 degree fiber; and one layer of 90 degree fiber, with the fiber optics embedded under the final 90 degree layer. A schematic diagram of the tube lay-up is shown in figure 4. The fiber optics, made by the Newport Corporation, are F-MSD multimode fiber. The core has a diameter of 49 μm with a combined core and cladding diameter of 125 μm. They are coated with an acrylic jacket. The fiber optics were layed in longitudinally up to the center of the tube with both ends of the fiber coming out of the same end of the tube to prevent spurious vibrations of the fiber optics during the testing of the composite tube.

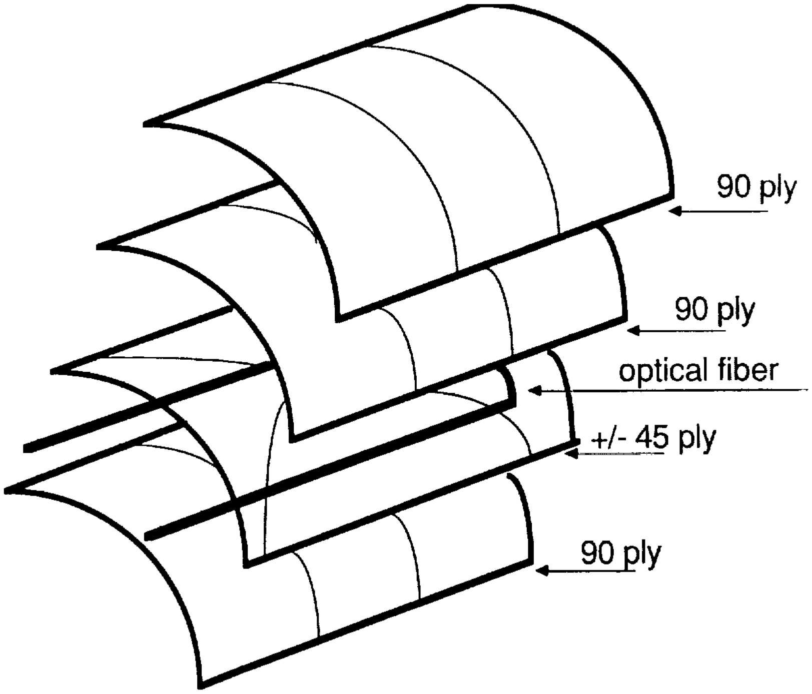


Figure 4

They were located every 90 degrees throughout the tube with a total of four sets of fiber optics embedded in the tube. After winding, the single tube was then bagged using standard bagging techniques. Special care was given in bagging the optical fibers since they are very delicate and fragile and due to the long leads coming out of the end of the tube. Prior to autoclaving, the optical fibers were coated with a high temperature silicone (RTV) coating. This coating prevents the flexible acrylic jacket from melting during the curing process which would then leave only the very brittle bare core and cladding and also acts as a stress relief where the optical fibers come out of the end of the composite tubes. The single tube was then placed in a Baron-Blaekslee autoclave and cured at 350 degrees F and 85 psia for four hours. Upon cooling, the tube was removed from the mandrel and cut in two, giving special care to the optical fibers. Both tubes were then packaged and delivered to NASA LaRC for strain and vibration testing. The third filament-wound tube was fabricated very similar to the first two tubes. The only differences were in the material, size, and the angle of the composite plies. The composite material used was graphite/epoxy prepreg roving from Fiberite composed of medium strength IM-6 graphite fibers from Hercules and 934 epoxy resin. The first tubes had a fundamental frequency of approximately 33 hertz when cantelivered. The third tube was designed to have a significantly lower fundamental frequency. A tube with a length of 68 inches and a ply orientation of 90-(+/-)60-90-90 has a fundamental frequency of 10 hertz. The fiber optics were embedded in between the 60 and the second 90 degree layer. In this tube only two sets of fiber optics were embedded at 180 degrees to one another. Also, the fiber optics did not come out of the end of the tube as in the first two tubes. The fiber optics came out of the circumference of the tube at a distance of four inches from the end of the tube. This change allowed clamping of the tube at the end without crimping the optical fibers. See figure 5.

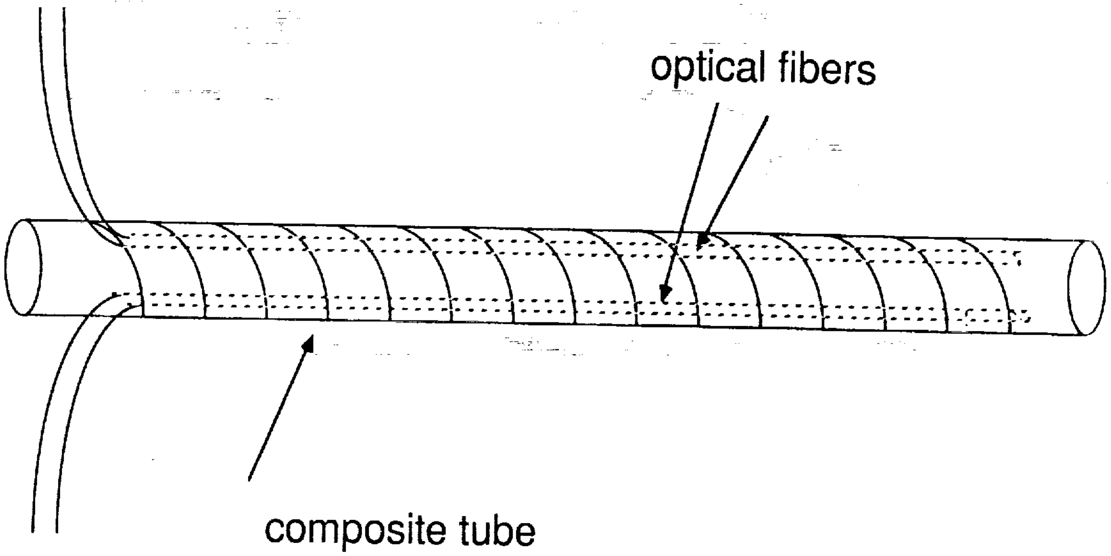


Figure 5

3. STRAIN AND VIBRATION MEASUREMENTS

The vibration and strain experiments were conducted at NASA Langley Research Center using a modulated diode laser and an optical phase locked loop (OPLL) system which is described in reference [3]. The optical fibers exiting the tube were fusion spliced to the fibers of the optical system. One end of the graphite/epoxy tube was clamped over a round piece of metal, which was inserted into the tube. For the first two tubes, this caused a problem with crimping of the optical fibers as they exited from the tube. For the first few readings, the data taken acted in a reverse fashion than as predicted. For the third tube, this problem was solved by having the fiber optics exit from the circumference of the tube, not from the end. The whole assembly was then clamped to an optical table to hold the end of the tube firmly in a cantilevered position. Four resistance strain gauges were attached longitudinally to the tube for comparison with the fiber optic sensors. The tube was statically stressed by hanging weights on a weight pan and attaching it to the free end. Data were taken while the weights were loaded and unloaded. When this force is applied to the tube, a strain is induced in the composite which in turn induces a strain into the optical fiber that produces a change in the modulation frequency of the OPLL. The optical fibers can measure both tension and compressive strain. This stain is governed by the equation change in frequency divided by the frequency is equal to the negative of the change in length divided by the length ($\frac{\Delta f}{f} = -\frac{\Delta L}{L}$). Strain on the surface of the tube was monitored with the strain gauges. The results of these experiments are shown in figures 6 and 7, which graphically indicate the correlation between the strain gauge measurements and the changes in modulation frequency. The data indicate very good correlation between the strain gauge readings and the fiber optic strain measurements. These runs were repeated with excellent reproducibility.

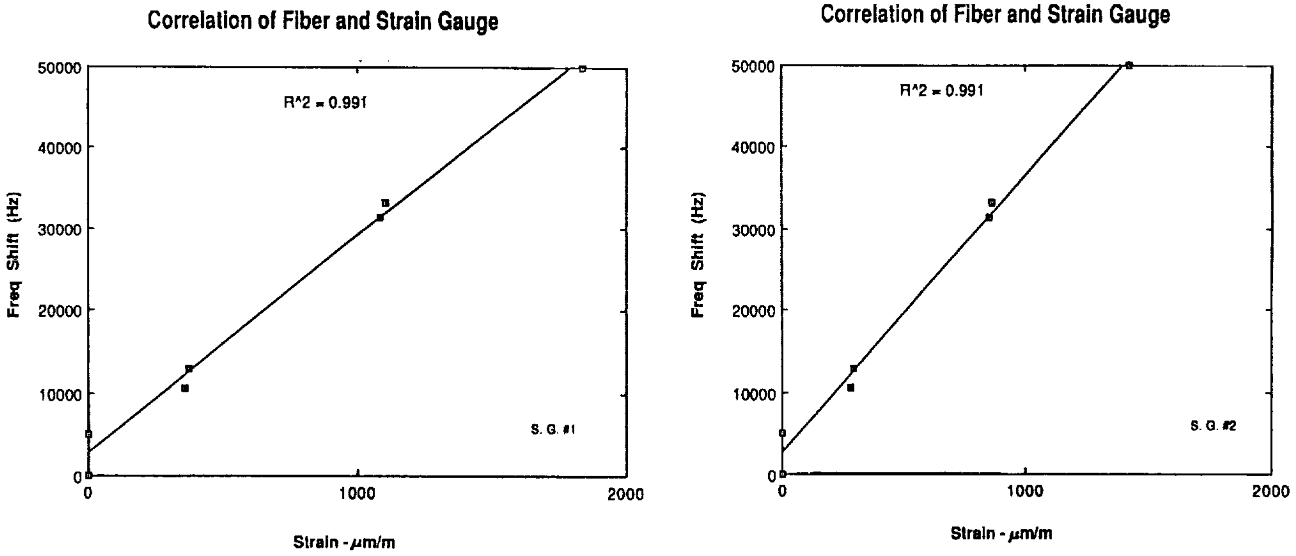
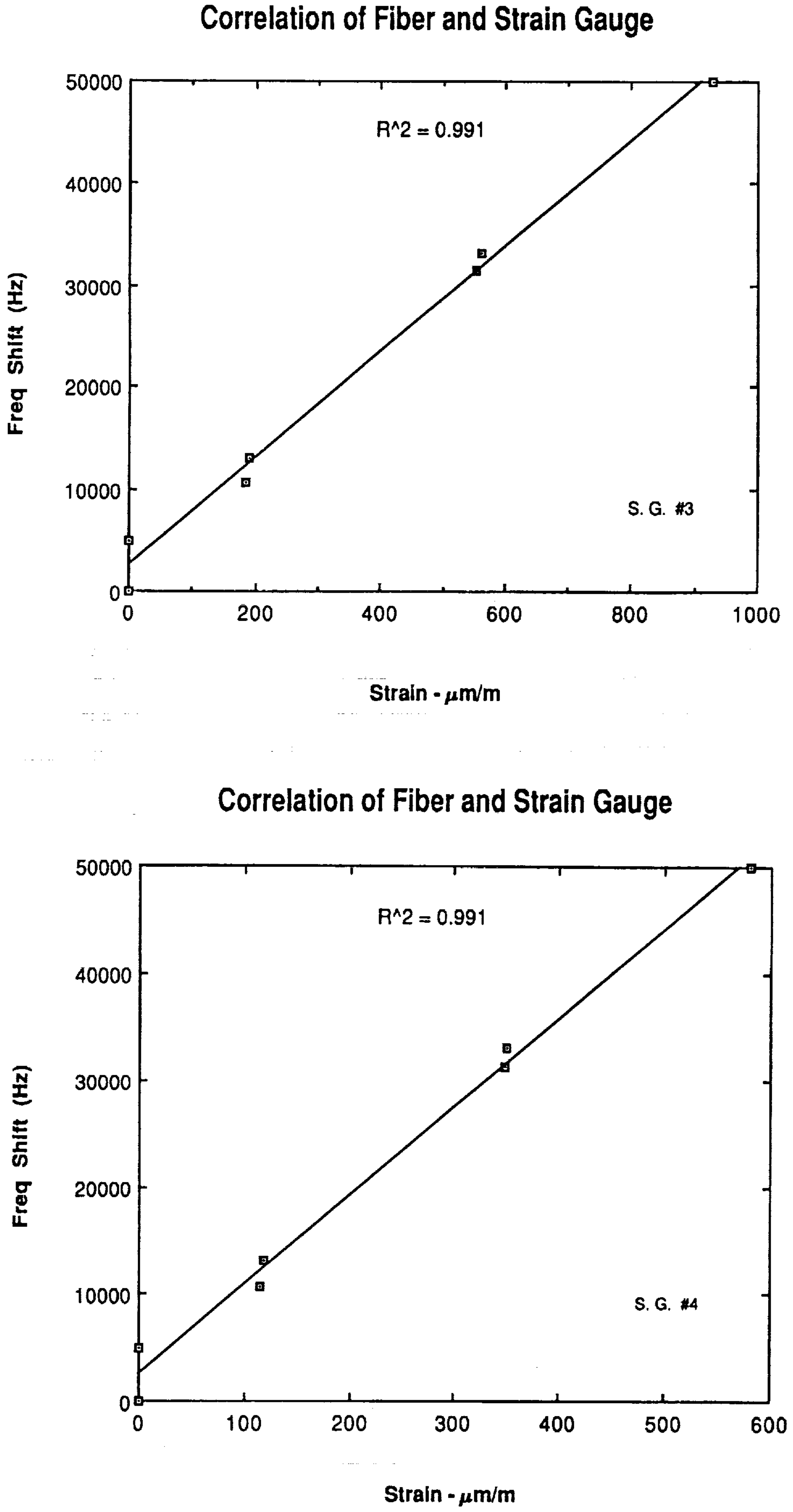


Figure 6


Correlation of Fiber and Strain Gauge
R^2 = 0.991
S. G. #3
Freq Shift (Hz)
50000
40000
30000
20000
10000
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200
400
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Strain - μm/m
Correlation of Fiber and Strain Gauge
R^2 = 0.991
S. G. #4
Freq Shift (Hz)
50000
40000
30000
20000
10000
0
0
100
200
300
400
500
600
Strain - μm/m

Figure 7

Strain measurements were also made while the tube was vibrating. The end of the tube was impacted and the vibration response was analyzed. Figure 8 compares the results obtained by simultaneously monitoring a strain gauge and the fiber optic signal for the third tube. The time domain and frequency domain data agree very well, showing a fundamental vibration frequency of 10.4 Hz, which is very close to the design vibration frequency of 10 Hz. As you can see from the data, the fiber optics can detect the vibration response significantly better than the strain gauges.

Dynamic Strain Measurements in G/E Tube

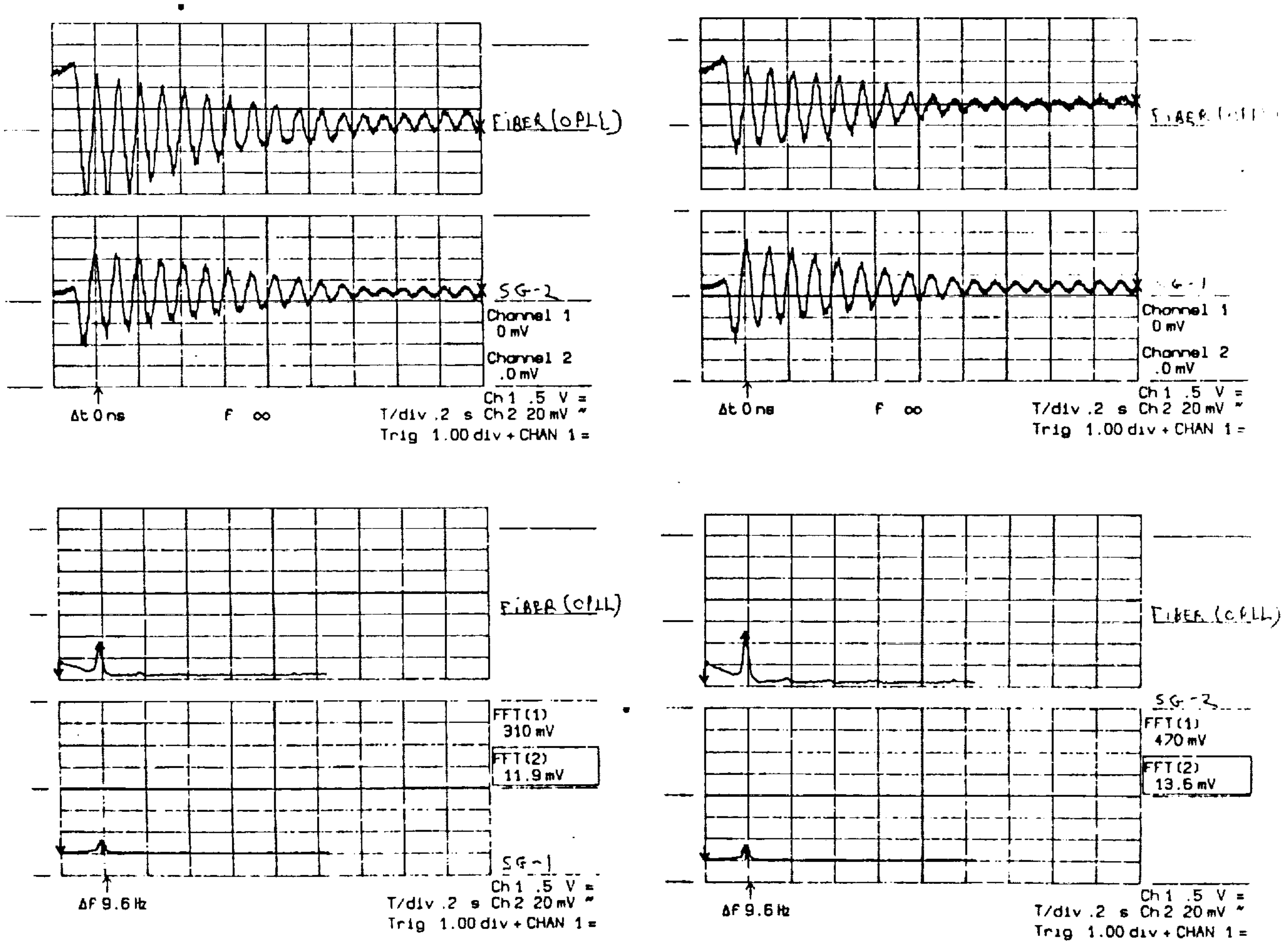

Figure 8

4. SUMMARY

Graphite / epoxy tubes were fabricated with embedded optical fibers to evaluate the feasibility of monitoring strains with a fiber optic technique. Resistance strain gauges were attached to the tubes to measure strain at four locations along the tube for comparison with the fiber optic sensors. Both static and dynamic strain measurements were made with excellent agreement between the embedded fiber optic strain sensor and the strain gauges. Strain measurements of 10^{-7} can be detected with the OPLL system using optical fiber. Because of their light weight, compatibility with composites, immunity to electromagnetic interference, and based on the static and dynamic results obtained, fiber optic sensors embedded in composites may be useful as the sensing component of smart structures.

REFERENCES

[1] The American Heritage Dictionary, Houghton Mifflin Co, Boston, MA 1982.

[2] Capt Ted Doederlein, Lt Douglas DeHart, Mr. Joe Sciabica, Smart Space Structures Project Directive, Air Force Astronautics Laboratory, Jan 1988.

[3] R. S. Rogowski, J. S. Heyman, M. S. Holben, Jr. and P. Sullivan, "A method for monitoring strain in large structures: Optical and radio frequency devices", Rev. Prog. Quant. NDE, vol 7a, p559 (Plenum Press, 1988).