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Alphonso C. Smith March 3, 1998

Subject: Final report for NASA Dryden Flight Research Center Grant # NAG4-0012, "Development of an Ultrasonic and Fabry-Perot Interferometer for Non-Destruction Inspection ~~of Aging~~ Aircraft"

The result of our research study is given in the attached final report. The experimental data obtained during the last year of the research was very convincing, and we are looking forward to advancing the work to develop a prototype system should there be funds available to advances the work to that stage.

Thanks for the support and we look forward to working with personnel at Dryden Flight Research Center on other research grants.

Note: There were no new inventions to be reported in this phase of the research

A list including a summary of accomplishments and other details of the work and student involvement is outlined below.

Summary of Accomplishments

- FPI sensor detection system was continued and refined modifications were made in the data acquisition and evaluation process during the last year.
- The ultrasonic and FPI detection system was improved from one to multiple sensor detectors.
- Physical models were developed to understand the physical phenomenon of this work.
- Multilayered flawed samples were fabricated for inspection by a prototype ultrasonic and FPI detection.
- Experimental data was verified with simulated results.
- Undergraduate students that were associated with this research gained valuable knowledge from this experience. This was a learning process helping students to understand the importance of research and its application to solve important technological problems.
- As a result of our students exposure to this research two and planning to continue this type of research work in graduate school.

- **A prototype instrument package was laboratory tested on actual airframe structures for documentation purposes.**

Relevance to NASA Strategic Enterprises, Benefits to Society and Student Achievements

This research support effort was obtained with the intent to help train underrepresented minority students enrolled in science and engineering disciplines at Hampton University. The objective of the proposal was to help NASA maintain its leadership in space, earth science and aeronautical research. We are seeking to help in this area by training our students in laboratory research programs directed toward solving state-of-the-art measurement problems. In so doing, we not only will help NASA meet its mission, but at the same time provide research training to underrepresented minorities and increase the pool of well trained scientist and engineers. Students graduating from Hampton University will then be in a better position to help meet the nation's critical manpower needs for engineers and scientist.

We envision our students becoming well trained in the areas of fiber optics sensor techniques, ultrasonics and instrumentation measurement science. This type of research program has provided an opportunity for our students to interact with researchers at NASA Langley Research Center. As a result of our students receiving support for three years on a program like this, directed toward a research effort, has greatly improve their research investigative skills and marketability.

Determination of Bond Quality of Aerospace Materials Using Fiber Optic Fabry-Perot Interferometer. A. C. Smith and V. Jagasivamani, Department of Electrical Engineering, Hampton University, Hampton, VA 23668.

Abstract

Fiber optic sensors have been designed and developed to inspect the bond quality of multilayered structures by applying temperature, load, and vibration to aerospace materials (e.g. aluminum 2024-T3). In this study, the fiber optic sensor was designed with a minimum airgap and was mounted at the front surface of the aluminum specimen. This sensor consists of two single mode optical fibers with a fixed airgap (airgap length ~5 to 10 μm) made within the two fibers. The minimum airgap was fabricated within the two single mode fibers and glued with a capillary tube. Laser light was injected into the sensor through a coupler. The change of phase in fiber optic interferometers are very sensitive with respect to temperature, load, and applied vibration changes. The temperature, applied load, and vibration, changes the optical properties within the fibers, at the gauge length. The intensity of the light within the fiber is modulated due to the strain-optic effect. The main focus in this paper is to determine the bond quality of material structures. This sensor can serve as a very useful tool for aircraft structures inspection. In this paper, experimental results of this type of sensor with variations in temperature, load, and vibration to the specimen are presented.

Introduction

There is a considerable amount of attention on Fiber Optic Fabry-Perot Interferometer sensors used for aerospace materials characterization. Currently, the aerospace industry has two major needs: 1) reliable nondestructive testing methods to assure safety of the aircraft life and 2) rapid test procedure to conduct inspections economically. Several groups have demonstrated the possibility of using optical fibers for inspection of temperature and pressure (1-5). G.B. Hocker (6) used Optical Fiber Sensors to sense the temperature and pressure by launching light waves within the optical fibers. Other groups have reported Fiber Optic Fabry-Perot Interferometer (FPI) sensors, used for strain measurements (7-10). This technique will definitely provide improved safety, especially when the aerospace industry consider to inspect aircraft structures by using a cost effective and reliable instrument.

The fiber optic sensor becomes an important inspection tool for many applications, such as aerospace industry, military airplane inspection, and medical diagnostics. This sensor mainly employs the study of the strain-optic effect. A specially designed inspection sensor for bond quality inspection for the first time was the key element in this work. In this paper, Fabry-Perot Interferometers (FPI) were designed and developed for sensing these parameters. This technique has the potential to detect defects within aerospace material. The performance of the optical sensor is discussed and how inspecting of defects can be employed for health monitoring in aerospace materials. This technique allows the detection of temperature, strain, and vibration in aircraft structure and has the potential to determine these parameters and quantify them. This technique can also provide information about the bond quality of the aircraft lap joints and doubler joints.

Fabrication of Fabry-Perot Interferometer

In this paper, extrinsic Fabry-Perot interferometers developed at NASA Langley Research Center were used to detect temperature, load, and vibrational wave, which were generated within the specimen. A single mode optical fiber was used to fabricate the FPI sensors. The diameter of the core was ~ 8 μm and the cladding ~ 125 μm. The optical fiber was cleaved and a capillary tube was used to bring the two single mode optical fibers within the capillary tube and epoxy was applied to glue the capillary tube with the fibers. Therefore, a small airgap was formed between the two single mode optical fibers. The endfaces within the capillary tube of the input and the output single mode fibers were used as optical reflectors. The endfaces of the two fibers were kept in parallel, and also maintained a fixed distance by using this capillary tube (hollow-core tube). In this study, the incident light from a 1300 nm laser source propagates through the input fiber and reflects at the endfaces of the fibers. A small portion of light reflects off, and the rest is transmitted through the airgap to the second fiber, due to their alignment. The reflected light is detected using a photodetector.

Experimental Set-up and Light Intensity Detection

A schematic diagram of the FPI sensor test setup with aluminum specimen is shown in Figure 1. The Fabry-Perot Interferometer sensor illustrated here is a single mode optical fiber. Two mirrors between the two endfaces of the single mode fibers acts as a Fabry-Perot cavity. Light from the laser (L) is launched into the input fiber and pass through a coupler towards the other side of the fiber connected to the FPI sensor. The output intensity of the system is detected using a photodetector (D). The optical path length of the cavity is modified due to changes in the cavity length and its refractive index. The change in optical path length modulates the phase of the light within the cavity. The reflected light in the cavity is sent to a photodetector which sends the light to a multimeter and the amplitude of the reflected light intensity is stored for subsequent analysis.

Fiber optic sensor was fabricated to determine temperature in aircraft structures. The optical sensors was used here to detect specifically thermal energy radiated from or absorbed by the specimen. A thermocouple was used to indicate the results obtained by the FPI sensor. The output of the sensor was the modulated light intensity, which was increased or decreased from its reference light intensity due to changes of temperature. In this study, the reference light intensity is considered as a constant environmental temperature.

Fabry-Perot Interferometer sensor has been used to measure the intensity of light from aerospace materials by applying loads to the airplane structure. This sensor is very sensitive with respect to temperature, applied load, and excitation, which changes the optical properties within the fibers at the gauge length. The experimental results are obtained when different loads are applied to the specimen. The experimental observation shows that this sensor is a very useful tool for material characterization. In this work, a fiber optic sensor, senses the applied loads to the specimen by detecting the modulated intensity.

Modulated light intensity measurements were also performed for sensing vibrational signal by applying various frequency excitations to the specimen. The sensor used here to determine the vibrational wave was the same sensor used for measuring the temperature and applied loads. Due to its performance, it was recognized that this type of sensor has a potential for aircraft structural inspection. The principal function of this sensor for sensing the vibrational wave is very simple. The light propagation into the fiber material depends on the properties of the fiber. The fiber optic sensor was mounted on the surface of the material in such a way that the longitudinal axis of the fiber was parallel to the propagation direction of the vibrational wave. The propagating wave modulates the gauge length within the capillary tube of the sensor mounted on the surface of the material. The sensor output intensity is modulated due to the intensity modulation that occurs at the gauge length. The optical signal amplitudes are smaller for higher frequencies of the vibrational waves and therefore small displacement occurs. Similarly, the amplitudes become larger for lower frequencies of the excitational waves and large displcement occurs.

Experimental Results and Discussions

One of the objectives of this work was to detect the bond quality of aircraft structures caused by temperature, vibration, and load changes. In this paper, experimental measurements were used to characterize the aircraft structure, and to study the effect of variations in parameter on the signals. This tehnique was developed to detect the intensity which carries not only the surface information, but also the internal structure of material. Experiments were performed on aircraft structures containing more than one layers of aluminum bonded together. The output of the FPI sensor is the modulated light intensity and is increased or decreased from its reference intensity due to changes in temperature. The total intensity is the actual modulated intensity due to temperature changes. The actual temperature is obtained by using the thermocouple at each position of the modulated intensity. The modulated intensity with respect to time for bonded and disbonded locations are shown in Figures 2 and 3, respectively. The aluminum 2024-T3 sample was heated by a heat gun and then cooled down. Experimental data were taken by cooling the specimen from 103° F to 78° F. In the disbonded area, the modulated intensity changes rapidly with respect to time. But the change in temperature was very slow at lower temperature from 85.4° F to 78.6° F. In the bonded location, the amplitude of the modulated intensity change slowly at the lower temperature as compared to disbonded location shown in Figure 3. In this case, temperature radiates very slowly from multilayered structures as compared to single layer structures and observed at lower temperature.

The phase change in the FPI was measured by monitoring the modulated light intensity and it was observed that the intensity was changing sinusoidally as a function of temperature from the cooling specimen. In this case, the phase shift in the interferometer was dependent on temperature variation during the cooling process. Figure 4 shows the phase shift in the FPI as a function of temperature as measured with a thermocouple. In Figure 4, the squares illustrates 2π radians separation from one to another for the disbonded location and clearly shows the linear plot. We believe that if there is any defects observed, the linearity will be deflected from its original position.

Figures 5 and 6 show the signal intensity as a function of time by applying loads parallel to the longitudinal axis of the specimen. The modulated light intensities were detected from disbonded and bonded locations by applying various loads. The modulated intensity changes the phase by applying loads at the edge of the sample. In this case, the phase of the modulated intensity changes with certain loads, especially disbonded locations shown in Figure 5. The same sensor was used to determine the applied load and the intensity of the light changes due to the applied load is shown in Figure 6.

Experiments were performed for detecting the vibrational wave by external excitation at the specimen with different excitation frequencies. Figure 7 shows the vibrational signal at 50 Hz obtained from the disbonded location. The same excitational frequency was applied to detect the signal from the bonded location as shown in Figure 8. The oscillatory part was slowly diminished at the bonded location and the experimental results were obtained. Figure 9 shows the intensity versus time measurement without applying any external excitation at the specimen. There is a significant difference between bonded and disbonded locations for these measurements that are shown in Figures 7 and 8.

The one dimensional detection was extended for a large area using two sensors and these sensors covered a large area and were moved along the structure. The measurement technique was the same as single sensor, but covered a large area with an array of FPI sensors. The detection system was faster than a single sensor system.

Conclusions

In this paper, we studied the fiber optic sensor response of single and multilayered structures caused by launching thermal, applied loads, and vibrational wave in the aircraft structure. The FPI sensor was very sensitive and was mounted externally on the surface of the specimen and has been used to sense temperature, applied loads, and vibration in aircraft structures. In this work, thermal and vibrational waves were launched in the aircraft structure by applying external temperature variation and vibrations at the specimen, and the fiber optic sensor detected the modulated signal. The Fiber Optic Sensor head was mounted at the center of the multilayer aircraft skin. From this position, the photodiode detected the modulated intensity changes in the cavity due to the applied temperature, vibration, and loads changes. Fiber optic sensor experimental measurements were used to characterize the bond quality of an aircraft structure, and to study the effect of parameter variations on the results. It was observed that the modulated light intensity and the vibrational wave from the bonded locations were significantly different from the disbonded locations. Results from this technique provides a good understanding of the technique itself and verify its validity.

Aknowledgements

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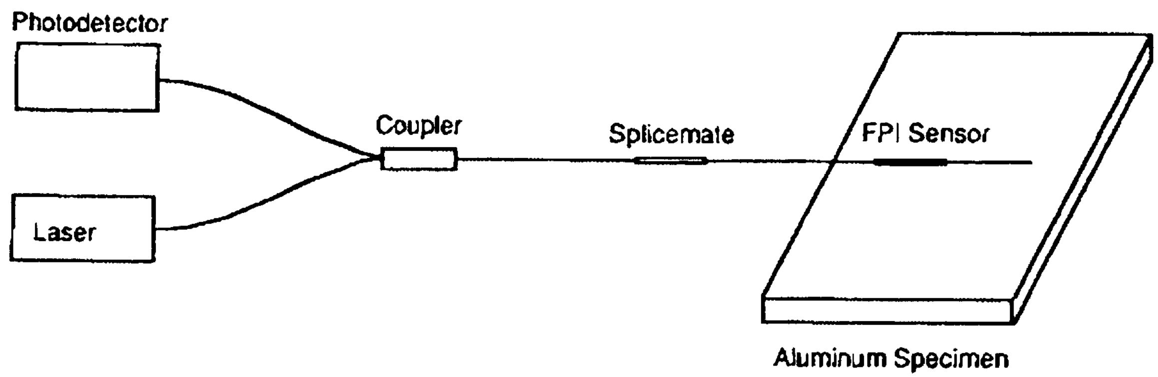

Figure 1. Experimental setup for detecting modulated light intensity using FPI sensor attached to the aircraft skin.

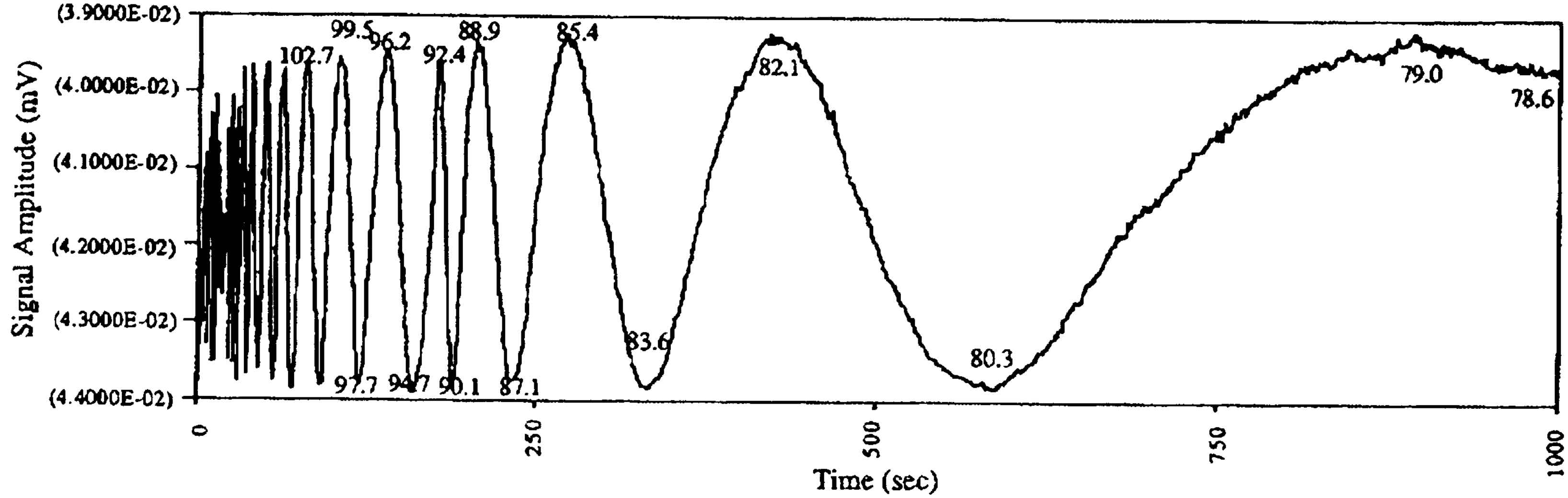

Figure 2. Modulated light intensity obtained from FPI sensor as a function of time by cooling the heated specimen on the disbonded location.

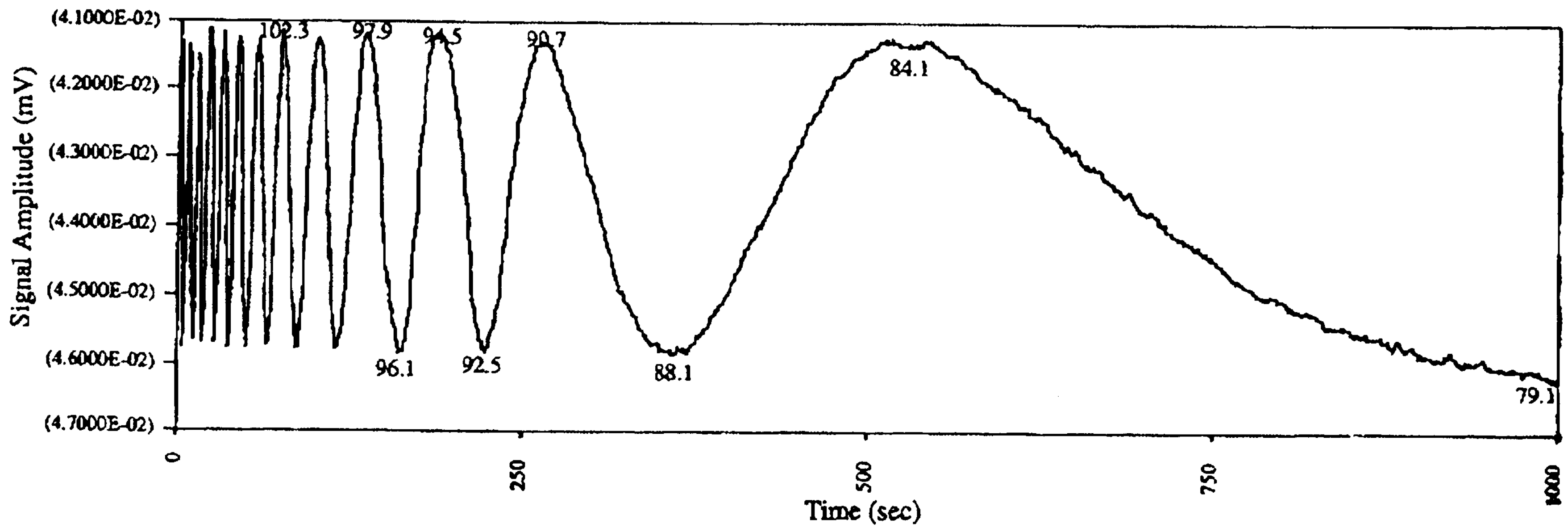

Figure 3. Modulated light intensity obtained from FPI sensor as a function of time by cooling the heated specimen on the bonded location.

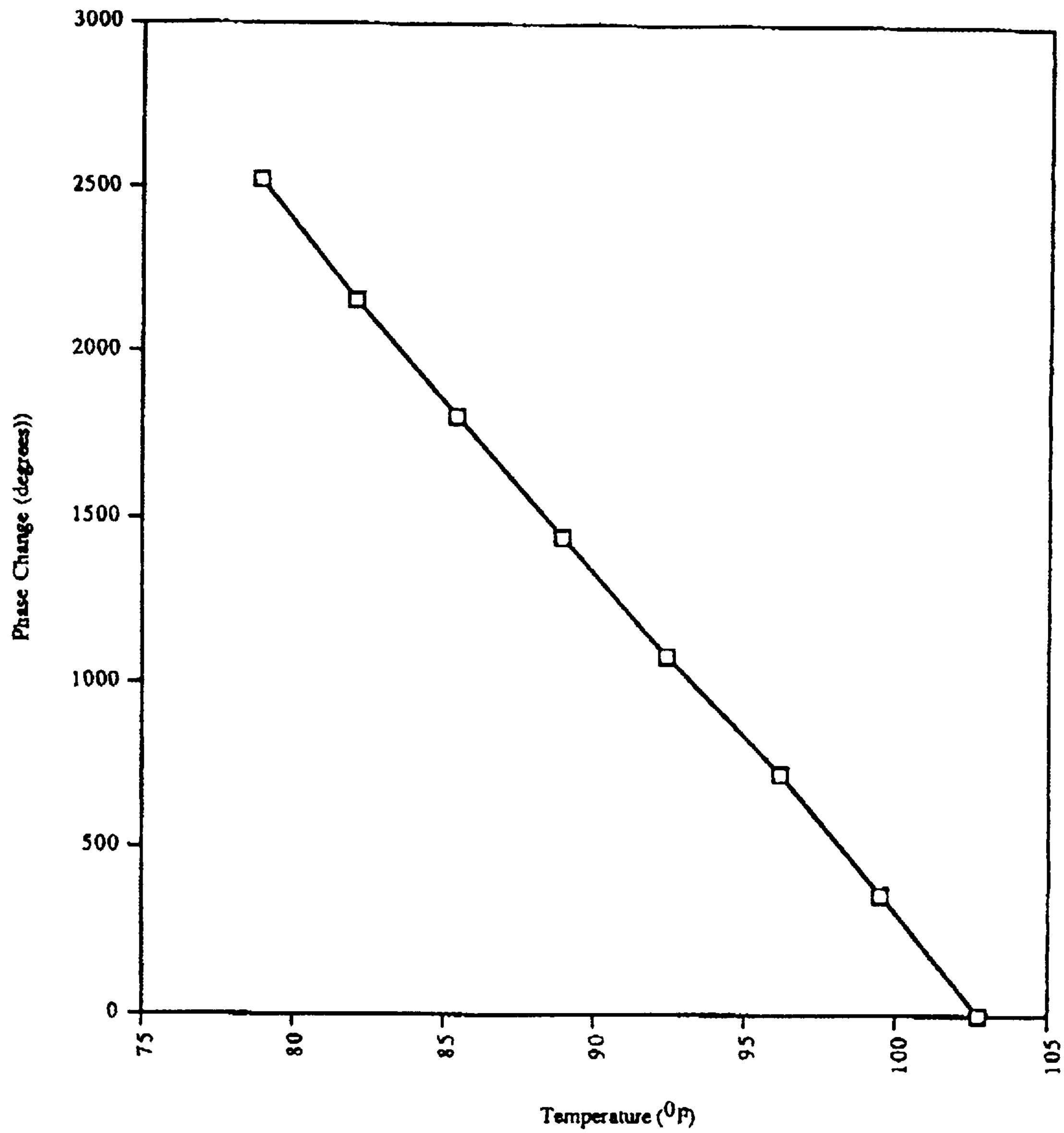

Figure 4. Phase shift in FPI sensor measured as a function of temperature with a thermocouple (disbonded location).

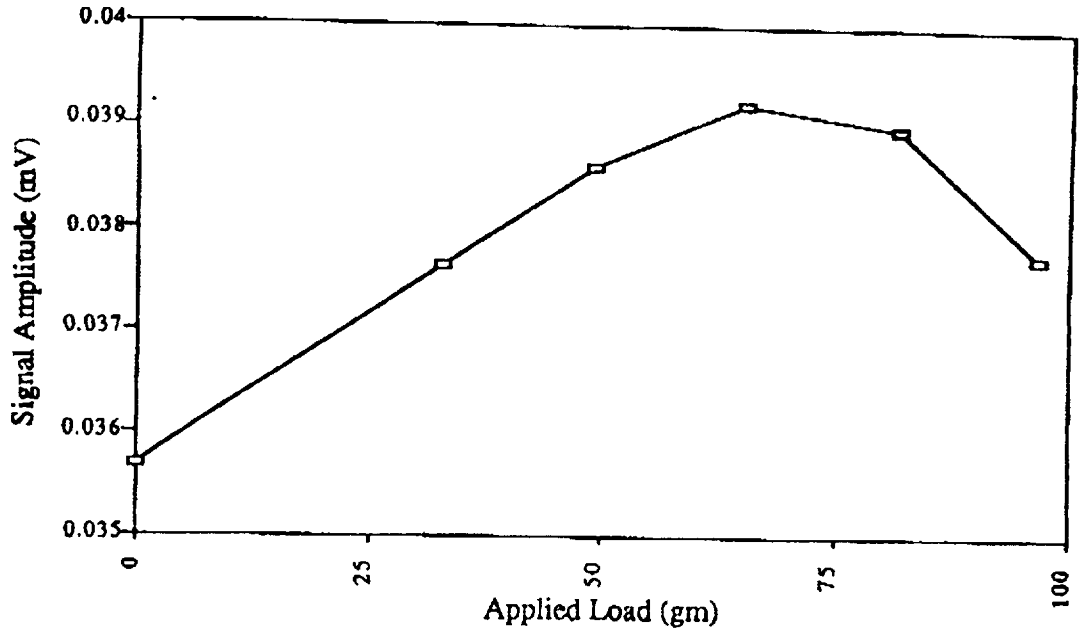

Figure 5. Modulated light intensities (signal amplitude) obtained from FPI sensor as a function of load.

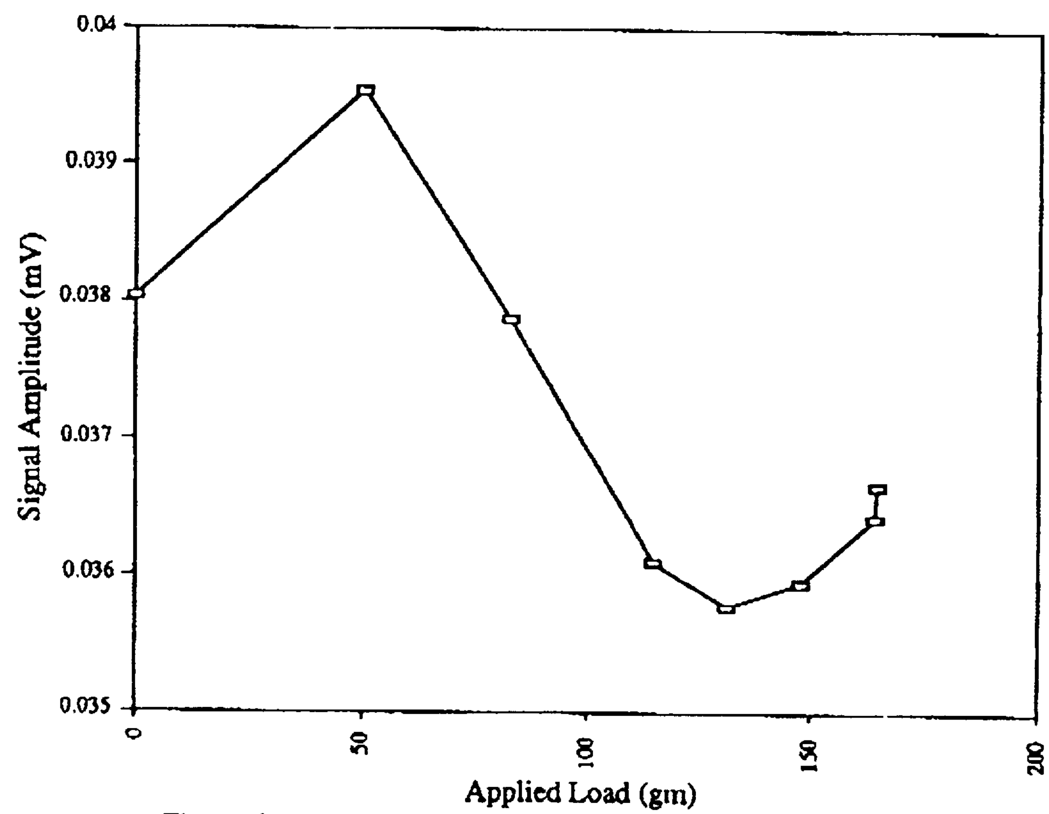

Figure 6. Modulated light intensities (signal amplitude) obtained as a function of load from FPI sensor.

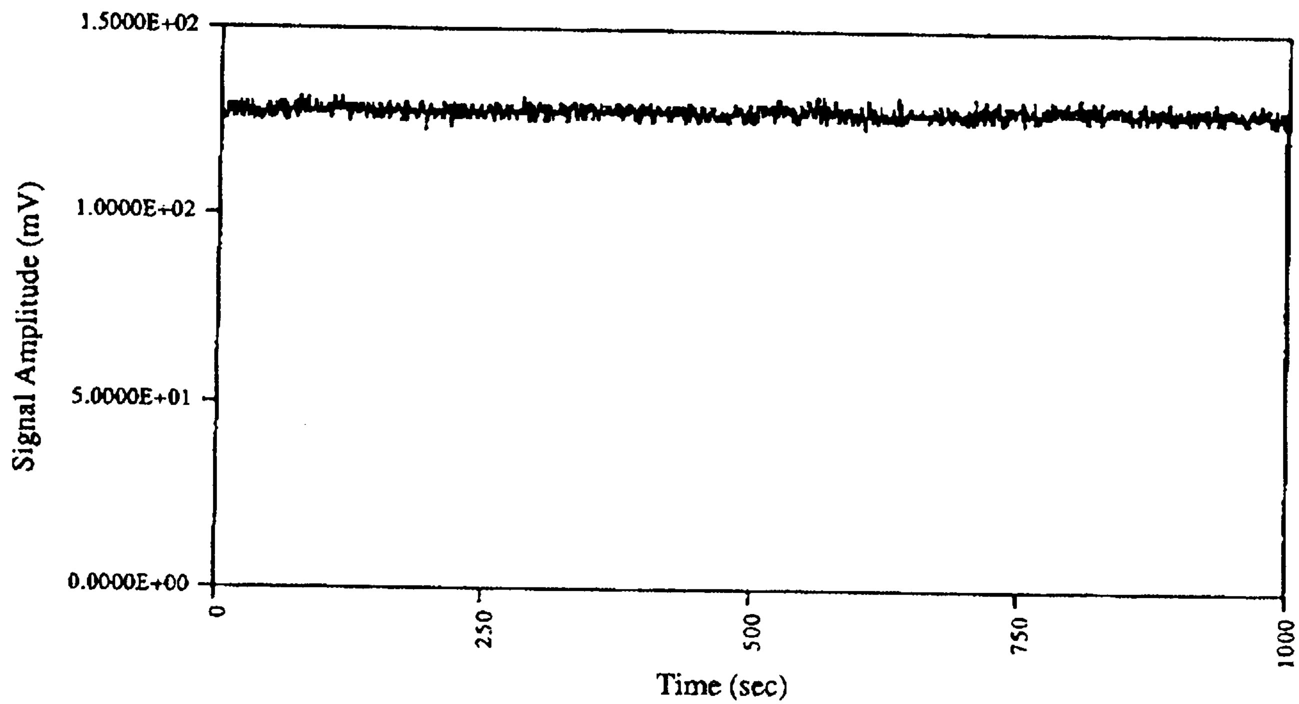

Figure 7. Modulated light intensity signal detected as a function of time from FPI sensor on the disbonded location (zero vibrational frequency).

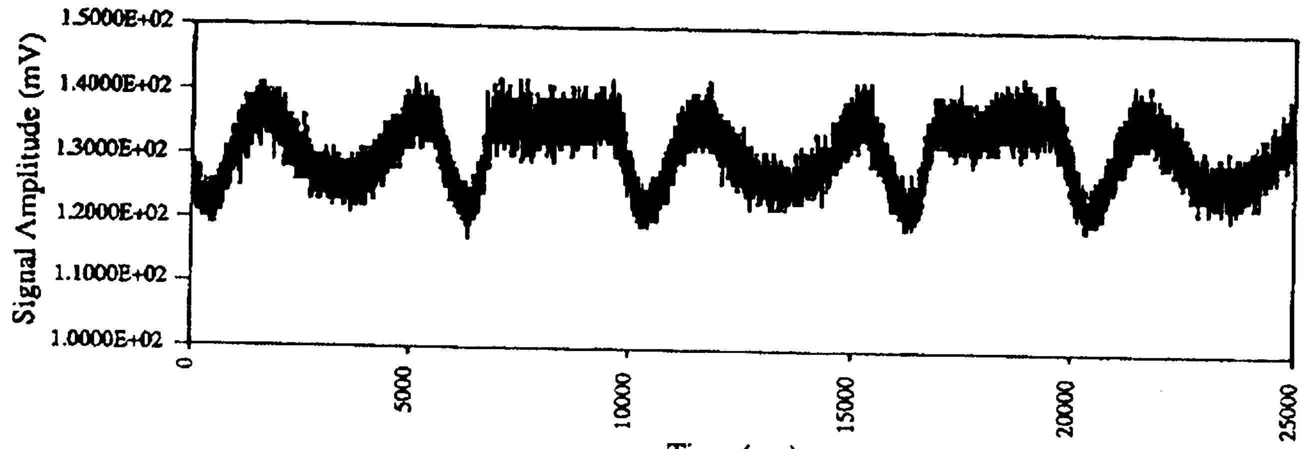

Figure 8. Modulated light intensity signal detected as a function of time from FPI sensor on the disbonded location (50 Hz vibrational frequency).

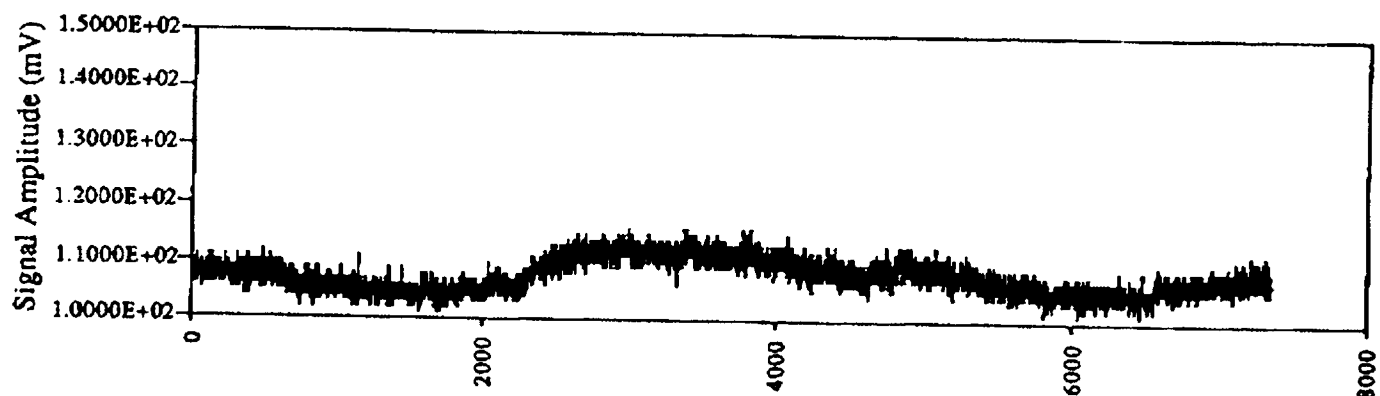

Figure 9. Modulated light intensity signal detected as a function of time from FPI sensor on the bonded location (50 Hz vibrational frequency).