FIBER-OPTIC STRAIN GAUGES

CRYSTAL YEE
DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF HAWAII
HONOLULU, HAWAII 96822

ABSTRACT

The purpose of this project was to design a fiber-optic strain gauge and prove its concept. This paper presents a simple fiber-optic strain gauge design and examines the effect of strain and temperature, theoretically and experimentally. Fiber-optic strain gauges can simultaneously measure many parameters including axial strain, transversal strain, and temperature. They can also be embedded during construction for use as a structural integrity check system. Their reliability and accuracy compared to metal-wire strain gauges is excellent. Fiber-optic strain gauges offer many benefits in the aeronautical and aerospace field as well as in civil applications.

INTRODUCTION

Today, NASA, the National Air and Space Administration, demands less expensive, lighter, and better aeronautical and aerospace vehicles. Every new experimental vehicle must be carefully tested to ensure its safety and reliability for space travel or flight at Mach speeds. Engineers test parameters including stress, heat, pressure, and airflow. The traditional method of testing these parameters is done with metal-wire (electrical) strain gauges. However, structural testing is not just necessary when prototypes are built, but as they age as well. Due to the high cost of building space vehicles, to replace them is impractical. Instead, space vehicles are microscopically inspected inch by inch for cracks that will compromise functionality. To not do so can have disastrous results. Fiber-optic strain gauge technology can also be applied to civil infrastructures such as bridges, dams, power plants, roads, pipelines, and buildings. They can also be used in automobiles and medical monitors. Many companies and countries around the world are researching and developing this technology.

Fiber-optic technology is the technology of the future. Using fiber-optic strain gauges is more advantageous than metal-wire strain gauges. They offer significant weight reduction, cost savings, greater versatility, and have multi-parameter test capabilities. In addition, they are more sensitive to changes and are immune to electro-magnetic interference which results in higher bandwidth and better signal quality. Since they are compose of silicon dioxide, they are not subject to corrosion and can be used at much higher temperatures.

Fiber-optic strain gauges offer an efficient way to conduct prototype testing and perform structural health monitoring. Traditionally in prototype testing, for each test point and parameter, a metal-wire strain gauges is used. However, the major benefit of using a fiber-optic strain gauges is that one fiber-optic cable can be used for several test points. It can also measure many parameters at once, such as axial strain, transversal strain and temperature (Navarro, 1999). For example, on NASA's F-18 Systems Research Aircraft (SRA), there are many areas of concern, shown in figure 1. The wings are susceptible to high vibrations. The significant amount of electronics for aviation and research induce a high electrical noise area in the fuselage. Near the jet engines, there is an area of high noise and temperature. Overheating is a concern. When engineers conduct strain tests, one square foot section could have at least 12 test points, each with its own wire (figure 2). However, one cable can be wrapped around the one square foot test section and measure all twelve test points (figure 3). This is a significant weight reduction and cost reduction compared to 12 metal wires. Because fiber-optic cables are not subject to corrosion, they can be embedded in construction materials for concrete bridges or space vehicles. As "health monitoring systems," they can accurately indicate and pinpoint cracks or fatigue immediately without the system needing to be overhauled.

Currently, fiber-optic technology is being actively tested at NASA-Dryden Flight Research Center. This project is meant to be a small scale version of the fiber-optic strain gauge research that they are doing. This pioneering research is multiple disciplinary, combining electrical engineering, optics, mechanical engineering, and electronics. With the help of my mentor, Dr. Jung-Chih Chiao, the fundamental phenomena was studied and the feasibility of an optical mechanical sensor was demonstrated. To achieve this, a fiber-optic strain gauge was designed.

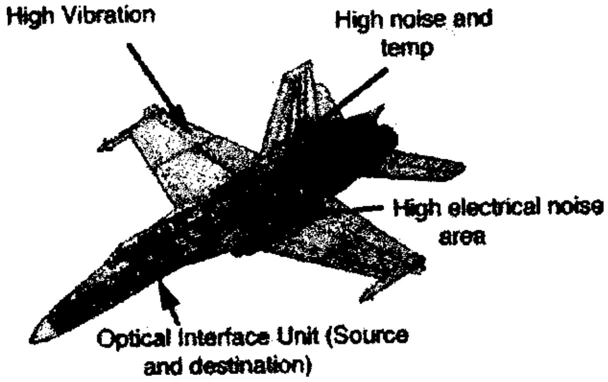

Figure 1: Concerned areas on the F-18 SRA for real-time monitoring (SRA website).

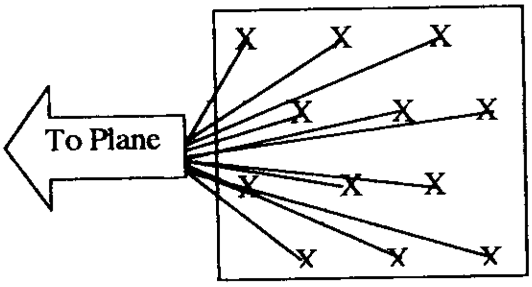

Figure 2: Sample square foot block test section with twelve test points measured by metal-wire strain gauges (Navarro, 1999).

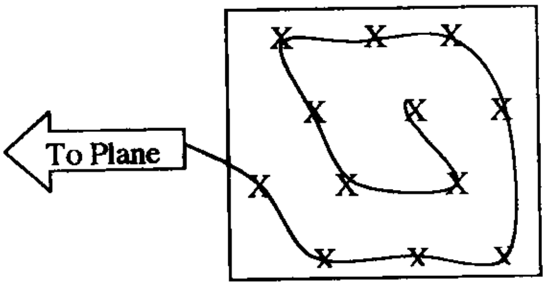

Figure 3: Same sample square foot block test section with fiber-optic strain gauge (Navarro, 1999).

METHOD

The intent of this research project was to design a fiber-optic strain gauge and prove its concept. A simple strain gauge was designed to determine the location of applied strain based on change in output intensity. The equipment used in this experiment were a laser, single mode plastic fiberoptic cable (due to no attenuation, durability and low cost), and a silicon photodetector.

The equipment was set up so that the laser would be polarized then transmitted into the fiber-optic cable. To simulate strain, 10 oz weights would be applied. Then the output wave was again polarized and passed to a photodetector. The resulting change in intensity was recorded using an oscilloscope. When strain is applied, the fiberoptic cable changes its shape at that point which affects the laser beam passing through it. At the pressure point, some of the wave in the fiber is reflected, some absorbed, and some transmitted. Thus the output intensity is less than the input intensity. Knowing the amount of change, the location of applied pressure can be calculated.

However, this is not easy. In the ideal control case, the laser beam will be received at the same angle and intensity as the input beam. Each additional pressure point will cause more power attenuation and phase change to the output wave. Since additional pressure points alter the wave again, there must be a way to segregate when each event occurred. To resolve this, polarization-maintaining single mode fibers, already embedded with Fiber-Bragg gratings of different wavelengths were used. Fiber-Bragg gratings work like a filter. When strain is applied, they reflect a certain wavelength of light (Bragg wavelength) but allow all other wavelengths to pass through.

After carefully calibrating the data collecting instruments, the above experiment was repeated for various number of pressure points, from one to three, and a standard analysis method was formulated to determine location of strain. The idea was that if the concept can be demonstrated for three test points, then it can be applied to the twelve or any number of test points.

RESULTS

From a basic understanding of fiber-optics and wave propagation before doing testing, several predictions were made. 1. There is a linear correlation between the amount of applied pressure and the decrease in output intensity. 2. There is a linear correlation between the amount of applied pressure and wavelength shift of the resulting wave. Therefore how many pressure points there are being applied can be approximated. If you know how much the intensity will drop with one applied pressure point, then the integer multiple of that will tell you how many pressure points there are. If you know what the phase shift of one applied pressure point is, then the integer multiple of that will tell you how many pressure points there are. The two integer multiples should also be the same.

In the original experiment, only strain was measured through the change in intensity of the laser beam. This is because to measure the actual phase shift required expensive and precise instrumentation which is unavailable. Because there are Fiber-Bragg gratings in the cable, if strain is applied at that point, then the Bragg wavelength, will be reflected and intensity at that wavelength will decrease by the amount of applied strain.

Due to the construction delay of the new fiber-optic laboratory, testing could not be conducted. Instead more research on the subject of fiber-optic strain gauges was done. From actual data from experiments performed around the world, hypothetical data was developed.

Theoretically, using the experimental setup, if no pressure is applied, then the intensity of the output should be the same as the input at all frequencies. There would also be no phase change. If one pressure point is applied, then the resulting intensity will be ideally zero at the Bragg frequency. If there is two pressure points applied, then there will be a zero intensity at the two different Bragg frequencies but all other frequencies should output the original wave. If the location of the Bragg grating and its Bragg frequency are known then the location of applied strain can easily be determine. If instead the Bragg frequencies were the same in the fiber cable and a single frequency laser was used, then with each applied strain the intensity will change by the same integer factor and the peak to peak separation of the wave will increase. By the amount of intensity and peak to peak separation, the distance of applied strain(s) can be determined.

DISCUSSION

From actual experimental data, it was confirmed that the relationship between applied load to displacement and applied load to phase change is linear. The state of polarization of the light output varies sinusoidally with respect to displacement. These three statements were confirmed by every experimental result obtained by research. From actual experiments it was proven that the wavelength shift ($\Delta\lambda/\lambda$) vs. temperature is linear and wavelength shift ($\Delta\lambda/\lambda$) vs. axial strain is also linear (Sivanesan, 1999). Actual experimental data also showed that as the amount of axial strain increases, the intensity of the wave remains the same but the wave will shift to higher frequencies. As the amount of transverse strain increases, the peak to peak separations of the resulting wave will increase (Shulz, 1998). From other experiments (Ansari and Libo, 1998) and (Lee, 1999), it was shown that fiber-optic strain gauges offer results very similar or more precise to that from metal-wire strain gauges.

These statements were also proven mathematically by Sivanesan, 1999. The phase of light in fiber is $\phi=\beta L$. Phase difference of the output that is caused by the strain is $\Delta\phi=\beta\Delta L+L\Delta\beta$. $\beta\Delta L$ is the response of the actual length change that is cause by the strain. Thus $\beta\Delta L=\beta L\varepsilon$ where ε is axial strain. $L\Delta\beta$ is the phase difference caused by the change of propagation constant. Therefore, $L\Delta\beta = L\frac{\partial\beta}{\partial n}\Delta n + L\frac{\partial\beta}{\partial n}\Delta D$ where Δn and ΔD are the changes of the refractive index and the diameter of the optical fiber. From the strain optics effect Δn can be expressed by $\Delta n = -\frac{n^3}{2}\left(\frac{P}{E}\right)\left[-\mu P_{11} + (1-\mu)P_{12}\right]$, where P is the tension stress. So $\Delta\phi$ can be expressed as $\Delta\phi = L(\beta\varepsilon + \frac{d\beta}{dn}\Delta n) = LP\left\{\frac{\beta}{E} - k_0\frac{n^3}{2E}[-\mu P_{11} + (1-\mu)P_{12}]\right\}$. The items in bracket are constant. E is the elastic modulus of the optical fiber material. So $\Delta\phi = LPM - L\varepsilon EM = L\varepsilon M'$

Therefore the phase difference is proportional to the fiber strain. M' is related to the strain coefficient of the optical fiber and the refractive index. $M' = \beta - k_0\frac{n^3}{2}[-\mu P_{11} + (1-\mu)P_{12}]$

Because optical fibers have different parameters, M' is obtained by a calibration test.

To get M', a plot of known strain, phase difference, and distance is made with experimental test data. This mathematical result shows the linear relationship of measured strain to phase difference.

At the same time, it was learned that taking advantage of the various Bragg conditions, strain and temperature can simultaneously be measured (Lee, 1999). Bragg wavelengths λ_b are given in terms of the effective index n and periodicy of modulation Λ, by $m\lambda_b=2n\Lambda$, where $m = 1, 2, 3$ is the order of the respective Bragg conditions. Taking m=1 and m=2, the first and second order Bragg conditions, the resulting wavelengths can be used to simultaneously measure strain and temperature. The 2nd order Bragg condition will result in a Bragg wavelength that is approximately half of the first order Bragg wavelength and will be roughly a factor of two less sensitive to strain and temperature than the first order Bragg condition. The optical power of the 2nd order Bragg condition will be half that of the first. By exploiting this large difference, both strain and temperature can be measured. Once the strain and temperature coefficients are determined, they can be used to make simultaneous strain and temperature measurements with an error band of 17.4 με/pm and 1.72°C/pm (Lee, 1999). The relationship between axial strain, temperature, and wavelength shifts can be determined by the following system of equations (Lee, 1999).

$$\begin{bmatrix} \dfrac{\Delta\lambda_1}{\lambda_1} \\ \dfrac{\Delta\lambda_2}{\lambda_2} \end{bmatrix} = \begin{bmatrix} K_{\varepsilon 1} & K_{T1} \\ K_{\varepsilon 2} & K_{T2} \end{bmatrix} \begin{bmatrix} \varepsilon_{zz} \\ \Delta T \end{bmatrix} \text{ but } \frac{K_{\varepsilon 1}}{K_{\varepsilon 2}} \neq \frac{K_{T1}}{K_{T2}}$$

where $\Delta\lambda_1$ and $\Delta\lambda_2$ are the wavelength changes of the 1st and 2nd order Bragg conditions, $K_{\varepsilon 1}, K_{\varepsilon 2}$ and K_{T1}, K_{T2} are the strain and temperature coefficients of the 1st and 2nd order gratings, and ε_{zz} and ΔT are the axial strain and temperature change in the fiber.

CONCLUSION

The purpose of this project was to design and test a fiber-optic strain gauge to prove its concept. The concept of fiber-optic strain gauges to simultaneously test temperature and strain has been shown to be feasible, experimentally and mathematically. Fiber-optic strain gauges have been in development for the last 10 years. However, successful results in applications have not been achieved until just recently. Fiber-optics is the technology of the future. They will replace metal-wire strain gauges in many applications due to their dropping cost, better accuracy, and infinite life span. Being able to embed fiber-optic cables in structures has many social benefits. It will decrease the need for governments to rebuild aging structures to ensure safety and reliability. Knowing whether or not a structure such as a space vehicle or bridge is safe will be as fast as the speed of light.

It has also been shown through experimental results that the accuracy and reliability of the fiber-optic strain gauge is just as good if not better than the metal-wire strain gauge. The cost and weight savings were discussed. The relationship between strain and temperature compared to wavelength shifts has been examined and shown to be linear, through both experimental results and mathematical calculations. The ability of fiber-optics strain gauges to test multiple points has also been shown.

Fiber-optic strain gauges still has a long way to go before it can be used readily. There is no standard for a fiber-optic strain gauge system. Each system must be individually calibrated, tested, then applied. This is because of the diversity of fiber-optic cables. Deciding on a fiber-optic system depends heavily on the purpose and important considerations. This includes ruggedness, bandwidth, cost, power, and attenuation. There is no one answer as there are tradeoffs that have to be made. Because of better technology, fiber-optic strain gauges will replace metal-wire strain gauges for testing. Outfitting public infrastructures and air, water, and space vehicles with fiber-optic strain gauges will also become standard practice.

ACKNOWLEDGEMENTS

The author would like to thank the Hawaii Space Grant College for making this research opportunity possible. Many thanks to Dr. J.C. Chiao for guiding this research project in the right direction, providing additional funding for equipment, and use of the new fiber-optics laboratory. The author would also like to thank Robert Navarro, Chief Engineer at NASA-Dryden Flight Research Center, who introduced the author to the concept of a fiber-optic strain gauge, and to Kwok Kee Tang for his fiber-optics and laser expertise.

REFERENCES

1. Ansari and Libo. (April 1998) Mechanics of Bond and Interface Shear Transfer in Optical Fiber Systems. *Journal of Engineering Mechanics.*
2. Communication with Dr. Jung-Chih Chiao, mentor. (September 1999- May 2000)
3. Communication with Robert Navarro, Chief Engineer F-18 Systems Research Aircraft. (June-August 1999)
4. Lee, Lee, Henderson, Taylor, James, Lee, Swenson, Atkins, Gemeiner. (March 1999) Railroad bridge instrumentation with fiber-optic sensors. *Applied Optics.*
5. Shulz, Udd, Seim, Laylor, and McGill. (1998) Single and multiaxis fiber grating based strain sensors for civil structure applications. *4th Pacific Northwest Fiber-optic Sensor Workshop.*
6. Sivanesan, Sirkis, Venkat, Shi, Reddy, and Sankaran. (March 1999) Simultaneous Measurement of Temperature and Strain using a Single Bragg Grating. *Smart Structure and Materials.*
7. Website. http://www.dfrc.nasa.gov
8. Website. http://www.dfrc.nasa.gov/Projects/SRA/