DESIGN OF A FIBER BRAGG BASED MEASUREMENT SYSTEM FOR STRAIN AND TEMPERATURE MONITORING

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ABSTRACT. The design of a fiber optic sensing system will be presented. The goal is to develop a measurement system that will be deployed in a manufacturing or field environment. The sensing elements will be formed from Bragg gratings and from Fabry-Perot interferometers constructed from fiber Bragg gratings. The novelty of the method presented in this study lies in the simplicity and speed in which stress and temperature can be simultaneously measured.

INTRODUCTION

To provide more efficiency in the design of systems involving engineering structures, adaptive structures and manufacturing processes, the ultimate limits of the engineering materials used in the systems are being approached. The reduced margins of safety for the material used in the design of the systems will require the use of sensing systems to measure strain and temperature. This will allow the designs to maintain safety and reliability.

The purpose of this paper is to introduce a design for direct measurement of dynamic stresses and temperatures in optical fiber sensors during processing, deployment, and in-service lifetime. This method utilizes the well known stress dependence of fiber Bragg gratings [1]. The novelty of the method presented in this study lies in the simplicity and speed in which stress and temperature can be simultaneously measured and the ability to actively monitor while the sensing fiber is being deployed. The goal is to develop a measurement system that will be deployed in a manufacturing or field environment.

This paper will discuss the sensing elements that are constructed from fiber Bragg gratings and from Fabry-Perot interferometers built from fiber Bragg gratings. A theoretical simulation studying the shifts in center wavelengths from the fiber Bragg and the Bragg Fabry-Perot at various strains and temperatures will be presented that supports the feasibility of separating strain changes from temperature changes. These results will then be used to specify the instrumentation.

FIBER BRAGG SENSORS

Fiber Bragg gratings are naturally suited to handle the rigors of manufacturing processing. When a grating is written into a fiber, the grating becomes part of the glass with minimal or no loss in mechanical strength. The Fiber Bragg grating reflects a
narrowband of wavelengths allowing for single sided and wavelength multiplexing measurements.

The transduction mechanism for a fiber Bragg sensor is simple and reliable. Variations in strain and temperature will cause a shift in the center wavelength of the reflected light. The sensing schemes become complicated and expensive when temperature effects must be separated from strain effects. The primary focus of this report is the efficient separation of temperature and strain measurements.

**DECcoupling strain and temperature effects**

A strain measurement scheme must use a strain transducer that is totally thermally insensitive or measure temperature and apparent strain in the fiber. The former is difficult to achieve in fiber sensors and the latter is implemented in Figure 1. Two sensors are incorporated into the same length of fiber: A hybrid Bragg Fabry-Perot (BFP) cavity and a Fiber Bragg Grating (FBG) can be used to separate temperature and strain effects. Two identical FBGs are used as partial mirrors which creates a FP sensor. A FBG sensor with a center wavelength outside of the hybrid cavity bandwidth is placed within the FP cavity. Thus the two sensors can operate independently.

**Fiber Bragg Grating**

A Fiber Bragg Grating (FBG) [1-3] is a wavelength selective device created by forming a grating which modulates the index of refraction in a core of an optical fiber. The FBG is a wavelength selective reflector. Figure 2 shows the simulated reflected spectrum for a FBG. The grating period and the effective index of refraction [3] determine the center wavelength of the reflected optical spectrum. The length of the grating [3] determines the bandwidth of the reflected spectrum. Thus changes in the location of the center wavelength in the reflected spectrum are caused by changes in the grating period or the effective index of refraction. The center wavelength and effective index of refraction within a FBG transducer are affected by changes in strain and temperature. This cross sensitivity also makes decoupling temperature effects from strain effects difficult.

The transmission spectrum is beneficial for wavelength addressing of a FBG in transducer arrays. Each grating transducer would be allocated to operate within a center frequency and bandwidth much like channel spacing in telecommunication systems. The gratings used for sensing applications do not need to match the performance of telecommunications gratings. The sensing gratings will be easier to manufacture and less expensive.

**Decoupling strain and temperature effects**

\[
\frac{\partial \theta_{FP}}{\partial T} / \frac{\partial \theta_{BG}}{\partial T} \neq 1
\]

**FIGURE 1.** Placing a FBG sensor within a hybrid BFP sensor can decouple temperature and strain if the center wavelength sensitivity ratio with respect to temperature and strain for the BFP sensor is not be equal to the identical ratio for the FBG sensor.
FIGURE 2. Reflection spectrum from a Bragg grating under a no load condition.

FIGURE 3. Power reflectivity as a function of wavelength for a hybrid BFP cavity. Note the transmission of light near the center of the Bragg grating reflectance peak at -1550.4 nm. This is the unloaded state of the sensor.
Fabry-Perot Cavity

A Fabry-Perot (FP) cavity [1, 4] is a wavelength selective device formed by placing two partial mirrors in the optical path. The Fabry-Perot cavity selectively transmits wavelengths that are integer multiples in value. The spacing between the transmitted spectral peaks (free spectral range) [4] are determined by the effective cavity length formed by the partial mirrors. The bandwidth and amplitude of the spectral peaks are determined by the mirror reflectivity. Thus changes in the location of the spectral peaks are only caused by changes in the effective cavity length.

The effective length of a FP cavity is affected by changes in both temperature and strain. This cross sensitivity of the effective cavity length makes decoupling temperature effects from strain effects difficult. The transmission spectrum also limits the use of FP cavities in transducer arrays. The transmission of multiple wavelengths through the FP cavity and the attenuation of off resonance wavelengths make addressing multiple transducers by wavelength problematic. The use of Fiber Bragg Gratings can mitigate the problems of cross sensitivity and wavelength addressing.

Hybrid Bragg Fabry-Perot

By combining the FBG with a FP cavity, the hybrid sensor’s response to strain and temperature changes will be substantially altered from a FBG response. Figure 3 shows the simulated reflected spectrum for a hybrid FP cavity created from FBGs. The hybrid FP cavity transmits all light outside of the FBGs bandwidth. When the optical wavelength approaches the FBG bandwidth, the FBGs begin to reflect the light. As the optical wavelength approaches the resonant wavelength of the hybrid cavity, the light begins to be transmitted. The hybrid cavity now behaves as a normal FP cavity until the wavelength of light falls out side of the FBG bandwidth.

Integrating the Sensors

The requirement to uncouple strain and temperature effects from the two types of sensors is given by the Equation in Figure 1. The equation states that the center wavelength sensitivity ratio with respect to temperature and strain for the BFP sensor must not be equal to the identical ratio for the FBG sensor. The greater the inequality, the greater the achievable measurement accuracy of strain and temperature.

Since the bandwidth of the FBG sensor is outside of the bandwidth of the FP cavity, the two sensors do not interfere with each other and are uniquely wavelength addressable. Their close proximity also assures that the two sensors are affected by the same local environmental conditions. However, the sensitivities of the two sensors with respect to strain and temperature are significantly different. The FP cavity is most sensitive to changes in the effective cavity length and the FBG is most sensitive to changes in the grating spatial frequency.

SENSOR SYSTEM MODELING

The grating sensors are modeled using fundamental models which are straightforward and simplistic. The models are linear in nature and will not accurately follow nonlinear changes in the fiber due to mechanical and thermal loading. The effects of loading are measured by following the changes in the center wavelength of the reflected spectrum from a Bragg grating and by monitoring changes in the transmission wavelengths within the reflective spectrum in the hybrid BFP cavity. The models have
have been tested and have been shown to provide for a linear change in center wavelength for strains from 0 to 0.02, for temperatures from 25°C to 250°C, and for the combined effects of temperature and strain.

The FBGs are modeled using the classical equation for reflection as shown in Equation 1. The small r denotes amplitude reflectivity. The notation can be found in Reference 3. The small r denotes amplitude reflectivity.

The Fabry-Perot cavity is modeled using the classical FP equation shown as Equation 2 [4]. The uppercase Rs denote the power reflectivity of the cavity (R), partial mirror 1 (R₁) and partial mirror 2 (R₂). θ is the optical path length as defined in reference 4.

\[
r = \frac{-\kappa \sinh(\alpha L)}{\alpha \cosh(\alpha L) - i\beta \sinh(\alpha L)}
\]

\[
R = \frac{(\sqrt{R_1} \sqrt{R_2})^2 + 4\sqrt{R_1 R_2} \sin^2 \theta}{(1 - \sqrt{R_1 R_2})^2 + 4\sqrt{R_1 R_2} \sin^2 \theta}
\]

The Bragg Fabry-Perot is modeled by substituting the reflectivity calculated by the FBG Equation 1 into the FP Equation 2 for the reflectance of the partial mirrors. Thus the hybrid BFP cavity will have the wavelength selective properties of a Bragg Grating along with the narrow band transmission of a FP cavity as shown in Figure 3.

Temperature and Strain can potentially be separated by only using the hybrid BFP. The reflective peak caused by the FBG can be followed as well as the narrow transmission lines due to the FP. However to make the processing easier due to the distortion of the reflective peak by the FP transmission lines, the response to a separate FBG sensor has been followed.

Figure 3 shows the reflected spectrum from an unloaded BFP sensor. Note that there is only one transmission line in the return spectrum. The monitoring of only one transmission line within the reflected spectrum will work well for small temperature and strain variations. However with large temperature and strain variations, the center wavelength changes will vary in excess of the FP free spectral range. Therefore, the BFP sensor should be designed such that the bandwidth of the FBG is slightly larger than the free spectral range of the interferometer. This will allow continuous monitoring of the changing transmission line wavelengths by accounting for the transition into and out of multiple FP free spectral ranges.

Even though separating temperature effects from strain effects is difficult, the interaction between temperature and strain is linear. This is demonstrated in Figure 4 by the two planes created by the two types of sensors. The changes in measured wavelength will be a linear function of loading in the sensors. Figure 4 also clearly shows that calibration of the sensors with respect to temperature and strain can be accomplished independently. This greatly simplifies the calibration procedure. Since the two planes intersect along a line, the wavelength combination for the FBG and the BFP sensors will be unique. Thus a lookup table can be created to determine temperature and strain from the measurement of wavelength provided by the two types of sensors or the sensing matrix can be inverted [1, 6].

SENSING SYSTEM DESIGN

The modeling has shown promise for the two sensors to separate temperature and strain. It is now appropriate to consider the design of the measurement system. The
measurement system must be able to meet the specified requirements. Table 1 gives a listing of the requirements and the corresponding implicit measurement requirements based on the models developed in this paper.

**Bragg Fabry-Perot and Bragg Sensors Wavelength Response to Temperature and Strain Variations**

![Graph showing wavelength response](image)

**FIGURE 4.** The calculated values for center wavelength in a FBG sensor and transmission wavelength in a BFP sensor for temperature and tensile loadings. The top plane is the response due to the FBG and the bottom plane is the response due to the BFP.

**Grating Based Measurement System**

![Diagram of measurement system](image)

**FIGURE 5.** Schematic of the measurement system designed to make measurements of the return spectra from the Fiber Bragg Grating Sensors and the Bragg Fabry-Perot sensors. The measurement system will be an instantaneous Optical Spectrum Analyzer.
A wavelength measurement system has been developed to meet the needed specifications given in Table 1 [5]. A schematic diagram of the system is shown in Figure 5. The measurement system is based on an instantaneous Optical Spectrum Analyzer. A broadband light source is used to interrogate the grating based sensors as they are being fed through the fiber processing equipment. The light spectra which is reflected by the sensors is guided to the optical spectrometer. The reflected light is incident upon a grating inside the spectrometer which spatially disperses the light based on wavelength. The linear array measures the light intensity as a function of wavelength along the linear array.

Since a broadband wavelength spectrum is taken at an instant in time, multiple sensors can be monitored at the same time (wavelength multiplexed) as long as the individual spectra from the sensors do not overlap. Sensors can be added or dropped without reconfiguring the measurement system. The system can be optimized for broadband wavelength (dispersion) coverage or for wavelength resolution by changing the spectrometer’s grating pitch. The center wavelength of the spectrometer can be changed to provide broad band coverage at maximum wavelength resolution. The spectral output will be useful when trying to use the sensors for other types of fiber loading such as bending, lateral compression, and to diagnose sensor failure mechanisms.

A commercial spectrometer will meet the needed specifications given in Table 1. The resolution of the spectrometer with a 50 μm aperture (pixel width) will be close to 0.1 nm and have 20 nm bandwidth for a 1.33 m cavity length. The spectrometer comes with a 256 x 1 pixel line camera which will acquire the entire wavelength spectrum at a rate of 7.0 kHz.

**CONCLUSIONS**

A measurement system design based on Fiber Bragg Grating sensors and a grating spectrometer measurement device has been presented. The measurement system is designed to simultaneously measure dynamic strains and temperatures. This will provide more efficiency in the design of systems requiring the ultimate limits of engineering materials. The stresses and temperatures in these materials can now be efficiently and dynamically monitored to assure that the ultimate limits of the materials have not been exceeded in a manufacturing or field environment.

The design contains sensing elements that are constructed from Bragg gratings and from hybrid Fabry-Perot interferometers built from fiber Bragg gratings. A theoretical simulation confirms that the shifts in center wavelengths from the fiber Bragg and the Bragg Fabry-Perot sensors at various strains and temperatures can be used to the separate
strain changes from temperature changes. The results of the study have been used to specify a commercial spectrometer and line scan camera as the wavelength monitoring device.

The grating based sensors can be wavelength multiplexed in a single fiber and monitored at the same time. Sensors can be added or dropped without reconfiguring the measurement system. The system can be optimized for broadband wavelength coverage or for wavelength resolution. The center wavelength of the spectrometer can be changed to provide broad band coverage at maximum wavelength resolution. The spectral output will be useful when trying to use the sensors for other types of fiber loading such as bending, lateral compression, and to diagnose sensor failure mechanisms. The novelty of the measurement system designed in this study lies in the simplicity and speed in which stress and temperature can be simultaneously measured.

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