Health Monitoring of Civil Structures using Fiber Optic Sensors

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Abstract

Objective: The monitoring of civil structures such as bridges, dams and buildings etc. is wide area of research and many researches had taken place in the past. This paper proposes the basic idea of using optical fiber as a sensor for monitoring civil structures and also discusses other methods of sensing. **Method**: The main idea behind using optical fiber as a sensor is detection of bending loss which occurs if there is any modification or bending in the structure. The fiber is attached to the structure to be monitored. The loss is induced due to scattering of signal which occurs when there is a crack or any such damage in the civil structure along its length where fiber is attached. **Findings:** This paper also discusses the method of using fiber grating sensor in sensing physical parameter and using it in monitoring of civil structures. **Improvements**: This basic method can be improved to using fiber sensors for effective measurement of any physical parameter which in turn can be used for civil structure monitoring to avoid huge accidents and human loss.

Keywords: Bragg Grating, Civil Structure Monitoring, Coupler, Filter, Optical Fiber, Sensor

1. Introduction

Health monitoring of civil structures is the recent research area that is motivated with the requirement of assessing the condition of the structures. Most of the repairing and maintenance works of huge civil structures like dams, bridges etc are done today based on visual observations only, which are subjected to change according to natural conditions. According to an earlier study, it is confirmed that more than 40 per cent of the civil structures are structurally deficient due to corrosion or other such natural calamity effects. In addition, many bridges and dams have experienced huge damage or collapse due to extreme natural disasters like earthquakes, hurricanes etc. It is important to detect damage in civil structures, as well as monitoring loads and fatigue on each structure's elements. Measuring and monitoring these changes, in the physical properties¹ of materials, is a field of study known as 'Structural Health Monitoring' and is based on the achievement of the periodic observation of a system

over time, the extraction of sensitive characteristics in the change of the variables and the processing of these features to determine the current state of a system. When structural damage is detected at some level, intervention must be performed in order to preserve health of the structure and safety for the persons involved, or planning the consequent and convenient maintenance actions. With the emerging new technologies, monitoring can be arranged from a remote central station. Optical fiber Sensors are to be attached along the civil structures at various locations. They will send information about some physical¹ parameters such as stress, strains, and accelerations to the central station from which warnings about any failure or damage can be obtained, thus the system can be made as a smart monitoring system.

Optical fibers as sensors are found as the best method for measuring wide variety of physical parameters which can be used in many applications. The monitoring of civil structures such as bridges, dams and buildings etc. is wide area of research and many researches had taken place in the past.

Fiber sensors are discussed as an attractive method for measuring some physical, chemical and biomedical parameters like stress, pressure, strain etc because of numerous advantages. The advantages are electromagnetic interference immunity, lightweight, smaller in size and ability to respond to a large range of measurements, electric sparks avoidance, harsh environment resistivity, remote operation, very good sensitivity, enormous potential bandwidth, and ease of implementation in multiplexed or distributed sensors. Due to these large number of advantages, the fibers have been developed as sensor in the last two decades². Stress, Strain, Pressure and Temperature are the most widely used physical parameters to monitor civil structures and the fiber grating sensors are found to be the best approach for such measurements.

Many sensors developed from fiber today are classified into two groups: interferometers and intensity based devices. Optical phase is affected in the former while the optical intensity is modulated in the later. In general, interferometer are advantageous with very high resolution, good accuracy and good configuration versatility³. But, they are disadvantageous in relative measurement, ambiguity in fringe direction, and costly signal processing^{4.5}. White-light interferometry⁵ is one of the commonly used method to overcome these problems, but at the cost of low-frequency response and reduced resolution. The intensity-based devices are in turn advantageous in signal demodulation simplicity, absolute measurement accuracy, and high frequency response. Equivalently, in addition to the physical parameter under measurement, the output of sensor is also sensitive to variations in source power and fiber bending losses and these are often misinterpreted as changes in measurand.

Various studies show the use of optical fiber sensors in wide range of applications in various engineering fields. Studies on fiber Bragg grating used as sensors in measurement of physical parameters which in turn is applied in civil structure monitoring⁵. The devices like add/drop filters, amplifier gain flattening filters, dispersion compensators, fiber lasers etc, when used with Fiber gratings can be used for optical communications⁶. FBGs respond to both strain and temperature. There are systems⁷ to detect hazardous materials or gases, liquid spills from ducts, tanks, tunnels etc. Some examples are leak detection systems made up of thin layers of polymers can be used to measure the liquid of interest. The subsequent process induces a micro bend at a specific location which can be detected from the fiber characteristics. An alternate method is to use a chemical coating on outer surface of the fiber cladding. Losses induced by the chemical properties of fiber cladding can be easily detected^Z. One such system under evaluation is to detect gases which are hazardous and toxic in buildings and tunnels. By changing the source of illumination to the fiber, the properties of chemically active cladding can be reactivated when excited to typical ultraviolet radiation.

The sensor is beneficiary in this way.

2. Optical Fiber as a Sensor

The technique used here is the optical fiber itself acting as a sensor for detecting bends trough which failure or damage in a structure can be detected. An optical fiber is a thin circular cylindrical waveguide which is made of glass and is able to support propagation of light in it. The light signal is guided by confining it in regions called core and cladding having different optical indices of refraction. The central portion is called the core which guides most of the light. Around the core, there is a region of smaller refractive index, called as the cladding. Light travels inside the core and along the fiber by a phenomenon called total internal reflection through bouncing off the interfaces with the cladding.

Properties of optical fiber make it easy to use as a sensing material. The objectives of this proposal are to use bending loss as a sensing constraint and detect macro bending and ignore the losses due to vibrations or micro bending by keeping suitable reference voltage.

2.1 Bending Losses

2.1.1 Macro Bending

Bends with larger radius of curvature with respect to fiber diameter are called Macro bends. Figure 1 shows the representation of a macro bending. The loss due to these bends is huge when the radius is smaller than few centimeters. Any waveguide with dielectric like optical fiber will radiate if it is not absolutely straight. The radiation loss in the cladding is produced by the bending of a dielectric waveguide even if the propagating ray is greater than the critical angle (dark region).



Figure 1. Representation of Macro bending.

2.1.2 Micro Bending

Losses due micro bending refer to attenuation of an optical fiber light signal due lateral pressure along the length of the fiber. Figure 2 shows the representation of micro bending. The loss is due to the coupling of fundamental mode to higher-order radiation modes. This kind of coupling occurs due to fibers undergo small bends randomly along the fiber axis when they are inserted into cables or outer jackets for safety purpose. This process causes mechanical stresses externally which will compress the fiber cable. Due to this random, high-frequency perturbations are introduced in to the fiber. Lateral stresses can be caused by pressure induced by manufacturing or installation or by temperature-induced dimensional changes in cabling materials that cause undesirable fiber/fiber or fiber/cable material interactions. These interactions can give rise to random microscopic bends or curvatures of <1-mm radius that create very small displacements of the fiber core from the fiber axis.



Figure 2. Schematic representation of micro bending.

2.2 Basic Method of Sensing

Figure 3 shows the setup for Damage detection and Alarming.

The LED can be used as a light source for the optical fiber and the light is passed through the optical fiber according to the law of total internal reflection. This light at the other end is given to the detector circuit i.e. photodiode. The detector output is further connected to the amplifier to amplify the weak detector signal to a desired level which is required for the working of LM358N. This Amplified output is given to the comparator circuit of LM358N. This gives output either high or low depending on the input signal and reference voltage given to it. These high low signals are given to the digital input pin of arduino board (micro controller) which treats it as zero when low and one when high. The arduino is programmed to ring the alarm when zero is there at the input pin i.e. when there is bending loss in the fiber it rings the alarm and if there is one at the input the alarm doesn't ring. This alarm indicates that there is some modification or damage in the civil structure and gives the alert for the safety of individuals.



Figure 3. Setup for Damage detection and Alarming.



Figure 4. Fiber in the roof of a Building.



Figure 5. Fiber along the bridge.

Figures 4 and 5show the use of optical fiber as a sensor for monitoring any damage in the structures like bridges and roofs. Two basic monitoring methods are available. One of the methods uses Rayleigh scattering changes along the length of a fiber [Figure 4 & 5]. These changes are caused either due to micro bending loss or cladding loss caused by measuring parameter. A mechanical coupling is essentially used in this method and the chemically changing environment induces the mechanical changes. Another method uses modifications introduced in a cladding material which is designed specially. In these methods, large losses will be produces in the base fiber due to interferences in its propagation characteristics. Hence these losses limit the distance range of this type of sensors to 10 kilometers.

3. Fiber Grating Sensors

Optical sensors based on Bragg gratings have shown many advantages in measurements of mechanical stress, temperature and other physical properties¹. Optical sensor² technologies have become very important due to their inherent optical advantages such as light size and weight, their ability to multiplex signals from various sensors along a single fiber and their applicability in explosive environments. These sensors are suitable to perform measurements in civil structures, where their inherent optical properties are useful, especially because of their ability to multiplex signals from each measurement point in order to perform distributed sensing.

Fiber Bragg grating sensors (FBGs) are one of the various optical sensors² currently available and basically consist of a periodic perturbation in the refractive index in the core of an optical fiber, which is usually induced by the exposure of the fiber to an UV writing beam spatially modulated by a periodic surface-relief pattern. After this perturbation is inscribed, the optical fiber acts as a selective filter for specific wavelengths, and it automatically becomes in a sensor when external physical variables affect the fiber and thus the reflected wavelength.

3.1 Fiber Gratings Types

Bragg fiber grating sensors have proved multiple advantages, especially in temperature and mechanical stress measurement, which is why they have had great success in civil engineering applications³, where it is more important to monitor variables than to measure them. FBG sensors are a relative new alternative to measure these variables⁶ because, they can be attached in small areas or with difficult access; they can even be embedded into the interest surface. They can be used in environments susceptible to explosion because they do not carry electricity so they cannot generate any kind of spark. They can perform distributed measurements of both mechanical stress and temperature along a surface.



Figure 6 (a). Bragg Fiber grating (b) long-period grating, (c) chirped grating.

Figure 6 shows fiber grating types. A Bragg fiber grating (BFG) is a sensor which couples modes in the core where one is forward propagating and the other is backward propagating, under phase matching conditions. A long-period grating (LPG) is the one in which the core mode is coupled to one or a few of the cladding modes where both are forward propagating. The third type shown in figure is a chirped fiber grating which reflects different wavelength components at various positions, resulting in a time delay difference for various reflected wavelengths. Thus it has a wider frequency spectrum. A tilted fiber grating is another type in which the forward propagating core mode is made to couple to the backward propagating core mode and a backward propagating cladding mode. A sampled grating fiber is the one in which several wavelength components are reflected at equal wavelength spacing. Various fiber grating sensors utilize all the above said fiber grating types and wavelength change interrogators. Among them, however, BFGs are the most widely used as sensor heads. In BFGs the Bragg wavelength $\lambda_{\rm p}$, or the light wavelength that is reflected, is given by $\lambda_{\rm B} =$ $2n_{\rm eff}\Lambda$, where $n_{\rm eff}$ is the fiber core effective refractive index and Λ is the period of grating. From the equation, it is known that the Bragg wavelength can be modified with a change in the period of grating or the effective index of refraction. The first change is for strain and the other is

for variation in temperature. The period of grating may also be modified with variation in temperature, but the effect of temperature on index of refraction is about one order of magnitude greater than that of thermal expansion (or contraction), around the room temperature.

Interrogators, otherwise called as demodulators are also required for BFG sensors. Their purpose is to extract the information about the measured physical parameter from the light signals which are from the sensor heads. The measured parameter is encoded in the form of a change in Bragg wavelength, and therefore, the interrogators are expected to read the wavelength shift and provide data about measurand.



Figure 7. Setup to detect Wavelength Shift.

Figure 7 shows a typical setup to measure the wavelength shift. The power change is detected from the setup and is used to monitor the shift in Bragg wavelength. The structure shown is simple and is been commercialized, but it is not suitable for sensors when multiplexed. This power-detection method does not use one of the key advantages of BFG sensors, that is, information about measured parameter is coded as change in wavelength and the fluctuations in light power will not affect the information. Figure 7 shows a power-ratio detection technique which is used to remove any loss or fluctuation in the light power.

There is a requirement of measuring dynamic strain in huge structures such as bridges and dams. The minimum detectable strain can be determined by the background noise-level, when the dynamic signal is measured. The magnitude of noise varies with the frequency period because the noise power in the detector and amplifying circuit depends on the frequency period. In general, by scaling the power spectral density (psd) of noise by the square root of the bandwidth, the amount of magnitude of noise in other bandwidths can be approximated. Thus, the minimum detectable normalized dynamic strain is displayed in units of ε/\sqrt{Hz} .

4. Future Scope

In the basic method of sensing bending loss of fiber, only alarming signal generation is proposed. It can be enhanced to provide control signals to a central monitoring section through GSM and GPS tools so that the damages detected in the structures can be repaired in time and/or to take necessary action immediately to avoid any major loss of resources or human beings. Fiber optic gyroscopes are the alternate choice of fiber grating. Due to its ruggedness and having no moving part, it can be used as the cost efficient solution in navigation and military applications. Using fiber optic current mirrors, sudden changes or failures in power systems can be detected and separated.

5. Conclusion

This paper discusses about a simple technique of using an optical fiber as a sensing tool for detecting any damage in the civil structures like bridges, dams etc. The technique is based on detection of micro bending losses due to any external stress or any other damage in the structure. This technique can be used ignoring macro bending losses and other relevant parameters. When implemented on a large scale basis, efficient technique using fiber bragg grating and other such sensors is also discussed. These fiber optic sensors are not only used for various traditional measuring parameters such as strain, pressure and temperature but also for new applications where biosensors play a major role. They also find wide applications in chemical, power and bio engineering fields.

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