Comparative Assessment of Fiber Optic Strain and Curvature Sensors in Automated Condition Monitoring

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Abstract: – Fiber optic strain sensors are routinely embedded in or attached to structures to achieve condition monitoring under mechanical loading. Main conceptual features of these sensors are summarised in the first part of the paper. They are then contrasted with literature reports about their ill-suitability for their main purpose: strain sensing. An alternative is suggested next, which is to monitor structural deflection-curvature as a means of assessing structural deformation (or external loads). This is followed by the overview of curvature measurement. The application domain is specified in which the curvature measurement offers advantages over the alternative of measuring strain in terms of the measurement sensitivity, flexibility to choose the location for the sensor placement, and immunity to the effects of microstructural interfacing between dissimilar materials that the sensor presence introduces. Mode coupling effects are introduced as the main drawback of curvature measurement even though they actually increase fiber bandwidth.

Key words: Deformation-curvature, Strain, Measurement, mode coupling

1 Introduction

While the fiber optic technology has already assured its prominent place in communications, its more widespread role in real-time structural monitoring seems to be equally promising. From bridges and dams, to aircraft and pressure vessels, the condition of almost any safety-critical structure could be monitored, and the information transmitted to a centre where the structure=s response to its environment and loading could be compared to that predicted by a computer model. Textbook reviews are available of the wide ranging existing and possible future applications of structural monitoring using fiber optic sensors [1-3]. A commonality between an aging aircraft frame and a building attacked by terrorists is that a prompt assessment of the structure=s condition following an impact, or a timely detection of progressive material-crack propagation, corrosion damage or fatigue degradation, can save many lives.

Optical fiber sensors are extremely small in diameter, very light, and resistant to corrosion and fatigue. Being dielectric, they do not represent electrical pathways within a host structure and are immune to electrical interference. The dual role for the optical fiber as a sensor and pathway for the signals simplifies the sensing architecture with respect to the conventional sensing technology. While many different measurands can be sensed, fiber optic strain sensors have been utilised for structural monitoring most commonly [2,3].

2 Fiber Optic Strain Sensing Concepts

The Michelson fiber optic interferometer is probably the simplest interference-based fiber optic sensor. As illustrated schematically in Figure 1, coherent (laser) light is divided by a coupler and sent down two optical fibers. One is a sensing and the other is reference fiber. Their mirrored tips reflect the light back to the coupler and further to the photodetector. The two reflected lightwaves reach the coupler with a phase difference because they travelled unequal path lengths along the respective optical fibers. This phase difference is the information content provided by the sensor. It varies as the sensing fiber is stretched/compressed with the surrounding structure relative to the reference fiber. Measurements by the Michelson fiber optic interferometer are distributed along the entire length of the sensing fiber. Such nonlocalized nature of this sensor may be unsuitable for many applications. Moreover, the need to shield the reference fiber from strain and temperature changes often represents a particularly serious problem for practical structures that are invariably subject to high levels of mechanical vibration [2].

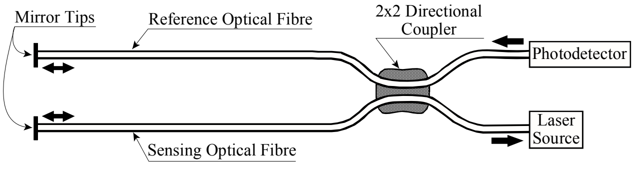

Figure 1: Michelson fiber optic interferometer

FabryBPerot fiber optic interferometer requires only the sensing fiber. Its design may include a mirrored tip and a fusion splice that forms a partial mirror (it is semi-transparent). These two mirrors must be perpendicular to the axis of the optical fiber. Between them, they define a resonant cavity of a desired gauge-length as depicted in Figure 2. The length of this cavity, and hence the phase difference between the waveforms reflected from the two mirrors, varies with the material strain of the surrounding structure. The semi-transparent nature of the mirror produced by fusion splicing allows interrogation of the interference conditions inside the resonator as well as the resupply of light by a detection system and laser source coupled at the far end of the fiber. Up to this mirror, the FabryBPerot sensor may be thought of as a Michelson interferometer with the reference and sensing fibers one and the same [2]. As they are therefore exposed to the same vibrations and strain, improved suppression of such noise affecting the fiber length that leads to the sensing element is possible electronically.

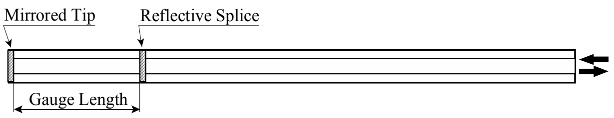

Figure 2: Fabry Perot fiber optic interferometer

Much research is currently focussed on fiber optic Bragg grating sensors of strain. Their particular potential is in multiplexing strain readings at a number of points along a single optical fiber. The sensor requires formation of a fiber optic Bragg grating, which is a periodic variation of the index of refraction along a section of an optical fiber. It may be produced by exposing the core of the optical fiber to an interference pattern of intense UV-laser light. This periodic perturbation in the core index of refraction gives rise to successive coherent scattering for a narrow band of the incident light centred around the "Bragg wavelength" λ_B. Thus, the grating acts as a stop-band filter, reflecting light with wavelengths close to λ_B, and transmitting wavelengths sufficiently different from λ_B. The Bragg wavelength λ_B is directly proportional to the periodicity of the variation of the index of refraction introduced along the section of the optical fiber. Any change in the local strain or temperature modifies the grating period and, consequently, changes the Bragg wavelength (causes a shift of λ_B). If multiple groups of Bragg gratings are built along a single optical fiber, each with a different period of grating, each would have its own reflection spectrum. Monitoring shifts of the corresponding Bragg wavelengths determines the main strain at the corresponding multiple locations. Such multiplexing eliminates much of the wiring of the conventional sensing systems.

3 Comparison of Strain and Curvature Measurement Concepts

3.1 Sensitivity Comparison

In bending of beams and plates, curvature *(K)* is functionally related to strain *(ε)* by $\varepsilon=zK$ where z in general is a constant proportional to the structural thickness and equals one half of it in the usual case of structures with symmetric cross-sections. Hence, an increase in curvature of ΔK corresponds then to an increase in strain of $\Delta\varepsilon$: $\Delta\varepsilon=z\Delta K$. Let ΔK be the measurement resolution of the curvature gauge (quantified later in this text). The special value of z, and therefore of the structural thickness (usually $2z$), can then be calculated such that $\Delta\varepsilon$ is exactly the measurement resolution of a strain sensing device that we want to compare the curvature gauge to. It follows that curvature measurements provide more resolution with structures thinner than this "breakeven" thickness. Conversely, strain measurements are more appropriate for thicker structures.

Relative to a strain gauge sensitive to 10 με as a reference, the sensitivity of one curvature sensor called "curvature gauge" (described later in this text) establishes the "breakeven" thickness between the two gauges (strain and curvature) at $2z$=16 mm. Similarly, with respect to a 1 με interferometric sensor [5], this "breakeven" thickness is 1.6 mm. In many practical applications, consumer products in particular, the latter boundary would tilt further in favour of the curvature gauge if the cost factor is considered as well; not including the data acquisition system, the cost of curvature gauge is just a few (~4) US dollars each.

3.2 Measurement (In-)Variability with Location

It is well known that strain in bending varies sharply across the structural section. Along the neutral plane, strain cannot be measured. In contrast, curvature measurement is position independent because the radius of structural deformation-curvature is five to seven orders of magnitude larger than the structural thickness. This property of the curvature-measuring concept is important for embedded sensory applications because the exact sensor position within the section need not be assured (precision is not required while embedding the sensor). Moreover, as measurements along the neutral plane are possible, curvature sensors may be sandwiched within two-ply composite materials where strain measurements are not possible. This allows designers the flexibility of leaving the surface of two-ply products free, thus achieving aesthetically more appealing designs with improved resistance to wear and tear. Multiple curvature gauges were embedded routinely at the neutral plane of the composite beam where axial strain could not be measured.

Moreover, being position independent, curvature gauges pre-calibrated in a laboratory in advance may be embedded with no need to repeat the calibration thereafter. This is unlike the application of any strain sensor that must be re-calibrated following its integration into the structure in order to account for its exact location.

3.3 Measurement Ambiguity

Because of the issues involved in the strain transfer to the sensing element, much work has been devoted to the question of "what do optical fiber strain sensors really measure?" [6]. While the fibers must be stretched or compressed by the applied loads in order to complete strain measurement, this is something they resist strongly. The micromechanics involving the sensor/structure interface materials (fiber jacketing, resin, adhesive,...) affects strongly the load transfer to the sensing element by cushioning the loads. While micromechanical analysis provides a framework for overcoming these problems by regarding the interface in question as a multiphase entity [6-8], it also introduces an additional degree of complexity to the strain measurement. In contrast, optical fibers render negligible resistance to bending. Moreover, as curvature is constant across the section, there can be no "curvature concentrations" B a term derived by analogy to the stress concentration problem affecting strain measurement. The ambiguity between the true and apparent values of the measurand, which can be a serious problem in measuring strain, is thus eliminated with fibre optic deflection-curvature sensors ('curvature gauges').

In addition to the measurement ambiguities associated with embedded strain sensors, it has long been known that the inclusion of sensors into composite materials produces adverse effects on the composite microstructure. Typically, a resin-rich region forms around the embedded fibre, representing a local discontinuity. While this is probably inevitable whether the fibre optic sensor measures strain or curvature, by eliminating the constraints on the sensor location, curvature gauge allows the designer to choose this location with the objective to minimise the degradation of gross structural properties caused by the sensor presence.

4 Fibre-Optic Curvature Sensors

Patrick *et al.* [9] have examined the changes in wavelength and attenuation of long-period fiber gratings subjected to bends with curvatures from 0.8 m^{-1} to 4.4 m^{-1}. They have concluded that the curvature-measurement resolution of 2×10^{-3} m^{-1} should be possible in principle with fibre grating devices. The same authors have also concluded that the magnitude of the bend-induced wavelength-shift depends on the rotation of the cylindrical fiber relative to the bending plane, and have observed a cross-sensitivity to strain and temperature. For this reason, they have placed their sensor at a strain-free location to avoid the wavelength shifts induced by undesirable strain.

Liu *et al*. [10] have reported on an effective new method of achieving bend-sensing based on the measurement of bending-curvature encoded resonance mode-splitting of long-period fiber grating. It is based on the observation by Rathje *et al*. of resonance mode splitting by an LPFG produced in a fiber with a large core concentricity error. Their experimental results demonstrate this mode splitting in a single-mode B/Ge photosensitive fiber. The bend-induced mode splitting exhibits a near-linear response and the bending sensitivity achieved is nearly four times that of the wavelength-shift detection method.

Gander *et al.* [11] were the first to demonstrate the measurement of curvature using Bragg gratings written in separate cores of a multimode optical fiber. Their gratings acted as independent, isothermal, strain gauges. The difference in Bragg wavelength between the two gratings provided a temperature-independent measurement of the local curvature. This approach promoted the mechanical stability and maintained both gauges at the same temperature, allowing the sensor to be deployed in thermally uncontrolled environments. Although the Bragg wavelengths of the individual FBGs will vary with temperature and with uniform axial strain, their difference $\Delta\lambda$ depends only on the bend-induced difference in strain between the isothermal gauges. The sensitivity of over 6 m^{-1} has been determined by bending the fiber on a template with machined circular arcs of known curvature and measuring the grating wavelength separation.

Curvature sensing was also achieved using bandpass filters based on phase-shifted LPFGs [12]. The transmission characteristics of the LPFG were altered by the tension- and compression-strain induced by the bending curvature. The LPFG was attached to a flexible plate with flat surface, so that tension or compression strain could be applied to the LPFG depending on the sign of the bending curvature. The strain applied altered the transmission spectrum by changing the grating period and including the stress-optic effect. As the tension is applied with positive bending curvature, the resonant wavelength shifts towards longer wavelengths with the increase of the grating period. On the other hand, it shifts towards shorter wavelengths with compression or negative bending curvature. The measurement range is from about 0.3 m^{-1}.

Ferreira [13] presented a new configuration based on the intrinsic bend sensitivity of Bragg gratings written in D-type fibers. This sensor can be embedded in any layer of a composite material to evaluate curvature independent of axial strain or temperature. It can also be used to measure other parameters such as acceleration, angle or acoustic pressure. The suggested configuration consists of a pair of D-type FBG sensors placed side-by-side along the plane defined by the D-shape cladding that exhibit differential sensitivity of bend and common-mode rejection to temperature and/or axial strain. During the experiments, they found that the system output ($\Delta\lambda_{B2} - \Delta\lambda_{B1}$) depended only on the applied curvature, while other physical quantities caused a common Bragg wavelength shift (of $\Delta\lambda_{B2} - \Delta\lambda_{B1} = 0$).

Gwandu *et al.* [14] reported the first simultaneous measurement of strain and curvature with temperature compensation. They used a single superstructure fibre Bragg grating (SFBG). The SFBG exhibited the properties of both the fibre Bragg grating (FBG) and the long period fibre grating (LPG) such that its spectral response facilitated strain measurement from the wavelength shift of the FBG-like characteristic, and independent measurement of curvature from the LPG-like mode-splitting. The dependence of the LPG mode-splitting on the mode order has also been investigated and utilized for the measurement of smaller curvatures. It was found that the splitting of the LP_{06} mode was not apparent for small curvatures due to the weak coupling strength of this mode. The pronounced mode-splitting for the LP_{03} and LP_{04} modes occured at significantly smaller induced curvatures, resulting in the resolution of 0.13 m^{-1}.

The major feature of all these curvature sensors is summarized in Table 1. It is evident that they can be used only for curvatures larger than 0.13 m^{-1}. In other words, the maximum detectable curvature radius is less than 8 m. This is far insufficient for monitoring elastic deflection-curvature of most engineering structures.

Table 1: Curvature sensitivity of different methods

Reference	***Basic measurement concept***	***Curvature resolution***	***cross-sensitivity to strain and temperature***
H.J.Patrick *et al.* [9]	Shift in the centre wavelength of LPG	0.8 m^{-1}	Must place the sensor at a strain-free location
Y.Liu *et al*. [10]	Resonance mode splitting of LPG	0.4 m^{-1}	None
YG Han [12]	Bandpass filter, phase-shifted LPFGs	0.25 m^{-1}	None
L.A.Ferreira *et al.* [13]	Two D-type fibres with FBGs, side-by-side along the plane defined by D-shape cladding: wavelength shift $\Delta\lambda_{B2} - \Delta\lambda_{B1}$	1.5 m^{-1}	Insensitive to temperature and strain
B.A.L.Gwandu *et al.* [14]	"Superstructure" fibre Bragg grating for simultaneous strain and curvature sensing: curvature modulates the spectral splitting of the SFBG loss bands	0.13 m^{-1}	The wavelength shift of the FBG harmonics determines axial strain

5 Curvature Gauge

As summarised in Table 1, the smallest detectable curvature (0.13 m^{-1}) has radius of curvature of 8 m or smaller. Only one remarkably simple device achieves higher resolution: 'curvature gauge' [15]. It is an intensity-modulated optical fiber sensor and can measure curvatures with the radius in the km range (curvatures of even less than 0.001 m^{-1}). As such, it can measure structural deflection-curvature [15]. Radii of structural deflection-curvatures are typically in a kilometre range, making such curvatures indistinguishable from straight lines under visual inspection.

In order to measure minute curvatures, the optical fiber of the curvature gauge is specially sensitised by precision machining into the core of a selected fiber segment. Such machining consists of hundreds of closely spaced cuts of uniform depth across the fiber. These cuts are made by a flywheel with a continuous blade. The pitch of cuts is below the width of the blade. The 'sensitive zone' thus produced introduces transmission losses by radiating the light out of the fiber (illustrated in Figure 3). The strength of the light source used must be adjusted for the zone length and depth. Because the fiber is machined asymmetrically on one side only, the convex ("positive") bending of the zone can be differentiated from the concave ("negative") one. Losses increase in the former and decrease in the latter case relative to that of the straight-line configuration. In the perpendicular plane, the sensor is virtual insensitive. Experiments have confirmed that a *cosine* function describes the sensor response between these two principal sensor planes defined by the plane of machining. With two gauges applied on beams with circular cross-sections, such preferential directional sensitivity allows simultaneous determination of both, the magnitude and the plane (direction) of beam bending.

The curvature gauge resolution of 1.6 km radius (0.0006 m^{-1} curvature) has been reported [15]. Moreover, by analogy to the placement of strain gauges, curvature gauges can also be employed in pairs arranged in opposition such that one bends concavely when the other bends convexly. Such arrangements improve the sensitivity further since algebraically subtractive readings are obtained for magnitudes with opposite signs. They also allow rejection of the common mode noise, including that of the light-source intensity-fluctuation.

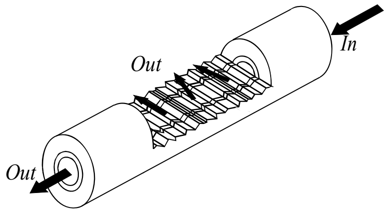

Figure 3: Curvature gauge schematics

6. Mode Coupling Effects

6.1Mode Coupling in General

Transmission characteristics of step index (SI) plastic optical fibers that curvature gauges are made of depend strongly upon power transfer between light-propagation modes caused by fiber impurities and inhomogeneities introduced during the fiber manufacturing process (such as microscopic bends, irregularity of the core-cladding boundary and refractive index distribution fluctuations). Referred to as mode coupling, this power transfer is from lower to higher order modes (with respect to the fiber axis).

In the absence of these intrinsic perturbation effects, light launched at a specific angle with respect to the fiber axis to form a sharply defined ring radiation pattern at the input fiber end would be imaged at the output fiber end as a similarly sharp ring pattern. For real POFs, however, this is true only for very short fibers (e.g. 2 m). Due to mode coupling, the boundaries of the ring become blurred at the end of longer fibers. This fussiness increases with fiber length. As the ring-pattern evolves gradually, it eventually takes the form of a disk covering the entire fiber cross-section in fibers longer than some “coupling length” (L_c).

There are only disk (not ring) patterns beyond the coupling length regardless of launch conditions, although these conditions still influence light distribution across the disk until the equilibrium mode distribution (EMD) is achieved at some longer length. EMD indicates the completion of the mode coupling process when the output light distribution is independent from launch conditions [16].

6.2Effect on Curvature Sensing

In addition to internal inhomogeneities, fiber curvature also contributes to mode coupling. It has long been known that the mean of the power distribution shifts towards the complex side of the curved fibre. This is illustrated in Fig. 4 that shows two orthogonal views (global YZ and XZ) of a fiber with a gradually increasing curvature. Ray trajectories are included for twelve meridional beams launched at the input fibre end marked as “Section A”. The three larger circles in Fig. 4 are the “true views” in the fiber cross-section that map locations of the rays within three selected fibre cross-sections: A, B and C. If the fiber was straight, the ray locations would have been as indicated in the three smaller circles. It can be noticed that as the fibre curvature increases, so does the shift of rays towards the convex side of the fibre section.

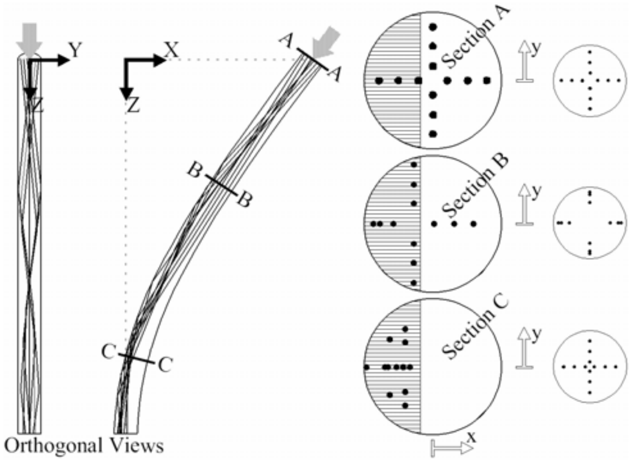

Figure 4: Power shift due to curvature

Fig. 4 in conjunction with Fig. 3 help explain the operation of the curvature gauge by revealing the modulation mechanism of the sensor. However, it is apparent that curvature of the lead-in section of the fiber will also be a factor contributing to the sensor reading. In other words, if a length of the fiber prior to Section-A in Fig. 4 is of varying curvature, the effect is equivalent to that of varying launch conditions and the sensor reading will vary even if the curvature to be measured at B and C is constant.

In terms of this noise effect, mode coupling by intrinsic fiber inhomogeneities (described in 6.1) have a positive effect. All that is needed is for the length of the fiber equal to at least the coupling length L_c preceding the measurement point to of constant configuration (curvature). The noise introduced by the lead-in section distance L_c before the measurement point is thereby eliminated. In practice, this would mean that a fixed coil of some 20m of fiber length is necessary before the measurement point.

7. Conclusions

While strain sensing is the usual choice when selecting how to monitor the structural response or external loads, it is not the best choice for many embedded applications (embedded in composite materials). The alternative approach that calls for monitoring of structural deflection-curvature to achieve the same objective is preferred especially for thinner structures. For an equal amount of deflection, the thinner the structure, the easier it is to measure deflection-curvature (rather than strain). Moreover, ambiguities associated with the strain measurement due to microstructural effects caused by the sensor presence and cushioning of the load transmission by the interface material (resin, jacketing, adhesive, etc.) are avoided. Structurally embedding curvature sensors is also simpler because the same readings are obtained anywhere throughout the structural cross-section, including along the neutral plane where strain cannot be measured. This means that no particular through-thickness location has to be assured for the sensor, so it may be placed within two-ply composites, or its location in a cross-section may be selected to minimise degradation of gross structural properties caused by the sensor presence. It is a disadvantage that in curvature sensing a fixed length (~20m) of fiber has to be fixed to the structure so that that the geometric configuration (curvature) of the lead-in length of the fiber would not affect measurement.

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