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REVIEW PAPER

Optical Fiber Sensors for Smart Structures : A Review

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ABSTRACT

This review describes recent advances in optical fiber sensors for smart structures. After discussing the fabrication technology and strain sensing of fiber-optic sensors in a brief introduction, the detailed accounts of signal processing techniques empolyed in them are given. The application areas of fiber-optic sensors are also described briefly with necessary references. Future trend of work is indicated in the concluding remarks.

1. INTRODUCTION

With the development of advanced composite materials, fiber-optic sensors embedded in them have been recently found to evolve 'smart structures' capable of monitoring continuously their own vibration, internal strain and deformation, temperature, and structural integrity. The fiber-optic sensors offer several advantages, such as small size and light weight, high corrosion and fatigue resistance, immunity to electromagnetic noise and interference, compatibility with composites, and practical insensitivity to initiating fires or explosions. These advantages make them suitable for embedding within advanced composite materials, where they can serve as sensors and conduits for the sensory signals or other optical signals. An issue of particular interest is the application of fiber-optic sensors to aerospace community.

A 'smart structure' can be called 'adaptive' if the information provided by a built-in sensing system controls the stiffness, shape, position, or orientation of a structure. Twenty-first century aircraft might rely on smart adaptive wings for optimised aerodynamic control and greatly reduced mechanical complexity, leading to concomitant reductions in maintenance, repair and downtime. The aircraft founded on smart structure technology could monitor their loads, check their structural integrity and airworthiness, reduce their vibration and flutter and moderate their gust response. They could also provide real-time corrective action in response to any mechanical failure and schedule post-flight repair and maintenance. As a consequence, it would improve safety with reduced operational cost[1-5].

A variety of fiber-optic sensors for 'smart' materials and structures applications has been proposed for monitoring the thermo-mechanical state of load bearing structural materials. Fabry-Perot (FP) type sensors have been extensively studied with intrinsic Fabry-Perot (IFP) and extrinsic Fabry-Perot interferometer (EFPI) configurations. The IFP uses semi-reflective surfaces deposited on the end faces of a fiber 'spacer' to serve as the FP cavity, while the EFP uses an air gap between two cleaved fiber end faces to serve as the cavity[6-10]. Both IFP and EFPI configurations have shown promise for structurally embedded applications due to their relative fabrication ease, lead-insensitivity and high strain resolution.

Embedded intrinsic interferometric sensors that are highly sensitive to strain have been demonstrated in composite materials by several researchers. Due to their high sensitivity and manufacturing difficulties, the interferometric sensors embedded in composite materials are designed with short sensing lengths of a few millimeters. Exceptions are the two-mode strain sensors which use sensing lengths in the centimeter range[11]. In general, intrinsic interferometric sensors are embedded between layers of composite materials for pointwise strain measurements[12-14]. Even with the small size of the sensors, some reduction of the layered composite structure's strength and durability can be

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expected[11-15]. Some researchers have rigorously treated the embedded sensor as an elastic inclusion in thehlost material[16,17]. Others have tested the hypothesis that the embedded sensor is unobtrusive such that the strain state in the host material is nearly unaffected by the presence of the sensor[14]. It has been shown that polymeric-coated optical fibers are usually used for non-destructive monitoring of structures and for deformation measurements. When these optical fibers are embedded in cement mortar bodies and exposed to concrete-specific chemical attacks, all of the coatings have been found to be changed depending on the extent of the mortar or of the exposure to chemical attack of alkaline solutions. But the coated fiber does not suffer serious damages which contribute to a deterioration of the long-term stability of the fibers and their components[18-20].

The polarimetric technique has also been fruitfully employed to detect internal strain in the composite materials[21]. This technique makes use of birefringent optical fiber and is capable of taking into account micro-mechanical strain transfer mechanism from the host material to the fiber, accurately. Fiber sensors embedded in composite materials are normally embedded after being stripped of their plastic jacket.

In the following sections, fiber-optic sensors particularly strain sensors will be presented. The Section 2 explains the basic principle of working of fiber-optic sensors, attention being paid on interferometric strain sensors. In Section 3, focus has been made on fabrication technology of smart structures which includes some issues on the embedding of optical fibers within composite materials, the special techniques and the choice of materials. Since strain is one of the important parameters associated with the smart materials, the basic theory of strain sensitivity of fiber-optic sensors has been discussed in Section 4. Signal processing of the electrical signal which is the result of opto-electronic conversion of optical signal associated with the strain is playing a key role for faithful recovery of strain sensing in smart structures. Thus various signal recovery issues have been critically examined in Section 5. Section 6 describes briefly the spectral encoding and decoding. Coherent detection and measurement of absolute strain have been discussed in Section 7. Some important applications of fiber-optic strain sensors in smart structures have been elaborated in Section 8. Section 9 on concluding remarks specifies the potentiality and the current state-of-the-art of fiber-optic sensor technology.

2. PRINCIPLE OF FIBER-OPTIC STRAIN SENSOR

Fiber-optic sensors can be classified into four major categories : intensiometric, interferometric, polarimetric and modalmetric. Three questions pertinent to the selection of the type of sensor are whether a single optical fiber is required per sensor; whether the sensing region is localised (made with insensitive lead-in and lead-out optical fibers); and whether the sensor can be single-ended. The sensitivity is also very important. Considering all these criteria, the interferometric sensors fulfill all the requirements unlike the other types and hence they have been successfully incorporated for strain-sensing in smart structures.

The working of the fiber-optic interferometric strain sensor is based on the principle of interference. The fiber-optic interferometers which are mostly used for strain-sensing are either Fabry-Perot interferometers or Michelson interferometers. Usually the sensing arm is generated by embedding the optical fiber (with its plastic jacket stripped of) within the composite material. The reference arm is another optical fiber of the same type passing outside the composite material. One end of each of the fibers is mirrored. The light from a laser source is at first split equally by means of 3 dB (50:50) coupler, and the two beams are allowed to pass through the fibers. If there is any strain occurring inside the composite material (sensing arm), the optical signal through the sensing arm will suffer an extra phase change. Thus the interference will take place owing to the phase difference between the optical signals through the sensing and reference arms. The interference associated with changes in the strain will modulate the intensity of the light output incident on the photodetector, and through appropriate signal processing techniques, the strain can be estimated.

The performance of these devices is promising; it may eventually surpass the performance of the conventional electrical strain gauges. These resistive-foil devices require a wheatstone bridge to recover the signal, whereas the interferometric-type fiber-optic sensors require phase modulation to recover the signal. The sensitivity of the wheatstone bridge is limited largely by its inherent imbalance. On the other hand, these optical sensors have a sinusoidal-type output and often cover tens of periods within the measurement range. Hence the fiber-optic interferometric strain sensor has been proved to be superior strain-measurement device in contrast to the resistive foil electrical strain gauges.

A fiber-optic sensor must satisfy several properties. It should be

(a) Completely fiber optical for operational stability, with not more than one optical fiber per sensor for minimum perturbation and common-mode rejection.

(b) Insensitive to interconnect phase interruption.

(c) Intrinsic to minimum perturbation and stability.

(d) Capable of sensing the direction of measured field change.

(e) Localised, so it can operate remotely with insensitive leads.

(f) Immune to shutdown of the signal-processing electronics[1,22].

3. FABRICATION TECHNOLOGY OF SMART STRUCTURES

The basic reason that the fibers are particularly attractive for embedding within composite structures is that for the most part they serve the dual role of sensor and pathway for the signal, and since they are dielectric in nature they are compatible with the composite material, avoiding the creation of electrical pathways within the structure. This is very important as composites are used increasingly in aircraft that have to fly through thunder storms. On the other hand, composite materials are specially suitable for smart structure fabrication as they possess some salient features, such as high strength and stiffness-to-weight ratio, low thermal expansion and high resistance to fatigue and corrosion. Furthermore, their elastic and thermal properties can easily be tailored. The optical fibers can either be bonded to the surface of metal, plastic, ceramic, or other structures or embedded within composite material structures during their manufacture[22].

An interferometric fiber-optic sensor satisfies all the divergent requirements to be used in smart structures. Hence it is best suited, as it exhibits the highest sensitivity and a very large dynamic range. C.E. Lee and his colleagues first demonstrated that intrinsic Fabry-Perot fiber-optic (FPFO) sensors could be fabricated. They formed each of the two internal mirrors by sputtering titanium oxide on the end of one of the two optical fibers and then fusion splicing the two fibers together[23]. This important step produced fairly robust sensors that can be embedded within composite materials with minimum perturbation of the host.

The higher reflectivity FPFO sensors are fabricated at the University of Toronto Institute of Aerospace Studies (UTIAS)[24] by depositing metal on the ends of both optical fibers before fusion splicing. The cavity is then formed between one of these reflective fusion splices and the mirrored end of the optical fiber. This high reflectivity makes it easier to work within real-world power budgets.

To assess sensor survival and response, uniaxial FPFO sensors have been embedded in graphite/PEEK (Polyether ether ketone) and Kevlar/epoxy[25]. The sensors were embedded one ply-deep in unidirectional 25 mm by 250 mm laminated composite specimens called 'coupons', with the re-inforcing-fiber direction always along the coupon's long axis. The sensor had gauge lengths (physical lengths of the active regions of fiber FP cavities) between 3 mm and 9 mm. All sensors were embedded 'bare' with no buffer or coating. The graphite/PEEK laminates were 12 plies thick and consolidated in a hot press, while the Kevlar/epoxy laminates were 10 plies thick and cured in an autoclave.

4. STRAIN SENSITIVITY

A low-finesse (low quality-factor) high reflectivity FPFO sensor can be modelled as a two-beam interferometer similar to Michelson fiber-optic (MFO) sensor which is in many ways easier to construct and use (Fig.1). In these optical systems, the interference produced by two beams gives rise to a cosine modulation of the intensity of light arriving at the detector and is given by

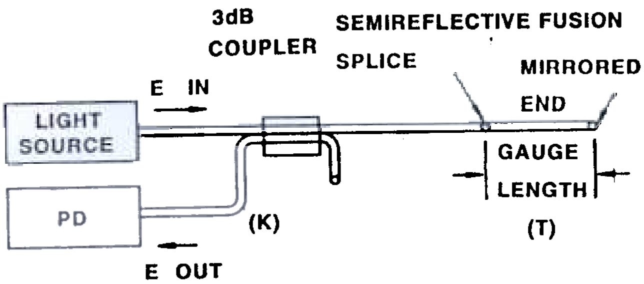
$$I_{out} = 1/2 * I_{in}(1+V\cos\varphi) \quad (1)$$

V = Visibility of the interferometer ($0 \le V \le 1$); $V=1$ for an ideal interferometer

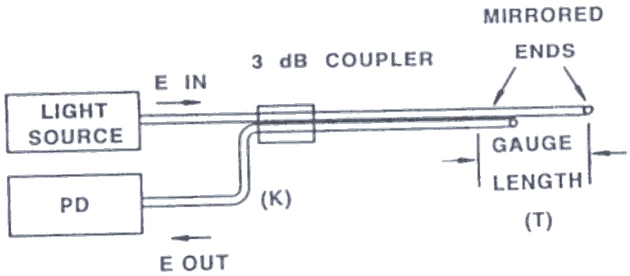
$\varphi = \varphi_s - \varphi_r$; φ_s and φ_r being the phase shift induced in the sensing and the reference arms of the interferometer.

So the phase retardation between the sensing and reference fields propagating along two paths with a total difference in length L can be expressed as

$$\varphi = \beta L \quad (2)$$



(a)



(b)

Figure 1. Schematic diagrams of (a) the low-finesse Fabry-Perot fiber-optic sensor; (b) the localised Michelson fiber-optic (MFO) sensor.

where β is the phase shift per unit length.

When the temperature and the wavelength are kept fixed, in that case we have

$$\Delta \varphi = \beta L \varepsilon + L (\delta \beta / \delta L) \Delta L \tag{3}$$

where ε is the path-integrated strain given by

$$\varepsilon = \Delta L / L$$

Now for an interferometric sensor, we know

$$\beta = n k_o$$

where n is the refractive index (R.I.) of the guided mode and k_o is the free-space propagation constant.

So, for this case, we have

$$\Delta \varphi = S L \varepsilon_z \tag{4}$$

where S is the interferometric phase-strain sensitivity. For pure axial loading it takes the form

$$S = k_o n \,[1-(n^2/2)*\{P_{12}-\sigma(P_{11}+P_{12})\}] \tag{5}$$

where

P_{11} and P_{12} = Strain-optic coefficients

ε_z = Axial strain

σ = Poisson's ratio for the fiber

L = Length of the sensor (essentially twice the separation of the mirrors for double-pass interferometric types).

The values of P_{11} and P_{12} determined by Berthholds and Dandliker for single mode fibers are 0.113 and 0.252, respectively[26]. Thus for silicon fibers operated at a wavelength of 633 nm, S = 11.3 rad/μstrain/meter gauge length, which is within 4 per cent of the experimental values that have been obtained for embedded FPFO strain sensors.

5. SIGNAL RECOVERY

If I be the photodetector current in the presence of the sensor and I_ϕ is photodetector current obtained directly from the source, then the response function $R(\varphi)$ can be expressed in accordance with Eqn (1) as

$$R(\varphi) = I/I_o = 1 + V \cos \varphi \tag{6}$$

The visibility factor V is introduced to cover partial-coherence situations.

Signal recovery is the conversion of the sinusoidal optical output from a fiber-optic sensor into an electrical signal linearly proportional to the phase retardation. In general, the total phase retardation can be written as

$$\psi = \varphi + \varphi' \tag{7}$$

where φ' is the drift, i.e., the non-measurand-induced phase retardation, which is equally introduced into two sets of readings and subsequently will be cancelled out while calculating the change of phase retardation. The phase retardation φ is the function of β, L and λ.

So ,

$$\varphi = f(\beta, L, \lambda) = f(n, L, \lambda) \quad [\beta = nk]$$

$$\Delta\varphi = (\delta\varphi/\delta n)\,\Delta n + (\delta\varphi/\delta L)\,\Delta L + (\delta\varphi/\delta\lambda)\,\Delta\lambda \tag{8}$$

Now,

$$\delta\varphi/\delta n = kL; \delta \varphi/\delta L = n k; \delta \varphi/\delta \lambda = -2\pi\, n\, L/\lambda^2 \tag{9}$$

Thus,

$$\Delta \varphi = k L \Delta n + n k \Delta L - 2\pi n L \Delta \lambda/\lambda^2 \tag{10}$$

The first two terms of this expression describe the transduction mechanisms by which optical fibers can act as sensors. But the problem is that since the fiber-optic response function

$$R(t) = 1 + V \cos [\varphi + \Delta \varphi (t)] \tag{11}$$

is sinusoidal, so it is multivalued and non-linear. Again, there is sign ambiguity and signal fading due to the nature of the cosine function. These issues will be addressed here.

There are two broad signal recovery techniques : one is passive and the other is active. Again they can utilise homodyne or heterodyne detection[27-29]. In homodyne detection scheme, there is a common frequency in both arms, whereas the heterodyne method makes use of a frequency which is the difference between the two arms.

5.1 Passive Homodyne Signal Recovery Techniques

This technique utilises a system that produces two outputs having a phase difference of $\pi/2$. These quadrature or orthogonal outputs overcome signal fading because one has maximum sensitivity when the other has the minimum. True quadrature outputs are usually best achieved with 4×4 directional coupler, but they can be approximated with 3×3 directional coupler also (Fig. 2).

The expressions for true quadrature signals are given by

$$I_1 = a\,[1 + \cos \Delta \varphi (t)] \qquad (12a)$$

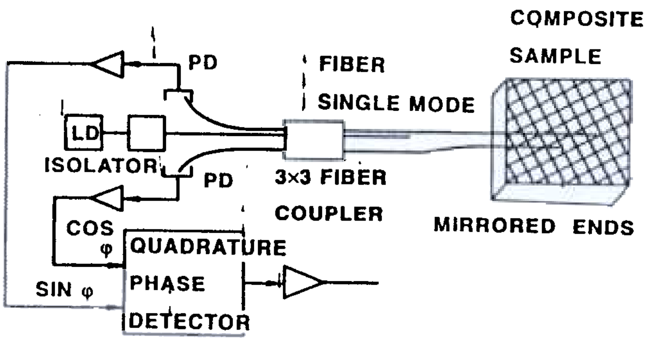


Figure 2. Schematic diagram of Michelson fiber-optic sensor based on passive quadrature detection by means of a 3 × 3 coupler.

$$I_2 = b\,[1 + \sin \Delta \varphi (t)] \qquad (12b)$$

a,b being the constants.

Signal recovery can be achieved by removing the dc-component to obtain :

$$X = a \cos \Delta \varphi (t) \qquad (13a)$$

$$Y = b \sin \Delta \varphi (t) \qquad (13b)$$

Subsequent differentiation, multiplication, subtraction and integration yields

$$\int (Y\dot{X} - X\dot{Y})\, dt = -\,ab\, \Delta \varphi (t) \qquad (14)$$

which is proportional to the phase retardation $\Delta\varphi (t)$. The differentiation and cross-multiplication in a circuit can be implemented as shown in the Fig. 3[30]

An alternative approach is to mix the non-dc quadrature outputs with a mutual orthogonal local oscillator signal. Thus,

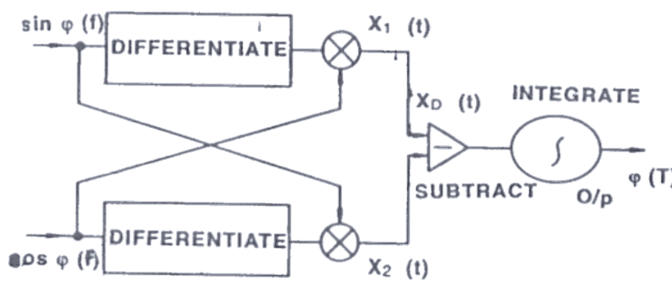


Figure 3. Differentiation and cross-multiplication demodulation scheme.

$$\sin wt \cos \Delta \varphi (t) + \cos wt \sin \Delta \varphi (t)$$
$$= \sin [wt + \Delta \varphi (t)] \qquad (15)$$

is formed which is then compared with the local oscillator's output, i.e., sin *wt* in a phase-detector. The output proportional to $\Delta \varphi$ (t) is obtained after having it low-pass filtered (Fig. 4).

5.2 Active Homodyne Signal Recovery Technique

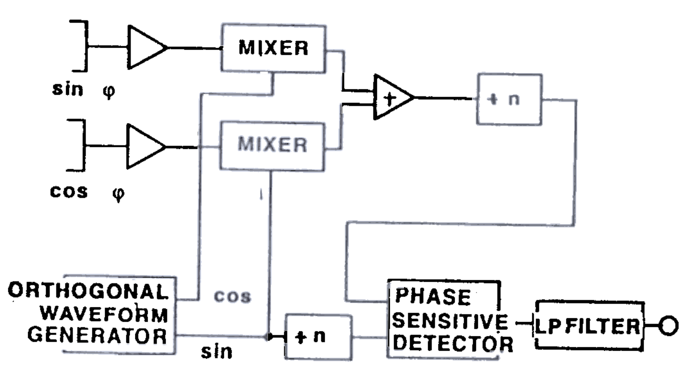


Figure 4. Orthogonal carrier wave demodulation technique.

Signal recovery is also possible through an active process, such as switching the laser frequency or using some form of phase modulation (PM). A Michelson fiber-optic (MFO) interferometer can be locked by active PM at its quadrature point at least for slow events (say < 100 Hz) which essentially provide a phase difference of $\pi/2$.

For implementing this technique, a piezoelectric (PZT) modulator can be used to strain a section of one of the interferometric arms, and desired phase difference of $\pi/2$ is thus produced. Appropriate negative feedback for such a system can be provided by low-pass filtering and integration[31]. This technique is schematically shown in Fig. 5. In case of small phase signals there is a linear relationship between the phase and voltage of the feedback signal for the piezoelectric (PZT) modulator. The modulator usually takes the form of a cylinder around which the portion of the fiber constituting one of the interferometric arms is wound. In the absence of the applied load, laser-induced phase-noise can be reduced by balancing the optical paths of the two arms, with inactive coil of the fiber in the other arm. Although distortion sets in for large variations of phase, this system is very sensitive to detect strain waves of low amplitude (phase changes <0.1 rad) and high frequency (>20 kHz), such as those associated with acoustic emission. This scheme may also be used for simultaneous measurement of low-frequency strains and high frequency acoustic waves.

5.2.1 Active Wavelength Strain Tracking

In active homodyne systems using single-fiber sensors; locking the system at the quadrature point by feedback control of laser wavelength may also be used for signal recovery. Feedback-loop phase-trackers based on this approach can be used, both for polarimetric[1,22] and FPFO sensors.

As we know,

$\varphi = \beta L$ and $\beta = nk_o$

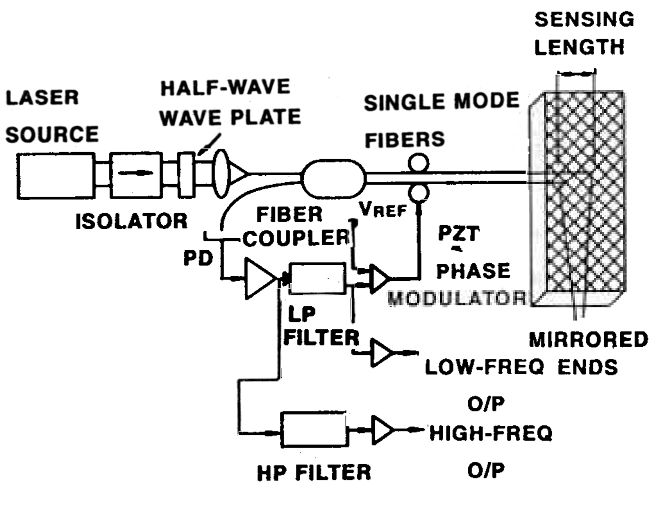


Figure 5. Set-up for piezoelectric active phase-demodulated MFO sensor employed for acoustic emission detection.

$$\delta\varphi/\delta\lambda = L(\delta\beta/\delta\lambda) + \beta(\delta L/\delta\lambda) \quad (16)$$

$$= L(\delta\beta/\delta\lambda), \text{ since } \delta L/\delta\lambda = 0, \text{ usually.}$$

Now, $\beta = nk_o = n\,2\pi/\lambda$

$$\delta\beta/\delta\lambda = (2\pi/\lambda)(\delta n/\delta\lambda) - 2\pi n/\lambda^2$$

Thus,

$$\delta\varphi/\delta\lambda = (2\pi L/\lambda)(\delta n/\delta\lambda - n/\lambda) \quad (17)$$

In practice the second term dominates; so to a first approximation,

$$\delta\varphi/\delta\lambda = -\beta L/\lambda \quad (18)$$

Combining this equation with Eqn (4), we can have the range of strain that can be tracked by varying the laser wavelength over an increment as

$$|\Delta\varepsilon| = (\beta/S\lambda)|\Delta\lambda| \quad (19)$$

When $S = 1.1 \times 10^7$ rad/m, n = 1.5 and $\lambda = 0.633$ µm, then $\beta = nk = 2\pi n/\lambda = 14.9$/nm for reflective FP strain sensor. So in this case, a laser tuning range of $\Delta\lambda = 10$ nm allows a maximum strain tracking range of $\Delta\varepsilon$ = 4284µstrain.

This range is probably restrictive for many applications. Now-a-days high-quality tunable diode laser devices have become commercially available, where frequency sweeping range (not continuously) can be wider than terrahertz by use of distributed feedback (DFB) lasers or grating extended cavity diode lasers. Researchers have reported the tuning ranges of about 2 nm, for continuous wavelength tuning and about 10 nm, for discontinuous (some wavelengths inside the tuning range cannot be obtained) tuning.

5.2.2 *Quadrature Phase Switching*

Researchers have also tried for strain tracking the pseudo-heterodyne approaches involving sweeping or switching the laser wavelength over an interval corresponding to a phase-shift of $\pi/2$ (or its odd multiple). Such techniques are sometimes called quadrature phase modulation (QPM). When the laser wavelength is switched between two values corresponding to a $\pi/2$ phase-shift, we can essentially extract orthogonal phase signals from the sensor. The required quadrature wavelength i.e., $|\Delta\lambda_\theta|$ can be calculated for an FP sensor using the Eqn (18) as

$$|\Delta\lambda_\theta| = (2N+1)\pi\lambda/2\beta L \quad (20)$$

where N is an integer, i.e., N = 0,1,2, ... called the quadrature order. If the guage length is less than

10 nm, then $|\Delta\lambda_\theta| = 0.02$ nm, which is well within the tuning range of a single longitudinal mode laser. Although most currently available lasers tend to mode hop when they are extensively injection-current tuned, the advanced 3-section distributed Bragg reflector (DBR) lasers can be tuned continuously over a spectral range of nearly 10 nm.

5.3 Heterodyne Signal Recovery Techniques

In this technique, the optical frequencies in the two arms of the interferometer are kept different. This is usually done by incorporating a frequency modulator in one of the two arms. The frequency modulators which are commonly used for this purpose are $LiNbO_3$ electro-optic element and an acousto-optic Bragg cell. Since they are not easily incorporated into the structurally integrated fiber-optic system, a range of pseudo-heterodyne modulation schemes have been mostly used.

5.3.1 Pseudo-Heterodyne Phase Detection Scheme

In semiconductor laser, the variation of the injection current results in a corresponding wavelength change. Thus the laser can directly be provided with phase modulation, which makes the interferometric sensor truly remote and localised. However, this scheme is particularly applicable to single-ended and single-lead sensors, such as FPFO sensors. In the case of Serrodyne (chirped wavelength) modulation of the laser diode, the optical frequency is swept over the range of frequencies. During the linear ramp part of the saw-tooth waves (having period $2\pi/w_m$) a constant rate of change of phase is produced in the interferometer by the shift of frequency[32]. This phase change is given by

$$\theta = [\varphi_m w_m / 2\pi]\, t \tag{21}$$

where φ_m = the depth of modulation of the phase

If $\varphi_m = 2\pi$

$\theta = w_m t$

which means that the normalised signal will be sinusoidal with angular frequency w_m over the linear ramp part of saw-tooth modulation. The normalised signal is of the form

$$I/I_o = \cos(w_m t + \psi) \tag{22}$$

Subsequently the signal is recovered by proper phase-sensitive detector (PSD). This technique might be suitable for sensors intended to make large strain measurement in smart structures (Fig. 6).

6. SPECTRAL ENCODING & DECODING

Usually the broadband light sources, such as LEDs are used for spectral coding methods of modulating and demodulating the sensor signals[27]. This technique also provides a repeatable and absolute measurement of the optical path difference and hence the phase difference. Moreover, it is insensitive to intensity variations associated with the sources, couplers, connectors, lead fibers and fringe-visibility variations due to changes of the state of plane of polarisation in the lead fibers. The approach works well with a single fiber sensor and finds suitable for sensor multiplexing too.

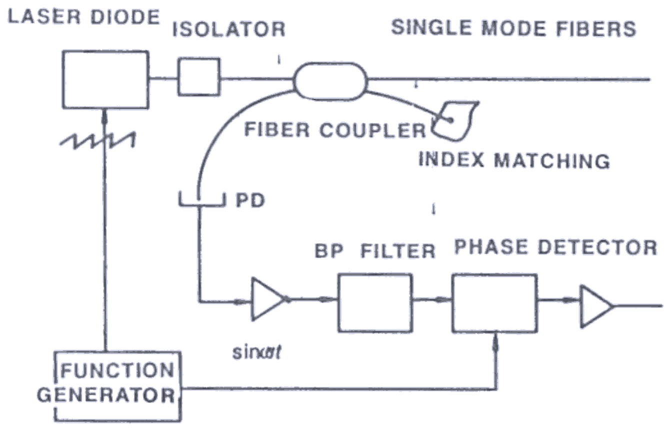


Figure 6. The signal recovery system for a FPFO sensor based on linear wavelength ramping of the laser diode.

Encoding principle can be explained as follows : Assuming the optical leads transparent and the optical source with spectrum function, $S(v)$, we consider the interferometric sensor as a filter with a response function $R(v,x)$ expressed by the relation

$$R(v, x) = 1 + \cos[2\pi\, v p(x)] \tag{23}$$

where v is the optical wave number and $p(x)$ is the optical path difference, being a function of the measurand (strain).

Spectral ratiometry can be used to demodulate the signal for sensors having OPD on the order of source wavelength. If LED is used as a broadband optical source and sensor is an FP cavity, then the back-reflected optical spectrum constitutes the sensor signal. This is nothing but the convolution of the source spectrum with FP response function, i.e.,

$$I(\nu,x) = R(\nu,x)*S(\nu) \quad (24)$$

As the measurand changes, the spectrum will also shift. If the free spectral range (FSR) of the FP sensor is larger than the spectral width of the source, the back-reflected light will take the form of a single spectral peak. The shift of the peak can then be ascertained by splitting the optical return into two parts, each of which is detected by a photo-detector (PD) after passing through a filter of different passband wavelength (Fig. 7). The ratio of the outputs from two PDs gives the measure of the spectral shift induced by measurand.

This method is highly attractive because of its simplicity, fast response and its ability to carry out absolute measurements. It is therefore immune to interrupts and makes alignment problems much easier to deal with since it can use multimode fibers.

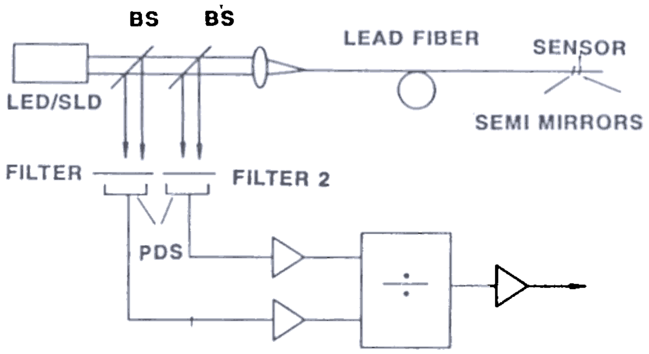


Figure 7. Spectral ratiometric demodulation for a FPFO sensor with a large FSR.

Unfortunately , for the FSR of the FP sensor (i.e., FSR = $c/2nL$) to be larger than the spectral width of the laser, the cavity length must be very small. This imposes a serious limitation on strain resolution which makes the sensor unsuitable for small strain measurement.

7. COHERENT DETECTION & MEASUREMENT OF ABSOLUTE STRAIN

Coherent detection can be employed only when the sensing length of a fiber-optic sensor is much larger than the coherence length of the light source. This is accomplished with a secondary interferometer whose optical path is controlled by an actuator that forms a part of a feedback loop. Since the source is of low coherence, the interference will only be detected when the optical path of the secondary interferometer is forced to be equal to that of sensing interferometer. When the measurand changes, the optical path and consequently the optical phase of the sensing interferometer will also be changed accordingly. The change is detected, amplified and fed back to force the optical path of secondary interferometer to follow the change and thus maintain the quadrature point. Thus the feedback signal is proportional to the measurand and can be used to track the variation of the measurand.

Intensity fluctuations produced by coupling, fiber bending and connector variations can be cancelled by the signal from a reference detector. Each time the system is switched on, a self-calibration is executed by scanning the secondary interferometer and measuring the separation between the central and side interference signatures. This self-calibration permits an absolute measurement of the optical path difference (OPD) and hence strain associated with the sensing fiber-optic interferometer. It also offers immunity to interrupt on the sensor, an important consideration within the smart structures concept.

8. APPLICATIONS OF FIBER-OPTIC SENSORS TO SMART STRUCTURES

A generic fiber-optic smart structure is schematically depicted in Fig. 8 which illustrates how the combination of a coupler and DEMUX/MUX interface would permit an array of structurally integrated single-ended fiber-optic sensors to be interrogated by a single input/output optical-fiber. The potential applications that can be undertaken with optical-fiber sensors embedded within composite materials can be divided into four groups : fabrication control; structural integrity; loading, shape, and vibration; and thermal state. Structural integrity (or damage assessment) and fabrication control (or cure monitoring) will be considered here in detail.

In terms of smart structures, strain and deformation represent two of the most important measurements. Furthermore, real-time measurements of the strain in a structure normally permit its state of vibration also to be evaluated. It is expected that for most smart structure applications local measurements of strain will be required.

An important consideration when considering any fiber-optic sensor system for a smart structure is the

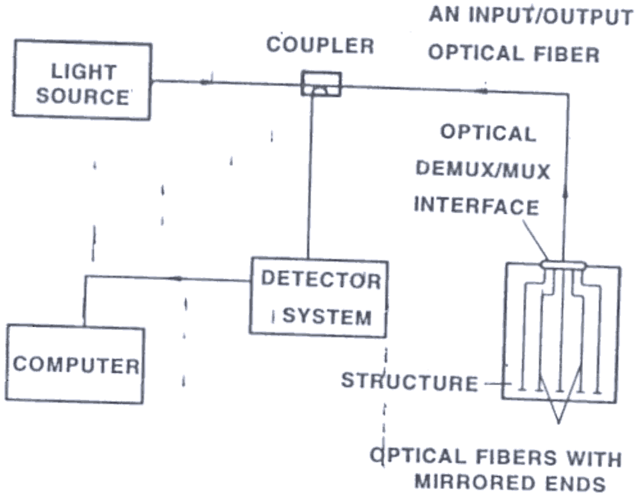


Figure 8. Generic Fiber-optic smart structure involving a light source, coupler, an input/output optical fiber (or bundle), optical fiber sensor array, the detector system and the interrogation system with computer.

relative ease of developing a practical interface. In the case of a set of interferometric fiber-optic strain sensors, this involves a rugged and reliable alignment of a number of single-mode optical fibers. This is not a minor problem, since the core diameter of each optical fiber is of the order of one micrometer. Although this task has been accomplished in the telecommunication field, smart structures impose a number of different constraints on the connector : it must be small (so as not to perturb the structure); it must not introduce any arbitrary phase, even when the structure is subject to all forms of vibration and motion; and must accurately maintain the alignment of many optical fibers simultaneously over a wide range of temperatures.

To compete with the conventional foil strain guage technology the fiber-optic strain sensor must have the following parameters to satisfy :

(a) Strain resolution : 1 μstrain

(b) Dynamic range : ±10,000 μstrain

(c) Frequency response : dc to 1 kHz

(d) Gauge length : 1 to 10 mm

These parameters are certainly attainable with fiber-optic strain sensors, whose capabilities actually go well beyond those of conventional foil strain gauges. For example, a fiber-optic strain sensor of guage length 10 mm and strain resolution of 1μstrain exhibits a phase retardation of 0.22 rad, while its dynamic range of ±10,000 μstrain corresponds to 4400 rad.

Its figure of merit may be measured by a phase bandwidth product, B. For previous sensor, it would be B = 4400 rad × 100 Hz = 0.44 MHz-rad, which corresponds to a strain wave with an amplitude of 10,000 μstrain and a frequency of 100 Hz or an ultrasonic frequency of 1 MHz. Such values might be needed in a structurally integrated fiber-optic strain sensor which is to track the large dynamic loads while simultaneously responding to acoustic emission.

To determine an arbitrary state of strain in two dimensions, a fiber-optic strain rosette has also been developed. The prototype device has been tested for use in smart structures by embedding it within graphite/PEEK cantilever beam and comparing its measurement of strain with that of a conventional resistive strain rosette adhered to the surface of the beam.

First strain measurement was undertaken using Michelson optical strain gauge and it was found that an excellent linear relation exists between the number of fringes and the strain produced by end-loading of the cantilever beam (Fig. 9). The strain gauge factor for this device when embedded within graphite/PEEK was determined[22] to be 13.9 (±1.1) degrees per μstrain per cm.

Presently, the fabrication of FPFO strain sensor for use with smart structures takes too much time, so people are using the Michelson FO interferometric sensor to test the potential of opto-acoustic sensor. This Michelson sensor having strain sensitivity almost identical to FPFO strain sensor, is much easier to produce. However, it is not a sensible candidate for

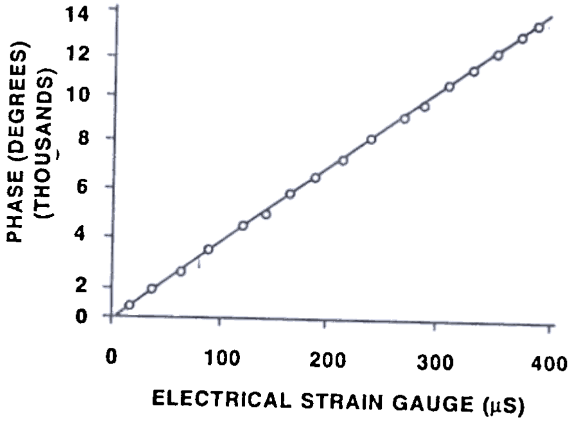


Figure 9. Strain response of a MFO strain sensor embedded within a carbon/PEEK thermoplastic cantilever beam.

eventual use with smart structures[1,22-23,26-29], so intense research is going on to improve production methods for FPFO strain sensor. Fiber-optic sensors exhibiting excellent performance to opto-acoustic sensing have two main applications within composite materials :

(a) Passive sensing and detecting acoustic emissions resulting from matrix cracking within composite materials[31], and

(b) Active probing of the composite structure for damage assessment or cure monitoring[33].

8.1 Detecting Acoustic Emission for Damage Assessment

Michelson fiber-optic sensors embedded within various multilaminated kevlar/epoxy and graphite/epoxy panels is used to study damage-induced acoustic emission. The sensor comprises a pair of unbuffered optical-fibers with mirrored ends embedded within the composite materials. In this work, quadrature detection was ensured by a low-frequency PZT phase-modulation feedback system that also eliminates drifts and slowly varying strains[31].

The panels were subjected to out-of-plane loading, and the high-frequency signals from the fiber-optic sensor are recorded. Then it is possible to demonstrate that embedded Michelson fiber-optic strain guages can detect acoustic emissions associated with threshold delamination. But, the complexity of composite materials will probably require neural networks to locate and assess the extent of damage associated with acoustic-emission signals in practical systems.

8.2 Opto-Acoustic Cure Monitoring

The state of cure of thermosets has been possible by measuring the velocity of acoustic waves transmitted through the material. The high sensitivity of interferometric fiber-optic sensors has led us to consider the possibility of measuring the velocity of optically generated acoustic waves within a thermoset, thereby monitoring the cure state with same sensor, that would later be used to determine the in-service strain and vibration state of the structure. This is attractive because the more functions an embedded sensor can perform, the greater is its cost-effectiveness.

The results of the experimental work done by Davis, et al[33] on it are encouraging : the variation in the initial arrival time for the laser-generated acoustic pulses appears to vary with the state of cure for the room-temperature-setting Hysol resin. Here also, Michelson fiber-optic sensor with active homodyne demodulation was used. The laser pulse was delivered to the surface of the Hysol resin specimen with a 600 mm core optical fiber during the resin's room-temperature cure[33].

9. CONCLUDING REMARKS

Fiber-optic interferometric sensors are likely to play a significant role in the development of smart structures. A number of advantages offered by their properties make them more suitable over their electrical counterparts, especially when they are embedded within a composite material. Even this sensor has capabilities that far exceed those of conventional foil strain gauge sensors, which is highly sensitive in responding to acoustic emission signals while tracking parallelly the high loads likely to be encountered in practical structures such as aircraft wings. More remarkable is the possibility that the same sensing system might be able to monitor the degree of cure during fabrication of the thermoset composite structures. Their strain sensitivity also makes them advantageous for use to smart adaptive structures.

The recent state-of-the-art of fiber-optic strain sensor technology has made use of the design of an in-line fiber etalon (ILFE) optical strain sensor formed by fusing a short section of hollow core fiber between two standard single-mode lead-in/ lead-out fibers[6]. The strain response of the sensor compares well with strain gauge resistance. The minimum detectable dynamic strain was measured using this technique to 30 nanostrain in the range of 0.5-2.5 kHz[6]. The primary limitations of the ILFE sensor stems from the fact that the light in the cavity propagates in the free space instead of being guided. As a result, light experiences a significant beam divergence, which limits the cavity lengths of the ILFE sensors to less than roughly 300 µm Not only that the short cavity length limits the sensor to moderate sensitivity applications, such as structural strain monitoring since sensitivity scales with cavity length.

The fiber-optic sensor technology in smart structures might also find applications to space platforms, especially those large, flexible space structures where active shape control is required, and robotic systems where human-like dexterity could be of value. But the best method of high frequency signal recovery for FPFO sensor is yet to be developed, especially when large sensor arrays are to be interrogated.

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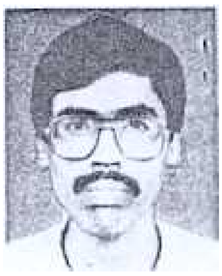
Contributors



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