STRAIN SENSING USING FIBER-OPTIC INTERFEROMETRY

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Abstract

A surface mounted interferometric strain sensor is experimentally studied for its strain sensing characteristics. Its sensitivity to environmental mechanical disturbances such as vibration is also discussed.

Introduction

Optical fiber based health monitoring can be used as part of on-line structural health monitoring systems. They can be either surface bonded or embedded. On metallic structures, surface bonding is the most suitable. On the other hand, embedding the optical fiber is possible with composite structures. Further, optical fibers are dimensionally similar to reinforcing fibers in composite fiber-reinforced structures, and immune to electromagnetic interference. Moreover, they can withstand high temperatures that are likely to be encountered at the time of curing, and are corrosion resistant [1].

There has been considerable research interest in optical fiber based structural health monitoring techniques. They range from simple load detection based systems to sophisticated strain monitoring sensors that detect damage from strain measurements. Optical fiber strain sensors are designed to relate changes in phase or amplitude to changes in strain. Broadly, fiber-optic strain sensors are classified as intensity based sensors, interferometric sensors, and spectrum based sensors. Intensity based sensors measure changes in transmitted light intensity through a fiber when subjected to loads. They operate on the principle of intensity modulation. They are rugged but sensitivity is poor. Interferometric sensors are based on relative optical path length change between a fiber subjected to mechanical loads and a reference optical fiber free of strain. Polarimetric sensors also rely on interferometry principle, but since the two interfering beams pass through the same path, external influences affect both beams equally. Spectrum based sensors, such as the Bragg grating sensor work on the principle of wavelength modulation due to mechanical loads or environmental effects.

These sensors are fabricated by etching a grating along the fiber length by exposing the fiber core to intense radiation [2,3].

This work presents an investigation on optical fiber strain sensing based on Mach-Zehnder interferometry. A strain field applied to the fiber produces mechanical response, which in turn produces an optical response. The optical response in this case is a change in optical path length. The optical path length change is due to the change in refractive index of fiber and change in fiber length. The change in refractive index is a result of wave-guide mode dispersion caused by induced changes in the fiber diameter. Step-index single-mode optical fibers are used to produce the fiber optic interferometric sensor. An interferometric optical fiber strain sensor measures the relative retardation between the light traveling in its reference and sensing arms and then relates this retardation to strain. Relative retardation is the difference between the total phase change in the light waves passing through the reference and sensing fibers. The relative retardation is produced by exposing both the reference and the sensing fibers to a strain field. A Mach-Zehnder interferometer produces interference fringes by superimposing the light waves transmitted through the reference and sensing fibers; the fringe count is then correlated to the mechanical strain [4].

Strain Sensing Using Fiber-Optic Interferometry

An interferometric fiber-optic strain sensor measures strain by measuring the relative phase change between the light traveling in its reference and sensing optical fibers. The relative phase change can be produced in two ways. The first option is the so-called Mach-Zehnder technique

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wherein the reference fiber is kept in a strain-free state, and only the sensing fiber is strained by suitably bonding it to the structure. This technique has its limitations, and the most notable is that in practical applications, it may be difficult to maintain the reference optical fiber strain-free. The second method of measuring strain by optical interferometry is to expose both the reference and the sensing optical fibers to strain; the requirement here is that the reference and optical fiber should have either different material properties, or different geometries.

In the present work, we use Mach-Zehnder interferometry together with exposing both the reference and sensing fibers to a strain field. This is realized by bonding the reference fiber on the host structure in the form of a circle. Integrating the effect of all the strain components along the circle results in a net effective zero strain. The active portion of the sensing fiber is however 'S' shaped. This causes the fiber to be strained in one direction, usually the axial or $e_{xx}$ direction. Both, the sensing as well as the reference fibers, are bonded to the host structure on its surface using adhesive. The strain is transferred from the host structure that is subject to mechanical loading, to the optical fiber through the adhesive interface. We assume that the adhesive bond is perfect, and consequently there is no shear-lag between the host structure and the optical fiber.

The fiber orientation on the host cantilever beam structure is shown in Fig.1. The S-shaped sensing fiber and the a-shaped reference fiber configuration is also known as a nonlinear configuration. This is in contrast to the linear configuration wherein the sensing fiber is mounted on the surface of the host beam structure at an angle of 45deg with respect to the longitudinal axis of the beam. This way each cross-sectional face of the fiber is parallel to a body face in which a shear strain acts [4].

If a differential section of a fiber is isolated for an incremental strain, then the optical path length is given by,

$$\Delta (n l) = n \Delta l + l \Delta n$$

(1)

where $l \Delta n$ is the component of optical-path-length change due to change in refractive index, and $n \Delta l$ is the component due to the change in fiber length. The change in refractive index is caused by the strain-optic effect and wave-guide mode dispersion due to induced changes in the fiber diameter. We ignore the wave-guide mode dispersion contributions since it has been shown to be negligible for surface-mounted fiber-optic sensors [5]. Both, the change in refractive index and the change in fiber length are related to the change in strain. The change in refractive index is a result of the strain-optic effect and manifests itself through the optical indicatrix [4]. The total optical path-length difference between the sensing and reference fibers is given by [4,6],

$$\Delta = (C_1 + n_o) [3l + 2\pi (a-R) e_{xx} + s\pi (a-R) e_{yy}]$$

(2)

From Eq.(2), the total optical path-length difference is a function of both $e_{xx}$ and $e_{yy}$. The loading conditions are such that $e_{yy}$ is proportional to $e_{xx}$. Further, in our case $R=a$ then Eq.(2) reduces to

$$\Delta = (C_1 + n_o) 3l e_{xx}$$

(3)

The optical-path-length difference can then be converted into a phase difference multiplying by $2\pi/\lambda$. One fringe represents a change in phase of $2\pi/\lambda$. Therefore,

$$\frac{2\pi}{\lambda} = (C_1 + n_o) [3l + 2\pi^2 (1-v) (a-R) e_{xx}] = 2\pi k$$

(4)

where $k$ refers to the fringe count. The above equation relates the phase change to the number of fringes passing the detection point. The strain is therefore determined from,

$$e_{xx} = kD_1$$

(5)
Experimental Setup

The strain measured by the fiber optic interferometric sensor had to be calibrated by an electromechanical resistive type strain gauge array. We briefly describe the strain gauge apparatus and subsequently the fiber optic interferometric measurement apparatus. But before that the mechanical properties of the aluminum specimen were first measured under ASTM E-28 test procedure. A tensile test was conducted to determine the Young’s modulus, E, and Poisson’s ratio, v. The measured values are tabulated Table-1.

The instrumentation used for measuring strain from the voltage across the resistive strain gauges was the usual Wheatstone bridge [6]. To cancel out the effect of temperature on the gauge wire, the commonly used technique is to use two strain gauges as adjacent arms of the Wheatstone bridge. The active gauge is bonded on the test specimen and the dummy gauge is bonded on a similar but unstressed member kept close to the stressed member so that both are subjected to the same thermal environmental conditions. The arms of the Wheatstone bridge circuit thereby cancel strain due to temperature, and only the output due to the stress-induced strain is recorded. The strain gauge indicator was calibrated and the strain gauge bridge balanced at no load using a potentiometer.

The geometric configuration of the optical fibers on the host beam structure has been shown earlier in Fig.1. A fiber optic Mach-Zehnder interferometric sensor consists of two directional couplers and two equal lengths of fiber, one serving as a sensing arm and the other as a reference arm, a laser light source, photo-detector, processing and display optics, and the required electronics. Mach-Zehnder interferometer set-up is shown in Fig.2. As shown in this figure, the light emerges from the laser and is launched into the fibers through couplers. Since the interferometer is very sensitive and ambient vibration could adversely affect the measurement, the experimental setup was mounted on an isolation table. The optical fibers were bonded onto the plate using an epoxy based adhesive. Single-mode optical fibers consist of a jacket, cladding, and core. The jacket was removed by dipping the fiber into acetone or di-chloro-ethylene solution before experiment. The core of the fiber was cut into right angles so that light was fully transmitted through the fiber without any loss of transmission and reflection. The cut-off wavelength of the fibers used was 633nm. Cut-off wavelength is the wavelength above which only one mode can propagate. The core radius of the optical fiber was approximately 7.3nm, and the refractive-index difference between the core and the cladding was 0.001662.

Results and Discussion

The specimen with mounted strain gauge and optical fibers was connected to the sensing arm of the interferometer. The specimen was cantilevered at one end, and the load applied at the free end in steps of 50gm from 50gm to 700gm. The strain value for a given load was noted down from the strain-gauge indicator. This was performed for each value of static loading, and for both increasing as well as decreasing loads. There was no hysteresis in the observations of the fringe counter or the strain gauge indicator during loading or unloading the beam structure.
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applied, the fringes move from the reference
point, and by removing the load the fringes come back to
the reference point. The number of fringes that shift across
the reference point was counted manually.

The results of the experiment on strain measurement
using Mach-Zehnder interferometry are shown in Fig.3.
Fig.3 shows the relation between the strain and the fringe
count. The strain values in this plot are computed using
plate theory for a cantilever plate with tip loading; the
strain is computed at the location on the surface of the plate
at a distance from the tip to the mid-point of the S-shaped
optical fiber. This mechanical strain is equated to the
expression given by Eq.(5), and \( D_1 \) computed. Therefore,
the slope of the best-fit line through the data points in Fig.3
gives the value of \( D_1 \). Thus, the fiber-optic sensor was
calibrated.

In order to verify that the strain measured by the
fiber-optic interferometer is indeed correct, we compared
the strains measured by calibrated interferometer, strain
gauge, and theoretical strain values using Eq.(5) and
Eq.(6) for a interferometric fiber-optic sensor, as a function
of mechanical loading. The results of this comparison
are presented in Fig.4. Note that the fiber-optic interferometer measurements are within 5-7% of the strain
gauge measured strain values. At lower values of the
mechanical loading, the error percentage is even lower.

We suspect that relatively large errors at higher loading
conditions could be a result of the effect of the adhesive
bonding layer on the fiber-optic strain sensor.

**Conclusions**

This work presents an investigation on optical fiber
strain sensing based on Mach-Zehnder interferometry. A
strain field applied to the fiber produces mechanical re-
sponse, which in turn produces an optical response. The
optical response in this case is a change in optical path
length. The optical path length change is due to the change
in refractive index of fiber and change in fiber length. The
change in refractive index is a result of wave-guide mode
dispersion caused by induced changes in the fiber diame-
ter. Step-index single-mode optical fibers are used to
produce the fiber optic interferometric sensor.

The primary focus of this study was to carry out a
proof-of-concept study, as well as note the sensitivity of
such fiber optic sensors to environmental mechanical dis-
turbances such as vibration. The strain sensing capability
of the Mach-Zehnder interferometric sensor was observed
to be very accurate; this was corroborated with strain-
gauge results and analytical predictions. However, this
sensor is extremely sensitive to environmental vibration
than as compared to strain gauges. In order to be effective
as a strain sensor, signal-conditioning electronics may
need to be incorporated to filter out the noisy data.
Further work needs to be done to embed these sensors in composite specimens. Since the optical fibers will have to be embedded into the composites before they are cured, their ability to withstand temperature, as well as their sensitivity to mechanical strain fields the composite specimen undergoes will need to be investigated. Analytical models to predict the opto-mechanical response of embedded optical fibers in composites also need to be developed.  

References