A distributed optical fiber bi-directional strain-displacement sensor

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Abstract A distributed optical fiber strain-displacement sensor is developed, which consists of an optical fiber gauge of strain-displacement and an optical time domain reflectometer (OTDR). The operational principle is the modulation of fiber loss in OTDR, i.e., the strain and displacement in monitoring position are obtained from the bending loss of optical fiber bonded on the optical fiber gauge of strain-displacement. After examining the strain and displacement in the cantilever and the micro displacement rack respectively, the result indicates that the distributed optical fiber gauge of strain-displacement can monitor strains or displacements in different sensitive lengths. The key technique for measuring bi-directional strain-displacement is the pretreatment of bending of the freely suspended optical fibers, which can be identified with OTDR by inserting time delay optical fiber.

Keywords: optical fiber bi-directional gauge of strain-displacement, optical time domain reflectometer (OTDR), fiber bending loss, strain, displacement.

Sensor systems that permit monitoring the magnitude of a measurand, such as strain, temperature etc., and also its variation along the length of a continuous uninterrupted optical fiber, offer a powerful and economical means for covering a large number of locations within a significant area and are particularly attractive for obtaining a graphical or pictorial presentation of information. The Elastica fiber sensor[1,2], an intrinsic fiber-optic strain-displacement sensor with high sensitivity and a wide sensing range, can work in an extremely simple and low-cost manner. Due to the flexibility in sensor responsivity, gauge length, and attachment methods, combined with the large sensing range, linearity, high sensitivity, extremely low force constant, and high temperature capability, Elastica fiber sensors are uniquely suited to a wide range of measurement and structural-monitoring applications.

We have used the distributed optical fiber strain gauge[3] and the distributed optical fiber bi-directional strain gauge[4] to monitor pipelines. In this paper, we will introduce an optical fiber bi-directional gauge of strain-displacement, and present OTDR[5-7] method for measuring the loss of backscatter light energy in the optical fiber bi-directional gauge of strain-displacement bonded on the measurand.

1 The optical fiber bi-directional gauge of strain-displacement

In the optical fiber bi-directional gauge of strain-displacement shown in Fig. 1, \( L = 100.0 \) mm is the gauge length, \( l_1 \) and \( l_2 \) are the lengths of freely suspended single-mode optical fiber (with the core diameter of 9 \( \mu \)m and the clad diameter of 125 \( \mu \)m), \( d_1 \) and \( d_2 \) are the distances between two bonding points of the freely suspended optical fiber. The optical fiber bi-directional gauge of strain-displacement includes a region sensitive to tension and a region sensitive to compression[4]. In Fig. 2 (a), when the gauge is stretched, the part of optical fiber in the sensitive section of tension is bended and the part in the sensitive section of compression is extended. On the contrary,
when the strain gauge is compressed as shown in Fig. 2 (b), the part of optical fiber in the sensitive section of tension is extended and the part in the sensitive section of compression is bended.

![Fig. 1. The schematic illustration of optical fiber bi-directional strain-displacement gauge.](image1)

![Fig. 2. The operational schematic diagram of the optical fiber bi-directional strain-displacement gauge, sensitive to tension (a), and compression (b).](image2)

The key technique is the pre-bending of the freely suspended optical fiber between two bonding points, which has two advantages: (i) enhancing the sensitivity of variation; (ii) preventing the tension of optical fiber. In detection, the tensile and compressive variation can be judged by sensing the bending loss of freely suspended optical fiber, when the distortion of optical fiber gauge of strain-displacement occurs due to the distortion of specimen. Because the bending loss in gauge is dependent on the bending of freely suspended optical fiber\(^1\), the bending sensitivity can be adjusted by altering the distances between two bonding points of freely suspended optical fiber, i.e. \(d_1\) and \(d_2\).

Additionally, inserting the time delay optical fiber in Fig. 1, the tensile strain and compressive strain can be identified by OTDR, which judges the position and magnitude of bending loss along the optical fiber. The OTDR technique\(^3,4\) based on Rayleigh dispersion is appropriate for inspecting the bending loss of an optical fiber bonded on the bi-directional strain gauge, incorporating the light transmission and sensing in one unit as shown in Fig. 3. The spatial resolution of breakpoint in our ODTR is about 0.5 m. The optical time-domain reflectometer consists of a pulsed laser source, a bi-directional coupler connected to the fiber under test, and an optical detector, as well as the further electronic circuitry used for data acquisition, signal averaging and processing, measurement control and display of the result. A short, high-intensity, optical pulse with a wavelength \(\lambda = 1.300 \mu m\) is launched into the single mode optical fiber and a back scatter measurement is made as a function of time. The signal consists of light scattered during the progress of the pulse down the fiber and recaptured by the waveguide in the return direction; it takes the following well-known form as a function of the position \(z\) of the scattering element \(dz\)\(^3\):

\[
P_s(z) = P_0 W v_a(z) S(z) \exp \left\{ - \int_0^z 2 \alpha(z') dz' \right\},
\]

where \(P_0\) is the power launched, \(W\) the pulse width, \(v_a\) the group velocity. Here \(\alpha\) and \(\alpha_a\) are the scattering and total loss coefficients, respectively, i.e. they respectively represent the proportion of the pulse energy lost per unit length of fiber by scattering mechanism and all loss mechanisms. Both can be a function of position along the fiber. \(S\) is the capture fraction, i.e. the proportion of the scattered light collected by the optical system. Just like a traditional radar system, the spatial length \(z\) is relative to the return-

![Fig. 3. The schematic illustration of distributed measuring via OTDR.](image3)
transmission time \( t \), which is given by
\[
t = \frac{2z}{v_g}.
\]  
(2)

Of course, the measurement position \( z \) is determined by the time for the pulse to travel the distance from the launching end to \( z \) and return.

The basic OTDR technique is capable of detecting, as a function of position along a fiber, the changes of several fundamental properties, such as the fiber diameter, numerical aperture and scattering loss in multimode and single mode fibers. Here, we introduce a modulation approach of fiber bending loss, as shown in Fig. 2. Thus, according to Eq. (1), if the loss of the fiber varies with the measurement of interest, the backscatter waveform on a logarithmic display can be expressed as
\[
\ln P_s(z) = -\int_0^z 2a(z)dz + C,
\]
where \( C \) is a constant relative to numerical aperture, scattering loss and fiber geometry of the fiber. Thus, the decay change between the two sampling points in OTDR can be given by
\[
\Delta a = -10\log_{10}(e)\int_{z_1}^{z_2} 2a(z)dz,
\]
where \( z_1 \) and \( z_2 \) mean the effective positions of two sampling points respectively.

2 The measurement of distributed bi-directional optical fiber sensor of strain-displacement

The tensile and compressive strains can be judged by sensing the bending loss of freely suspended optical fiber, when the distortion of optical fiber gauge of strain-displacement occurs due to the distortion of the specimen.

In Fig. 4 (a), the gauge is bonded on the equi-intensity cantilever. \( d_1 \) and \( d_2 \) are the distances between the bonding points of the freely suspended optical fibers (through the pretreatment of bending), and both are 2.0 mm. The strain is derived from the bending of cantilever by appending weight. It can be expressed by
\[
S = \frac{3G}{h^2\tan(a/2)} \cdot E,
\]
where \( S \) is the strain (\( \mu \)), \( G \) weight (g), \( h \) and \( a \) are the geometrical size of equi-intensity cantilever, and \( E \) is the Young’s modulus. Thus, the strain variation \( \Delta S \) is linearly dependent on the weight variation \( \Delta G \).

When the time delay optical fiber is inserted, the tensile and compressive strains can be identified by the trace taken with high spatial resolution in OTDR. In detection, the bending losses of optic fiber owed to the tensile and compressive strains have been obtained from OTDR and are shown as open circles in Fig. 4 (b). Fitting the experimental data of optic fiber bending loss in Fig. 4 (b), the bending loss versus strain can be expressed as
\[
\Delta a(\Delta S) = 0.748 + 0.211 \times 10^{-3}\Delta S - 0.519 \times 10^{-3}\Delta S^2,
\]
where the positions of two sample points are \( z_1 = 1320 \) m and \( z_2 = 1362 \) m respectively. The range of bending loss is \( \Delta a = 0 \sim 3 \) dB, as the range of strain is \( \Delta S = -70 \sim 70 \) \( \mu \). The standard deviation of 0.14 dB between the experimental data and the fit-
ting data obtained from Eq. (6) is less than the intrinsic loss of 0.45 dB in the optic fiber with the same length.

In Fig.5(a), both $d_1$ and $d_2$ are 10.0 mm. The displacement is derived from the displacement of micron displacement rack. Similarly, if inserting the losses versus displacement can be expressed as

$$\Delta a(\Delta d) \approx 0.130 - 0.439 \times 10^{-3} \Delta d + 0.695 \Delta d^2 + 0.426 \times 10^{-4} \Delta d^3,$$

where the positions of two sample points are $z_1 = 1463$ m and $z_2 = 1502$ m respectively. The range of bending loss is $\Delta a = 0 \sim 3$ dB, as the range of displacement is $\Delta d = -2 \sim 2$ mm. The standard deviation of 0.08 dB between the experimental data and the fitting data obtained from Eq. (7) is less than the intrinsic loss of 0.45 dB in the optical fiber.

3 Conclusions

In this paper, we have designed the optical fiber bi-directional gauge of strain-displacement (referred to Figs. 1 and 2), which includes two different sensitive regions suited to tension, and compression respectively. The key technique is the pretreatment of bending sections of freely suspected optical fiber. At the different distances between bonding points of the freely suspended optical fiber, the bending loss is adapted to (i) the strain, $-70 \sim 70 \mu\text{e}$, where $d_1$ and $d_2$ are 2.0 mm shown in Fig. 4 (a); and (ii) displacement, $-2 \sim 2$ mm, where $d_1$ and $d_2$ are 20.0 mm shown in Fig. 5 (a). The standard deviations between actually experimental data and fitting data obtained from Eqs. (6) and (7) are 0.14 dB and 0.08 dB respectively, which are less than the intrinsic loss of 0.45 dB in the optical fiber.

In addition to the ability of measuring tensile and compressive strains or displacements, the optical fiber bi-directional gauge of strain-displacement also renders its various sensitivities dependent on the gauge length, and attachment methods. Thus, based on detecting the single point value markedly different from that of the remainder of the fiber, the loss-modulation approach of optical fiber bi-directional gauge of strain-displacement is appropriate for measuring strain and displacement.

References