Experimental study on vibration frequency response of micro-bend optic-fiber sensor

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We make an experimental study on vibration frequency response of micro-bend optic-fiber sensor, and single-mode fibers and multi-mode fibers are used as the sensitive optic-fibers. Contrast between the two sensitive fibers is presented. Result shows that the micro-bend optic-fiber sensor has good frequency response characteristics and strong ability to restore the waveform. With the frequency varying in the range of $500-4762$ Hz, the vibration sensors using multi-mode optic-fiber as the sensitive fiber is more sensitive than that using single-mode optic-fiber. And the former has better frequency response characteristics and stronger capacity of waveform revivification. But with the frequency in the range of $287-500$ Hz, the latter is better.

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Optic-fiber sensor is widely used now[1−3], and Micro-bend optic-fiber sensor is an important optic-fiber sensor. Since Fields *et al.*[4] brought out the principle of Micro-bend optic-fiber sensors (MFS) for the first time in 1980, MFS has gotten much attention because of its advantages such as simple structure, low cost, easy equipment, and so on[5]. MFS was first applied in an optic-fiber hydrophone system by the Institute of the U.S. Navy, but without technical report. After that, Micro-bend optic-fiber modulator principle was expanded to the applications of sensing displacement, acceleration, and other physical parameters. The resolution ratio of detecting displacement can reach up to the level of 0.1 nm, and the detection dynamic range can reach to more than 100 dB[6]. In 1991, Lumholt *et al.*[7] pointed out that MFS showed high sensitivity in temperature in the range of $20-180$ K. Also, sensors could be more sensitive on temperature and suffer less changes of its sensitivity while changing the wavelength of light by selecting the appropriate signal wavelength. MFS used in multi-parameters measurements has also been reported[8,9]. Someone brought out an MFS with grating fiber for double-parameters which could sense strain and temperature at the same time. The optic-fiber micro-bend mechanism is used to modulate the reflected light of FBG center wavelength and the light intensity at the same time, and only the varying of temperature can change the FBG center wavelength. By detecting the signal reflection of its peak center wavelength and intensity at the same time, measurements of the strain and temperature distinctively can be effectively realized. Simultaneously, the temperature and strain cross-sensitive problem has been effectively solved. Moreover, its linear response can reach to 0.995.

Since vibration phenomenon can be found in nature easily, e.g., the high-rise buildings or the suspension beams bridge can gain vibration in the action of wind, under the shock of explosions wave, even caused by the earthquake, and so on. Sensing the vibration mentioned above can study whether the subjects are working in normal or there are the security risks. So we can take actions to evaluate the original design and construction. In other words, monitoring the seismic is meaningful. Early detection of vibration is made by using mechanical sensors, but its detection range is very narrow. Then, a type of electromagnetic sensors came up, which still had shortcomings such as low sensitivity and poor anti-jamming capability. Compared with electromagnetic sensors, micro-bend optic-fiber sensors have a wide dynamic range, high sensitivity, strong anti-jamming ability, and other advantages. However, the work of using micro-bend optic-fiber sensor to sense the frequency response of vibration has not yet been reported. The experiment in this letter is to study the micro-bend optic-fiber sensor used for sensing the frequency response vibration.

MFS makes use of the intensity modulation induced by micro-bend loss in sensitive fibers as a transduction mechanism for detecting environmental changes, such as displacement, strain, temperature, and so on. In the MFS, the transmission of high-end total internal reflection mode in the optical fiber is affected by environmental changes. Part of the energy escapes from the side of the fiber in the curved section. By detecting the changes in light intensity, corresponding physical parameter can be gained[10−13]. The structure of MFS is shown in Fig. 1. Usually, the deformer is formed by a pair of tooth plates, and sensitive fiber goes through the middle tooth plates. Under the action of the tooth plates, sensitive fiber can get a periodic micro-bend. When the tooth plate affected by external disturbances, the micro-bend degree of the optic-fiber changes, leading to the change in output light intensity. By measuring the change in the output light intensity, the level of the external disturbances can be measured indirectly. And the function of a micro-bend optic-fiber sensor is achieved.

In response to an appropriate environmental distur-

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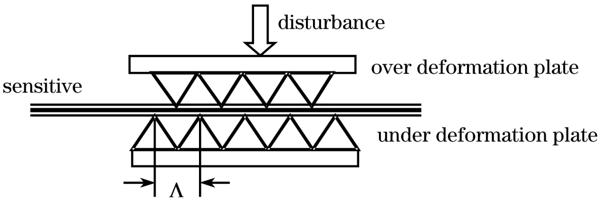


Fig. 1. Schematic diagram of the micro-bend fiber-optic sensors.

bance ΔE, applying a force ΔF to the micro-bend fiber can cause the amplitude of the fiber deformation X to change by an amount of ΔX. The transmission coefficient for light propagating through the micro-bend fiber T is in turn changed by an amount of ΔT, so that[13]

$$\Delta T = \left(\frac{\Delta T}{\Delta X}\right) D\Delta E, \tag{1}$$

where $D\Delta E = \Delta X$ and D is a constant which depends on the environment disturbance ΔE. In terms of the applied force ΔF, Eq. (1) becomes

$$\Delta T = \left(\frac{\Delta T}{\Delta X}\right)\Delta F\left(K_{\mathrm{f}} + \frac{A_{\mathrm{s}}Y_{\mathrm{s}}}{l_{\mathrm{s}}}\right)^{-1}, \tag{2}$$

where K_{f} is the micro-bend fiber force constant and $A_{\mathrm{s}}Y_{\mathrm{s}}/l_{\mathrm{s}}$ is the force constant involved with changing the length of the deformer spacers. Here A_{s}, Y_{s}, and l_{s} are the cross-sectional area, Young's modulus, and length of the deformer space, respectively.

The deformer converts the change in the environmental parameter ΔE to a force ΔF on the micro-bend fiber, which is

$$\Delta F = \Delta E \cdot \mathrm{C}, \tag{3}$$

where C is a function of external disturbances. For a pressure sensor, C is simply equal to the area of the deformer plate A_{p}. Thus Eq. (2) becomes

$$\Delta T = \frac{\Delta T}{\Delta X} A_{\mathrm{p}}\left(K_{\mathrm{f}} + \frac{A_{\mathrm{s}}Y_{\mathrm{s}}}{l_{\mathrm{s}}}\right)^{-1}\Delta P, \tag{4}$$

where ΔP is the change of pressure. For a high sensitivity pressure sensor, $A_{\mathrm{s}}Y_{\mathrm{s}}/l_{\mathrm{s}}$ is so small that the effective compliance is determined by that of the bent fiber which is quite large. In this case, Eq. (4) can be simplified as

$$\Delta T = \frac{\Delta T}{\Delta X} A_{\mathrm{p}} K_{\mathrm{f}}^{-1}\Delta P, \tag{5}$$

where $\Delta T/\Delta X$ is a sensitivity factor, and it depends on the Λ value of the deformer and mechanical devices, where Λ is the plate period. It can be seen that there is corresponding change law of transmission light intensity with the different parameters change of the environment. Hence, a variety of parameters in the outside world can be measured with MFS.

The transmission theory of optical-fiber[13] shows that, there is an optimal micro-bend period Λ_{c}. With this optimal period, the transmission modes will couple with each other completely, so the micro-bend loss in fiber can be the largest. For step-fiber, the optimum period Λ_{c} is

$$\Lambda_{\mathrm{c}} = \frac{\sqrt{2}\pi a n_0}{\mathrm{NA}}. \tag{6}$$

For the parabolic-type fiber gradually, the optimum period Λ_{c} is

$$\Lambda_{\mathrm{c}} = \frac{2\pi a n_0}{\mathrm{NA}}. \tag{7}$$

In Eqs. (6) and (7), a is the core radius, n_0 is the core index, and NA is the numerical aperture of the optical fiber.

The experimental device of vibration sensor for frequency response is shown in Fig. 2. The light source is laser, and the disturbance signals acting on the deformer come from the piezoelectric ceramic, which is connected to flexibility fixtures. In the experiment, the period of tooth plates is 1.5 mm. The fixtures are flexible to have a cushion effect, so the deformer's vibration can be more peaceful. The detector is an infrared semiconductor materials (HgCdTe) detector. The display is a new digital oscilloscope. The signal generator is a multi-wave-shape signal generator. And sine wave-shaped is used in this experiment.

Via acting the sine voltage signal which is from the signal generator on the piezoelectric ceramic, the piezoelectric ceramics start to vibrate. In addition to the role of the flexible device and the over tooth plate of the deformer vibrancy, the vibration frequencies are the same as these of the electronic-signal. So the sensitive fiber going through the deformer occurs periodic micro-bend, and then the power of light transferred to the detector will be periodically lost. Hence, the signal intensity incepted by the detector will change periodically, and the frequency change in light intensity is the same as vibration of over tooth plate. Such a change is displayed by the oscilloscope placed behind the detector. Utilizing a digital oscilloscope, the change frequency of light intensity can be read, which responses to the vibration disturbance. So the aim of making use of a micro-bend optic-fiber sensor to sensing vibration frequency is achieved.

Two types of sensitive optical-fiber are used in this experiment. One is ordinary single-mode optic-fiber of communications, and the other is a common multi-mode optical fiber. Typical results of the experiment are shown in Fig. 3. In Fig. 3, the left one is the result of frequency response to vibration for MFS sensor by using a multi-mode optic-fiber as the sensitive fiber, and the right one is the result of frequency response to vibration for MFS sensor by using a single-mode optic-fiber as the sensitive fiber.

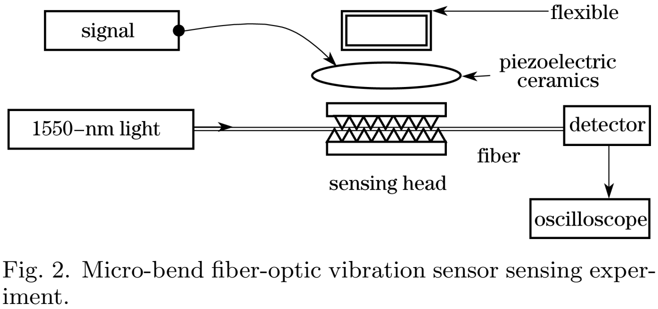
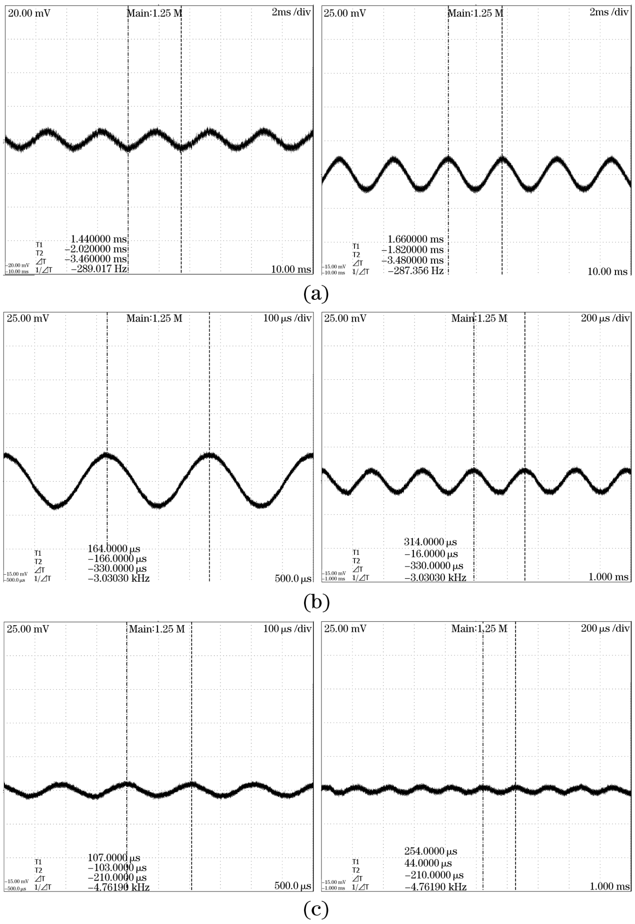


Fig. 2. Micro-bend fiber-optic vibration sensor sensing experiment.



(a)

(b)

(c)

Fig. 3. Typical experimental results for (a) 287, (b) 3030, and (c) 4761 Hz frequency response vibration sensor.

As shown in Table 1, the characteristic of these two types of MFS is displayed. The same electronic-signal frequency is used for them, the range of which is from 287 to nearly 4762 Hz in the experiment. Here, in order to reflect the non-accidental of measurement, the electronic-signal changes with the frequency in randomness. When the frequency is less than 1000 Hz, measurements are taken nearly every 100 Hz. The measurements are taken every a few hundred Hz in the range of 1000−4762 Hz. Table 1 shows that, in the range of low-frequency (287 − 500 Hz), the single-mode optical fiber is better than the multi-mode optical fiber for sensing the vibration frequency response. But in the range from 500 to 4762 Hz, multi-mode fiber is better.

Through Table 1 and Fig. 3, it can be seen that, in the range of 500 − 4762 Hz, multi-mode optic-fiber sensor has better frequency response characteristics and better wave shape reducibility than single-mode optic-fiber sensor, and the relatively error is smaller. But in the range of 287 − 500 Hz, single-mode optic-fiber sensing has better frequency response and wave shape reducibility than multimode optic-fiber sensor. This is due to the different micro-bend lose mechanisms of multi-mode fiber and single-mode fiber. The mode transmission in multi-mode fiber at a time includes basic mode, low-mode, and high-mode while single-mode with basic mode only. So when multi-mode fiber bends slightly, the high-mode couples to loss mode easily and then micro-bend loss happens; and considering single-mode fiber, the basic mode will couple to the loss mode only when the single-mode fiber bends up to a certain degree, resulting in micro-bend loss. This difference makes that multi-mode optical fiber used as a sensitive fiber perform better than single-mode fiber in the range of 500 − 4762 Hz. However, the reasons of that single-mode fiber used as a sensitive fiber of vibration sensor performs better than multi-mode fiber in low frequency band need further study.

Table 1. Characteristic of Single-Mode Fiber and Multi-Mode Optical Fiber Used as Sensitive Fibers to the Frequency Response of MFS

Signal (Hz)	Multi-Mode (Hz)	Single-Mode (Hz)	Multi-Mode Error (Hz)	Single-Mode Error (Hz)
287.4	289.0	287.4	1.6	0
387.6	386.1	387.6	−1.5	0
485.4	487.8	485.4	2.4	0
588.2	588.2	588.2	0	0
689.7	689.7	689.3	0	−0.4
787.4	787.4	787.4	0	0
885.0	885.0	884.9	0	−0.1
980.4	980.4	980.4	0	0
1183.3	1183.4	1183.4	0.1	0.1
1770.0	1770.0	1769.9	0	−0.1
2083.3	2083.3	2083.3	0	0
2403.9	2403.9	2403.9	0	0
3030.3	3030.3	3030.3	0	0
3906.3	3906.3	3906.3	0	0
4761.9	4761.9	4761.9	0	0

The periodic disturbance of tooth plate of deformer is affected by periodic expansion of the piezoelectric ceramic. The under tooth plate is fixed and the over tooth plate will be under pressure when the piezoelectric ceramic elongates. After piezoelectric ceramic shrinks, the over tooth plate moves upward relying on the sensitive fiber to shrink itself. The contraction capacity of an optic-fiber depends on its own strength, so when the vibration frequency of piezoelectric ceramic reaches a certain value, the contraction of sensitive fiber fails to react in time. And when the piezoelectric ceramic stretches again, the tooth plate has not yet gone back to its original state, and the plate is down pressure by the piezoelectric ceramic again, which makes the sensitive-fiber's period of micro-bend no longer reflect the vibration frequency of vibration disturbance. Signals received by detector are weaker, where the sensor does not work normally. What's more, the piezoelectric ceramic used to load vibration in the experiments is a capacitive component, and its dynamic response is slow. Therefore, when the frequency of a sinusoidal signal is greater than 5000 Hz ($t < 0.2$ ms, and t approaches the time it takes for response), the piezoelectric ceramic can not respond to the vibration frequency, so the upper limit for measuring of this experimental device is around 5000 Hz. From the above analysis, the upper limit of this device sensing frequency response is determined by the strength of the sensitive fiber and the dynamic response of piezoelectric ceramic, and the strength of multi-mode fiber is slightly stronger than that of the single-mode fiber. Near the upper limit, as shown in Fig. 3(c), multi-mode optic-fiber sensor in response of vibration frequency is better than the single-mode optic-fiber sensor.

In addition, the semiconductor photodetector used in the experiment is HgCdTe photovoltaic detector, and when the low-frequency optical signals are translated into the current signals, they will suffer 1/f noise which is a low-frequency noise due to the potential barrier existing internal or on the surface of the semiconductor, and the power spectral density of low-frequency noise is inversely proportional to the frequency. Therefore, when signal frequency is lower than 250 Hz, impaction of 1/f noise is so large that the signal current is flooded by noise current, resulting in the sensor failing to response to the vibration frequency.

In conclusion, the basic structure and the working principle of micro-bend optic-fiber sensors are introduced. The experimental study on the vibration frequency response of micro-bend optic-fiber sensor in range of $287-4762$ Hz is done. In the experiment, single-mode fiber and multi-mode fiber are used as the sensitive-fibers of the MFS in vibration frequency response, and the contrast between two sensitive fibers is presented. It is shown that this MFS device sensing vibration response can perform good frequency reducibility in the range of $287-4762$ Hz. And 4762 Hz is the upper limit frequency respond of this device. The frequency below 287 Hz is to be further studied. This study on the micro-bend sensor vibration frequency response development has guiding significance for fiber-optic sensors.

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