A bio-signal monitoring sensor based on the microbending effect of fiber

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Abstract. In this paper, the focus of the study is the bio-signal monitoring sensor based on microbending effects and bending loss in fiber, the physical natures of the microbending effects and bending loss of multimode fiber are expounded through the microbending principle of fiber, and the effect of displacement on the microbending loss of fiber is explored and analyzed by deriving the microbending loss formula under the optical fiber theory. After putting the sensor on the back of a chair and letting the subject sit on the chair with the back on the sensor, the degree of microbend or radius of the fiber change as the change in chest volume during breathing results in the change in the external force, i.e., the force applied to the sensing part of the fiber. The physical change in the fiber induce changes in the amount of light energy transmitted in the fiber, causing optical loss. The respiratory rate is obtained by measuring the optical loss. The results show that the waveform displayed on the computer has good traceability performance, on which the frequencies of respiratory signals including normal breath, deep breath, and rapid breath can be distinguished. Experiments show that the sensor has good traceability feature and can automatically recognize the breathing conditions, with a signal-to-noise ratio of over 28dB

Keywords. Fiber sensing; microbending loss; respiratory signal modulation; spectrum analysis.

1. Introduction

With the development of scientific research and the continuous improvement of living standards, people's pursuit of health is also increasing, and the accuracy of medical diagnosis is also improving. As a high-precision interference-type fiber-optic sensor, the fiber-optic microbend sensor has the advantages including its simple structure, small size, high sensitivity, and insensitivity to electromagnetic interference, and has broad industrial application prospects. In recent years, great progress has been made in researches on wearable bio-signal monitoring sensors at home and abroad. The sensors are mainly photoelectric volume sensors and piezoelectric sensors that are large in size, uncomfortable to wear, and are not feasible for long-term monitoring.

Due to its advantages including the ease of forming a distributed sensor network, insensitivity to electromagnetic interference, simple structure, small size, and long life, microbend fiber is receiving increasing attention from scholars at home and abroad. At present, microbend fiber has been successfully
applied in areas including civil engineering, oil well monitoring, aerospace, medicine, and biology, etc. This study proposes a bio-signal monitoring sensor based on the microbending effect of fiber for measuring respiratory rate. The major components of the system include the light source, optical fiber, respiratory signal modulator, photoelectric converter, and software. Through simulation and experiment, it is proved that the sensor proposed in this paper not only has the advantages including high efficiency and high sensitivity in measurement, but also makes up for the disadvantages including high cost, large size, and susceptibility to electromagnetic interference of other respiratory signal monitoring sensors. The sensor is comfortable to wear, small in size, and high in measurement sensitivity, so more waveform details can be collected. Due to the unique feature of the bio-signal detected by fiber-optic microbend sensor, it is necessary to conduct researches on the data processing. Using the distributed microbend fiber to form a vibration sensor to measure the heart rate signal of the human body provides useful references for the construction, measurement, and data processing algorithms of fiber-optic microbend sensors in various types of detectors.

2. Principle and design of fiber-optic microbend sensor

The fiber-optic microbend sensor mainly consists of four parts, including the light source, optical fiber, respiration modulator, and photoelectric detector. The respiration modulator designed in this paper is sawtooth-shaped, because such structure is relatively simple, convenient and easy to implement. The sensitivity of the sawtooth-shaped respiration modulator depends largely on the length of the microbend fiber and the distance between serrations, i.e., the microbending period.

2.1. Microbending loss of meridional ray

The plane passing through the axis of the fiber is called the meridian plane. The light in the meridian plane is called the meridional ray. The law of reflection of light stipulates that the incident ray, the reflected ray, and the normal are all on the same plane, that is, in the meridian plane. The specific way in which light travels is shown in Figure 1. The following is an analysis on the optical loss when the fiber is bent with a radius of R based on the ray theory.

Let the diameter of the fiber core be 2a and the bending radius be R, i.e., OB. The refractive index of the fiber core is n1 and the refractive index of the cladding is n2 (n1 > n2). Assuming that the cross section of light intensity in a straight line fiber is Lambertian, that is, \( I = I_0 \cos \varphi \), in which \( I_0 \) is the light intensity on the cross-section normal, the distribution is assumed to be uniform, and \( \varphi \) is the angle between a certain beam of light P and the cross-section normal (i.e., the fiber axis). When \( \varphi \leq 90^\circ - \theta_c \left( \sin \theta_c = n_2 / n_1 \right) \), light is totally reflected in the fiber. This portion of the light can be transmitted along the straight-line segment of the fiber.

Assuming that light P enters the curved segment at point C. The height of point C from the bottom point B of the core is h. The incident angle of the light P in on the curved segment is \( \theta \). When \( \theta \geq \arcsin n_2 / n_1 \), total reflection of light occurs. Since the incident angle \( \theta' \) when the light is again reflected at the fiber interface is greater than \( \theta \), the multiple reflections after in the curved segment are always total reflections. Therefore, the light can travel in the curved portion. When \( \theta \leq \arcsin n_2 / n_1 \), the light partially enters the cladding and is refracted multiple times at the interface, and is eventually lost. Therefore, this portion of the light cannot be transmitted to the output along the curved segment. In order to study the proportion of the light transmitted in the straight segment that cannot be transmitted in the curved segment, the relationships of \( \varphi \), h, and \( \theta \) need to be studied.
In ΔACO, based on the law of sines, the following holds:

\[ \sin \theta = \frac{(h + R) \cos \varphi}{R + 2a} \]  

(1)

The condition under which the light is totally reflected in the curved segment is \( \sin \theta \leq n_2/n_1 \).

That is,

\[ \cos \varphi \frac{R}{h + R} \geq n_2/n_1 \]

\[ h \geq n_2 \frac{(R + 2a)}{n_1 \cos \varphi} - R \]  

(2)

In summary, in order make total reflection occur in the curved segment, in addition to the above conditions, the following must be true:

\[ |\varphi| \leq \arccos \frac{n_2}{n_1} \]  

(3)

\[ 2a \geq h \geq 0 \]  

(4)

On the BO cross-section, within \( \varphi \rightarrow \varphi + d\varphi \), the luminous flux is \( I_0 \cos \varphi \cdot d\varphi \). Since the light of \( h \leq h_m \) cannot be transmitted in the curved segment, \( h_m = \frac{n_2 (R + 2a)}{n_1 \cos \varphi} - R \), that is, the part \( \frac{h_m}{2a} I_0 \cos \varphi \cdot d\varphi \) is attenuated. Therefore, the total luminous flux that cannot travel along the meridional plane of the curved portion (i.e., the lost portion) is:

\[ \varphi_v = \int_{-\varphi_0}^{\varphi_0} \frac{h_m}{2a} I_0 \cos \varphi \cdot d\varphi \]  

(5)

The total luminous flux that travel along the meridian plane is:

\[ \varphi_v = \int_{-\varphi_0}^{\varphi_0} \frac{h_m}{2a} I_0 \cos \varphi \cdot d\varphi = 2I_0 \sin \varphi_0 \]  

(6)
In the above formula:

\[
\phi_0 = \arcsin \sqrt{\frac{n_2^2 - n_1^2}{n_1^2}}, \quad \left| \phi_0 \right| = \arccos \frac{n_2}{n_1}
\]  

(7)

The microbending loss coefficient is the ratio of the total light intensity lost along the curved segment to the total light intensity entering the curved segment. By formula (5) and formula (6), the following holds:

\[
\alpha = \frac{\phi_r}{\phi_{r0}} = \frac{\phi_0}{\sin \phi_0} \cdot \frac{n_2}{n_1} \left(1 + \frac{R}{2a} \right) - \frac{R}{2a} = \left( \frac{\phi_0}{\sin \phi_0} \cdot \frac{n_2}{n_1} - 1 \right) \frac{R}{2a} + \frac{n_2}{n_1} \cdot \frac{\phi_0}{\sin \phi_0}
\]  

(8)

The coefficient of \(\frac{R}{2a}\) in formula (8) is:

\[
\frac{\phi_0}{\sin \phi_0} \cdot \frac{n_2}{n_1} - 1 = \frac{\arcsin \sqrt{n_1^2 - n_2^2}}{n_1} \cdot \frac{n_2}{n_1} - 1 = \frac{\arcsin \sqrt{n_1^2 - n_2^2}}{n_1} - 1
\]  

(9)

In summary, the microbending loss of multimode fiber increases sharply with the decrease of the microbending radius. The purpose of studying the microbending loss of multimode fiber is to provide reference for designing fiber-optic microbend sensors. Therefore, for a given fiber, its microbending loss is greatly affected by the microbending radius. When designing the sensor, in order to control the radius of the microbend thus improving the sensitivity of the sensor, it is necessary to consider the displacement and the distance between serrations.

2.2. Description on the structure of the sawtooth-shaped respiratory signal modulator

The sawtooth-shaped respiratory signal modulator mainly consists of the upper and lower sawtooth-shaped plates. The middle is the sawtooth and has an auxiliary structure around it. The upper and lower sawtooth-shaped plates are rectangular parallelepipeds with a thickness of 8 mm, a length of 260 mm, and a width of 210 mm. There are 15 sawtooth in the middle. Under mechanical disturbances such as body motion, the sawtooth-shaped plates squeeze the fiber and produces 30 microbends in the fiber. There is a cylinder with a spring on each side of the plates that makes the respiratory signal modulator to automatically continue to the next round of measurement after being squeezed. In addition, it produces a reaction force to protect the optic fiber when being squeezed.

The fiber is sandwiched between the two plates. When the measured parameter of the outside changes, the upper plate has a displacement under the external force, which acts on the fiber to cause periodic microbending of the fiber. The degree of microbending changes with changes in the external force. At this point, the optical loss through the fiber changes, from which the changes in measured parameters can be detected. As shown in Figure 2.
Figure 2. Schematic diagram of the structure of the plates

When in use, in the respiratory signal modulator, the light from the light source is transmitted through the fiber, and after passing the bio-signal sensor, the transmitted light is converted into an electrical signal by a photoelectric converter and a signal acquisition module. The host computer transmits the signals through serial communication and displays the signals in real time. The force from the breath acting on the upper plate causes the upper plate to have a corresponding displacement, after which the fiber has a corresponding microbend to produce microbending loss. When the force disappears, the upper plate returns to the original position by the elastic force of the spring. The frequency of breathing can be derived by monitoring the number of times the loss in light intensity occurs in one minute.

2.3. Parameter design of the sawtooth of the respiratory signal modulator
In order to improve the sensitivity of the microbend fiber and enhance the optic loss in the microbend fiber. The profile of the sawtooth was analyzed and designed with the coupled-mode theory. The optimal microbend period of the graded index multimode fiber is $A_c$.

$$A_c = \frac{2\pi an_c}{NA}$$ (10)

On the respiratory signal modulator, for the design of the upper and lower sawtooth shapes, the basic tooth profile is an equilateral triangle. To prevent the fiber from being broken, the design must have chamfering at the tip of the tooth, that is, making the tip a little blunt.

Figure 3. Sawtooth shape of the signal modulator

Through the relationship between microbending loss and bending radius of multimode fiber and the relationship between displacement and bending radius of the respiratory signal modulator, the relationship between displacement and bending radius of microbending loss can be obtained. Then the loss produced by the respiratory signal modulator is:
In the above formula, \( N \) is the number of microbending periods (sawtooth-shaped). The microbending period and the number of microbending periods have an important impact on the microbending loss. The analysis and simulation are shown in Figure 4.

![Figure 4. Relationship between the microbending period and the loss when \( N=15 \)](image)

As shown in Figure 4, for different microbending periods, the loss increases as the displacement increases. The curves are different. When the microbending periods are 4mm and 5mm, respectively, the curve can well meet the requirement on sensitivity, but for the fiber, there is the risk of breaking. When the microbending periods are 7mm and 8mm, respectively, the stiffness makes the fiber unable to achieve good performance. The optimal microbending period determined is 6mm.

3. Experiment and discussion

When performing a breath test, the subject sits with the back on the respiratory signal modulator, and the periodic force generated by breathing causes the upper plate to move periodically, which causes the fiber to periodically bend and straighten, resulting in periodic optical loss. The photoelectric converter is mainly responsible for photoelectric detection and data acquisition, converting light intensity change into current change, and transmitting the obtained digital signal to the host PC. On the PC, the data is read through serial communication with LABVIEW, so the respiratory waveform can be displayed in real time and the number of breaths can be simultaneously displayed in digits. The light source used in the experiment is the distributed feedback laser (DFB) of CONQUER with an output wavelength of 1550 nm and an output current of 10 mA.

3.1. Experiments and results

After the experiment platform was set up, the measurements on the breaths of different subjects under different conditions were carried out. Fast Fourier transform was performed on the obtained data to obtain the spectrum distribution curves. The appropriate filter frequencies were set according to the specific frequency distributions.

3.1.1. Normal breath. As shown in Figure 5. There are noises in the breath signals. Through analysis, the major causes of noise are the insensitivity of the spring and the friction of the limiting posts. Figure 5-(a) shows the frequency of the breath signal. The wanted signal is obtained through filtering at a frequency of 0.324 Hz, as shown in Figure 5-(c).
3.1.2. Deep and slow breath. Figure 6 shows that the frequency of deep and slow breath is 0.204 Hz. The amplitude of the breath signal in Figure 6 is greater than that of Figure 6 but with smaller frequency, which is consistent with the fact that deep breath is heavier and slower than normal breath.

There are still some deviations in the data obtained from the experiment. The main reasons are that the sensor was in contact with the human body during measurement and was susceptible to temperature and that manual operation also introduced errors during the experiment. In addition, the algorithms related to signal denoising and extraction are not sophisticated enough and require further improvements.

3.1.3. Rapid and shallow breath. Figure 7 shows that the frequency of shallow breath is 0.324Hz. The amplitude of the breath signal in Figure 7 is smaller than that of Figure 6 but with higher frequency, which is consistent with the fact that shallow breath is lighter and faster than normal breath.
3.2. Analysis of experiment data and results

Figure 6 shows the waveform of the breath signal has been shifted up and down, two peaks appear in the spectrum analysis, and there is low-frequency noise. The noise brings more attention. Therefore, it is necessary to analyze the breath signals under different conditions.

In the study, the experiment on subject 2 and subject 3 was carried out with the above method. The frequency distribution was obtained through fast Fourier transform. Eventually, it was found that the rate of breath is between 0.2Hz and 0.5Hz. The low-frequency noise at 0.044 Hz. The reasons are the slow recovery of the springs and the friction of the limiting post. In addition, there are a lot of moderate-amplitude high-frequency noises that need to be filtered out. Finally, after passing the 0.18 Hz-0.5Hz window, the signal turns into a useful breathing waveform. The feasibility has been proven.

There are still some deviations in the data obtained from the experiment. The main reasons are that the sensor was in contact with the human body during measurement and was susceptible to temperature and that manual operation also introduced errors during the experiment. In addition, the algorithms related to signal denoising and extraction are not sophisticated enough and requires further improvements. For noise, with the further improvement of the device, the signal-to-noise ratio can be as high as 28dB. In addition, the texture of the materials used, the position of the subject and the means of measurement may also have an impact on the results.

4. Conclusion

In this paper, a bio-signal monitoring sensor based on the microbending effect of fiber is proposed, the sensor is designed and packaged, and the analysis of the collected signal data is conducted to obtain the heart rate of the subject. The results show that the model and the presumption are theoretically valid. The sawtooth structure makes the respiratory signal modulator simple to manufacture, low in cost, and high in accuracy. The method does not require electrodes, does not affect the daily life of the subject, and makes it possible for the subject to monitor heart conditions at home. The design parameters of the respiratory signal modulator are optimized by derivation and simulation. The experiments conducted on the human body show that the sensor proposed in this paper is able to effectively measure the breath rate. This method is of certain significance for assessing conditions of people’s daily life including stress from work, fatigue, and mental status.

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