Design of reflective optical fiber displacement sensor using double optical paths

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Abstract

A reflective optical fiber displacement sensor using double optical paths is designed based on the principle of reflective optical fiber displacement sensor. The sensor has double optical paths composed of random fiber and semicircle fiber. The output signal of double optical paths is disposed by using the preamplifier, intermediate amplifier, band-pass filter and AC to RMS circuit. The ratio and the displacement of the output signals of the two optical paths have linear relationship, effectively enlarging the measuring range on basis of the accuracy of measurement.

Keywords: Displacement Measurement, Reflection, Optical Fiber

1 Introduction

Optical fiber displacement sensor makes up of LIOFDS (Laser Interferometric Optical Fiber Displacement Sensor) based on phase modulation and ROFDS (Reflective Optical Fiber Displacement Sensor) based on intensity modulation. The former is used for detection by interference principle of coherent light, so it has a good performance in accuracy, but it requires the optical source stable and has a high price [1]. However, the later has lots of advantages – simple structure, stable performance, low price, flexible design and working in harsh environments, thus being widely used and occupying a very important position in optical fiber sensors. The output characteristics of ROFDS present a parabolic approximation, so the linearity is low within the measurable range. Only the front slope with a high linearity is used for measurement in actual application, thus limiting the measuring range and application [2]. Because the semicircle type fiber displacement sensor and the random type fiber displacement sensor have different peak positions, the ratios are calculated as the outputs of the former divided by those of the latter. So the obtained ratios and the displacements have a good linear relation. The function is realized by circuit design, making good compensation and enlarging the range of fiber displacement sensor.

2 Principles for temperature measurement with fluorescent lifetime

Figure 1 shows the principle diagram of ROFDS. The fiber, divided into two parts – the transmitting fiber and the receiving fiber, is used for signal transmission. The surface of the reflector corresponding to the fiber probe is a reflecting surface. The optical emitted by the optical source goes through the transmitting fiber and irradiates displacement reflection. Then the reflected optical goes through the receiving fiber and is received by the photo sensor. The output intensity is determined by the distance between the reflector and the fiber probe, that is, if the displacement changes, the output intensity will change as well. The displacement is got by the detection of the output intensity.

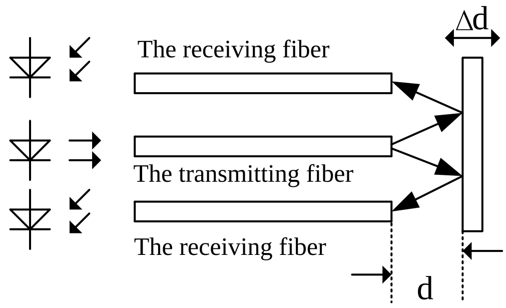

FIGURE 1 Principle diagram of reflective displacement fiber sensor

Figure 2 shows the method of equivalent coordinates analysis. Firstly, the mirror of the receiving fiber about the reflection is drawn; secondly, the optical intensity received from the optical field of the transmitting fiber end; at last, the equivalent results of the system is calculated as the optical intensity multiplied by the reflectivity of the reflection.

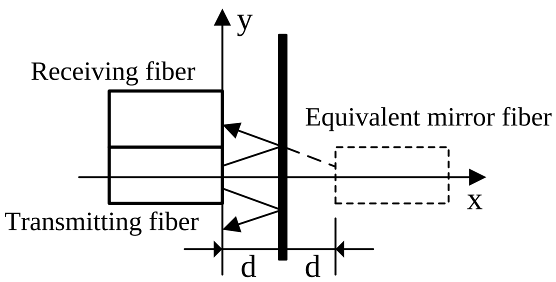

FIGURE 2 Equivalent coordinates analysis

For the multimode fiber, the output optical field flux distribution function of the fiber end is calculated as:

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$$\Phi(d,r) = \frac{k_0 I_0}{\pi(a_0 + K\tan\theta_c d^{3/2})^2}\exp\left(-\frac{r}{a_0 + K\tan\theta_c d^{3/2}}\right), \quad (1)$$

where I_0 is the optical intensity of the transmitting fiber coupled with the optical source, $\Phi(d,r)$ is the optical flux density in the position (d,r) of output optical field, k_0 is the optical power loss coefficient of the transmitting fiber, a_0 is the fiber radius, K is the coupling parameter, θ_c is the fiber maximum incidence. If the fibers of the same kind are put in the output optical field as the detection receivers, the received optical intensity can be expressed as:

$$I(d,r) = \iint_s \frac{kk_0 I_0}{\pi R^2(d)} \cdot \exp\left(-\sum_i \eta_i r_i\right) \cdot \exp\left(-\frac{r^2}{R^2(d)}\right) ds. \quad (2)$$

In equation (2) $R(d) = (a_0 + K\tan\theta_c d^{3/2})$, where k is the optical power loss coefficient of the receiving fiber, $\exp(-\sum_i \eta_i r_i)$ stands for the added loss because of the winding of the receiving fiber, S is the core area. For convenience, in the output optical field, the optical intensity in the center point of the receiving fiber end can be as the average optical intensity of the whole core surface. Approximately, the detected optical intensity of the receiving fiber end can be calculated by:

$$I(d,r) = \frac{Skk_0 I_0}{\pi R^2(d)} \cdot \exp\left(-\sum_i \eta_i r_i\right) \cdot \exp\left(-\frac{r^2}{R^2(d)}\right). \quad (3)$$

Figure 2 shows that the optical intensity received by the fiber in the reflected optical field is equivalent to the receiving optical intensity of the mirror fiber multiplied by the reflection coefficient R of the reflector. The coordinate of the equivalent receiving fiber center (shown as the dashed line) is $(2d,r)$, where r is the distance between the center of the transmitting fiber and that of the receiving fiber. The coordinate is substituted in equation (3):

$$I(2d,r) = \frac{S_1 k_0 k_1 I_0}{\pi R^2(2d)} \cdot R \cdot \exp\left(-\sum_i \eta_i r_i\right) \cdot \exp\left(-\frac{r^2}{R^2(2d)}\right). \quad (4)$$

Equation (4) shows that when the reflector, that is the detected object, is determined and the incident optical source remain stable, the modulation function of the fiber probe will be related to the displacement d. Namely the change of optical intensity reflects that of the displacement. So, the measurement of the displacement is transferred into that of the optical intensity [3].

3 Design of reflective fiber using double optical paths

At the end of the fiber probe, the transmitting fiber and the receiving fiber have four kinds of distribution: the random distribution, the semicircle distribution, the coaxial internal emission distribution and the coaxial external emission distribution. In the work, the random type and the semicircle type fiber are used. The transmitting and receiving fiber at the end of the random type are randomly distributed; the transmitting and receiving fiber at the end of the semicircle type occupy the semicircle region. Figure 3, the output curve of random type fiber and the semicircle type fiber, shows that the ROFDS has a poor linearity within the measuring range. Both the semicircle type and the random type have a peak value in the output curve, and the displacement related to the peak value of the random type is smaller than that of the semicircle type. Meanwhile, the curves have a bad linearity in the top region. In the actual measurement, only the front slope with a good linearity is applied, limiting the range of measurement and application. According to reference [4], the ratio of the output signals of the semicircle type and the random type probe (B/A) has a good linear relation with the displacement. Figure 4 shows that if the B/A output characteristic curve is fitted by the least square method, the nonlinear error will be less than 2.5%. So the double optical paths are used in the design. Figure 1 shows that one receiving fiber uses the random type, the other uses the semicircle type. The nonlinear error of the sensor is decreased by the method and the using range of the fiber displacement sensor is enlarged to about 4 mm.

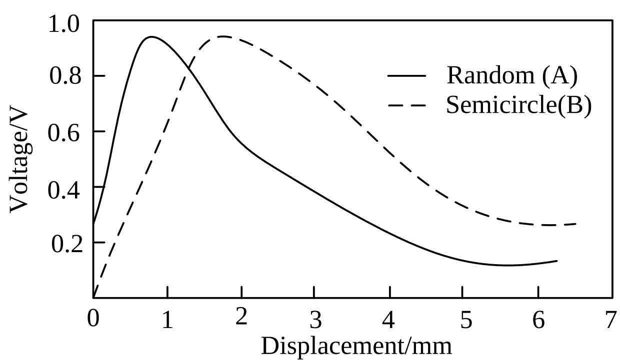

FIGURE 3 The output curve of random type fiber and semicircle type fiber

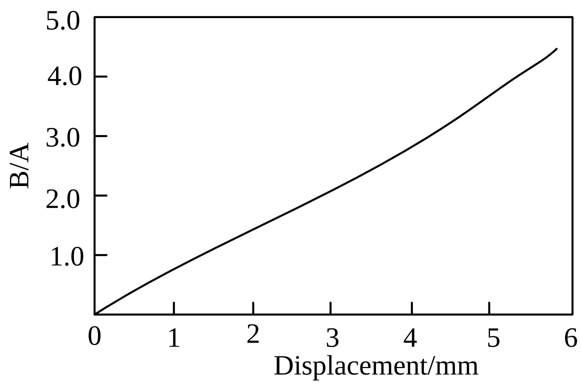

FIGURE 4 B/A output characteristic curve

Figure 5 shows the reflective fiber displacement measurement system using double optical paths. It is made up of the light source driver, the photoelectric detector, the preamplifier, the filter and the AC to RMS conversion circuit. The working process is as follows: firstly, The LED, driven by the square wave generator made up of 555, emits the optical pulse waves with a wavelength of 940 nm suitable to the low loss window of the quartz fiber. The optical pulse waves are focused by the lens, poured into the transmitting fiber, received by the semicircle and random type fiber after being reflected and transformed to the electric signals through the photoelectric devices. The electric signals are transformed to the DC signals through the preamplifiers, the filters and AC to RMS conversion. The DC signals are sent to the divider to get the ratio of the optical intensities of the two receiving fibers in the form of DC. After A/D module transformation of the SCM MSP430F449, the ratio-displacement function is obtained by linearization of the measuring data, using polynomial interpolation. In actual measurement, the detected displacement can be obtained by substituting the ratio of a position back into the function.

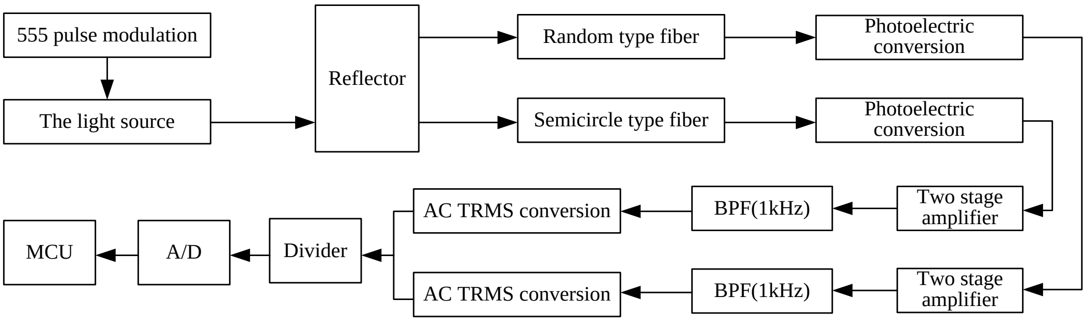

FIGURE 5 Diagram of the displacement measuring system

4 Design of light source driving and signal processing circuit

4.1 LIGHT SOURCE DRIVING CIRCUIT

The colorless and transparent LED L51R4 is selected as the light source in the circuit. It is considered that the error signals caused by external disturbing light are usually slowly changing DC or random signals, and those caused by the dark current of the photoelectric detector and the drifting of the amplifier circuit are also DC error signals. In order to eliminate these error signals, the LED is driven by the square wave driving circuit. The pulse is generated from the 1 KHz square wave generator, made up of the timer 555 and the peripheral resistance capacitance element. By using this method, the LED is in the intermittent working state with low power consumption, making the fiber sensor system work steadily for a long time. When the displacement changed, the amplitude of the pulse light will be modulated by the detected displacement signals. So, the signals arriving at the photoelectric detector are the wave signal after amplitude modulation with a message of displacement.

4.2 PREAMPLIFIER AND THE INTERMEDIATE AMPLIFIER

To get stable outputs of the preamplifier, the integral type light I/V conversion circuit is used in the system. The integrated circuit LF351 with low power consumption and noise is used for the preamplifier. Figure 6 shows the practical preamplifier circuit with low noise, where C_1 is the anti-hunt capacity used to make the performance of the preamplifier more stable. C_1, usually valuing from 30 to 100 pF, is 68 pF here. And the output voltage of the preamplifier is expressed as:

$$U_o(t) = -I_{ph} R_f \,, \tag{1}$$

where I_{ph} is the output light current of the detector; R_f is the feedback resistance. In order to make the preamplifier have enough linear dynamic range and provide enough output voltage signals for the lower amplifier; R_f values 2.2 $M\Omega$. The dynamic range of the output signals is about 0.7 V, being in the linear part of the preamplifier [5].

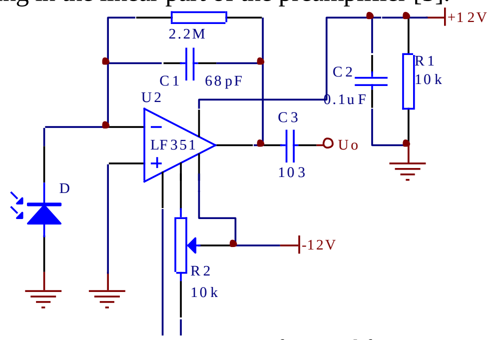

FIGURE.6 Circuit of preamplifier

In order to make the preamplifier have stable performance and good linearity within the dynamic range of the signals, the I/V conversion coefficient should not be too large. Meanwhile, considering the working performance of the narrow band filter, an intermediate amplifier is set between the preamplifier and the filter circuit. The circuit LF353A, integrated by double operation amplifiers with low power consumption and noise, is used to make up of intermediate amplifier with double paths, and the gain G, determined based on the whole condition of the system, values 5 more or less.

4.3 BAND-PASS FILTER

In this system, the static displacement is measured. If the light source is driven by using the pulse driving mode, then only the 1 KHz pulse optical intensity modulation signals will be related to the displacement variable. Besides, all the high and low frequency signals caused by the stray light and the electromagnetic field, except the above signals, are disturbing signals. The voltage controlled voltage source filter circuit is used to filter the noises and unnecessary frequency components added in the detected signals. The 1 KHz signals can pass through the filter, and the signals with different frequencies decay fast, increasing the signal-to-noise ratio of the system. Figure 7 shows the circuit and Fig. 8 shows the filter amplitude-frequency characteristics. The band-pass width is a narrow frequency range making the modulation frequency as the center frequency.

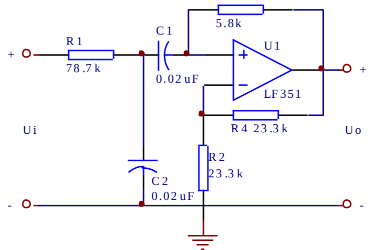

FIGURE 7 Circuit of BPF at 1.0 kHz

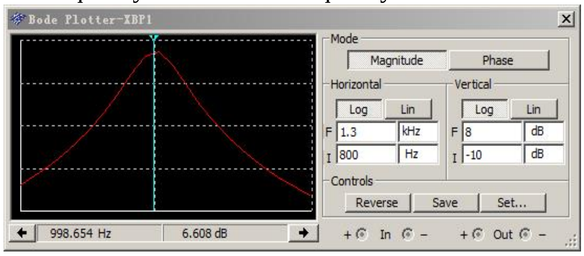

FIGURE 8 Filter amplitude-frequency characteristics

4.4 AC TO RMS CIRCUIT AND DIVIDER

Compared with the average conversion circuit, the RMS to DC integrated chip has many advantages, e.g. high integrated level, perfect function, less peripheral component, simple circuit connection and good performance in electric. So, the chip AD536 is selected to measure the RMS of all kinds of voltage wave form accurately and in real time. The high precision conversion within the measuring range can be achieved by only a capacitance, without considering the wave form parameter and distortion. AD536, supplied by double sources voltage or single source voltage ranging from +5V to +36V, compute the RMS of the input signals of AC or AC plus DC and output a equivalent DC signal. The maximum error within the wider dynamic range is 0.5%.

The divider is used to eliminate the wave of the light source, the difference of the reflectivity and the influence of the fiber loss [6]. The preset adjustment single chip multiplier or divider AD532 can control the maximum multiplication error within ±1.0% and the range of the output voltage within ±10V. The output data are converted to digital signals after entering the A/D converter. Then the digital signals are entered to the MCU and the results are achieved and shown on the MCU.

5 Data analysis and results

The high precision dial gauge calibrator with a resolution of 0.5 μm and a range of 0.5 μm is used as the calibration device to make a calibration to the system within effective measuring range. The reflector is controlled to move along the radial of the fiber, making the received light quantity decrease, and the output voltage is measured at certain intervals of displacement. Then the linearization revise is performed to the measuring results by using the least square method. The MCU system reads all the A/D conversion results, calibrates them, computes the gradient k and the intercept b of the fitting lines and stores them in ROM. In actual measurement, the fitting coefficients are called to compute the displacement according the measuring results. Table 1 shows the results of the experiment.

TABLE. 1 Experiment data of the displacement sensor

Displacement (μm)	Actual Output	Fitting Value	Displacement (μm)	Actual Output	Fitting Value	Displacement (μm)	Actual Output	Fitting Value
0	3.573	3.7690	400	2.749	2.6954	750	1.776	1.7560
50	3.474	3.6348	450	2.627	2.5612	800	1.649	1.6218
150	3.349	3.3664	500	2.478	2.4270	850	1.498	1.4876
200	3.251	3.2322	550	2.326	2.2928	900	1.379	1.3534
250	3.148	3.0980	600	2.179	2.1586	950	1.124	1.2192
300	3.026	2.9638	650	2.024	2.0244	1000	1.001	1.0850
350	2.873	2.8296	700	1.901	1.8902	1050	0.903	0.9508

The fitting linear equation of the working curve by using the least square method can be calculated as: $y = -0.002684 * x + 3.769$

The degree of linearity of the sensor is 2.3%, the resolution of the sensor reaches 0.5 μm within the range of 0~1.2 mm and the repeatability error is 0.6%. Fig. 9 shows the experimental results and the fitting line. In application, the reflector cannot be replaced because the surface roughness of the reflector has influence on the change of the reflective optical.

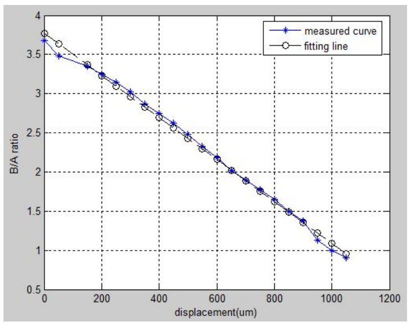

FIGURE 9 Measured result of displacement sensor

6 Conclusions

The output characteristic curve of ROFDS has a good degree of linearity in the fore slope. The traditional fiber displacement sensor only uses the fore slope, ensuring good degree of linearity, but greatly reducing the measuring range of the fiber sensor. In the work, ROFDS is designed to do division to the output signals of double optical paths using the different output characteristics of different types of fiber probes to get the ratio that has good linear relationship with the displacement, thus ensuring the degree of the linearity and enlarging the measuring range. In addition, the fiber is sensitive to temperature and vibration, and easily affected by environment. These problems are to be improved in the process of application for fiber sensors.

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