A disturbance detection interferometric fibre optic sensor system

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Abstract

This study proposed a Mach-Zehnder interferometer (M-Z)-based disturbance detection interferometric fibre optic sensor system. In this system, two single-mode optical fibres passing through the central tube of cable were used as the signal arm and reference arm of the M-Z interferometer. In the coherent length range of laser light source, as long as encountering suitable optical path difference, can the photosynthesis generate a series of alternately dark and bright interference fringes. Reference arm is dependent from the external signals, while the signal arm is subject to the disturbance of external signals. Affected by the disturbance, signal interference fringes significantly generated fluctuations with the variation of the optical distance between the two arms. The interference signals were then collected and stored through digital storage oscilloscope. By detecting the variations of the interference fringes from stability to instability, and from regularity to irregularity, it had access to judging whether or not there was external disturbance invasion. Experimental results suggested that the sensor system was very sensitive. In case of slight touch on the cable, the waveform will generate variations.

Keywords: interferometer, optical fibre senescing, disturbance, optical path difference

1 Introduction

Optical fibre can serve as the sensor in security protection. Once optical fibre sensor is influenced by external interferences, will part of characteristics in the light transmitted in the optical fibre generate variations. By analysing the signals collected by optical sensing devices and comparing the characteristic variations of the light detected, it is accessible to detecting and monitoring a number of invasion events and corresponding status. As for the optical fibre-based disturbance detection system, the intensity-modulated vibration sensor is advantageous in its simple structure, easily achievable optical path, and low production cost. However, it shows low precision and thus can merely used in the detection system with low requirements [1, 2]. Its working principle is indicated as that: by changing the phase difference of the two optical signals in Michelson interferometer [3], Mach-Zehnder interferometer [4-6], or Sagnac interferometer [7, 8] using vibration signals, the interference output changes with the sensing arm’s length. According to the changes, the detection on external vibration signal detections is realized. However, such detection is conducted based on the internal structure of interferometer to trigger the variations of interference fringe when external signals reach to the interferometer. This is the traditional application of interferometer.

This paper proposed an M-Z interferometer-based new perturbation detection interferometric fibre optic sensor system. This system integrated the fibre in optical cable and the two arms of the M-Z interferometer into a new structural interferometer. On the basis of light interference theory, two single-mode fibres in the central tube of a 60 m cable were used as the two arms of the M-Z optical interferometer respectively. One arm was set as for reference, while the other one was used for sensing. Such application is difference with the transformation of general fibre interferometers. The fibre used as the reference arm is irreverent with the external signals and the optical phase delivered from this arm keeps constant, while the fibre serving as the sensing arm is subject to the disturbance of external signals. The variations of sensing arm are prone to cause the slight variations of the optical path. Thus in the coherent length of laser source, interference fringes generate significant variations. By detecting the variations of the interference fringes from stability to instability and from regularity to irregularity, it has access to judging whether or not there is external disturbance invasion.

2 The principle of the system

2.1 THE SENSING PRINCIPLE OF M-Z INTERFEROMETER

The sensing principle of Fibre M-Z interferometer is indicated as follows: by modulating the measured object, the optical properties of the measuring arm of interferometer, such as frequency and phase etc., generate

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variations. Since the modulated light is correlated with the local oscillator of the reference arm, intermediate frequency signals can be obtained through the frequency mixing by photoelectric detection components. The related information of the measured object was thereby perceived to realize the sensing function on the pre-measured information. Fibre M-Z interferometer is generally composed by single-mode fibre, two X or Y type couplers, light source, and photoelectric detection system [9]. Single-mode optical fibre, acting as the sensing element, receives and transmits the signals. Two optical fibre couplers are used as a multiplexer demultiplexer of light. As shown in Figure 1.

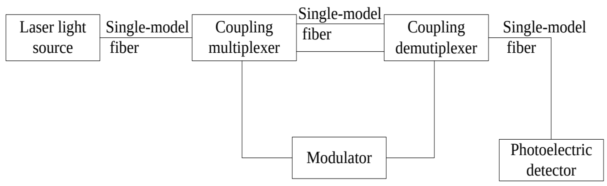


FIGURE1 The composed figure of M-Z interferometer

Being free of modulation, the optical transmission mode of the single-mode fibre is expressed as Equation (1) under the approximation of weak waveguide [10].

$$E_i(r)=\begin{cases} A' J_0\left(\dfrac{\mu}{r}\right), & 0<r\le a \\ A'\dfrac{J_0(\mu)}{K_0(\mu)}K_0\left(\dfrac{\omega}{a}r\right), & r>a \end{cases}, \quad (1)$$

where, i=x or y expresses that the electric field component of the fibre polarize along direction x or y. a is the radius of the core of single-mode fibre,

$$\mu^2=a^2(n_1{}^2K^2-\beta^2),\ \omega^2=a^2(\beta^2-n_2{}^2K^2);\ k=2\pi/\lambda;$$

n_1 and n_2 refers to the refection rates of the fibre core and outer layer respectively; $\beta=K_z$ is a longitudinal propagation constant; in the case of weak waveguide approximation, the longitudinal component E_z and H_z in optical fibre are very weak. Thus, the light in the fibre is approximated as the propagation of plane wave in the fibre. Considering the time factor of electric field component, the component is recorded as [10]:

$$E_i(r,t)=E_i(r)\cos(\omega_0 t+\varphi_0), \quad (2)$$

where, ω_0 and φ_0 refer to the angle frequency and initial phase of incident light respectively.

Under certain modulation, the maculated optical signal and the signals of the local oscillator in the other arm are combined by coupling demultiplexer and then irradiate to the surface of the photoelectric detector. In case of the electric vectors of the two beams being parallel, the total wave field is given as:

$$E_i(r,t)=E_{L0}(r)\cos(\omega_{L0}t+\varphi_{L0})+E_{M0}(r)\cos(\omega_{L0}t+\varphi_{L0}), \quad (3)$$

where, L_0 and M_0 represent the corresponding quantity of the local oscillator and modulated light respectively. The light current formed in the photocurrent photoelectric conversion can be expressed as:

$$i(t)=\frac{e^{\eta}P(t)}{h\gamma}, \quad (4)$$

η refers to the quantum efficiency of photoelectric detector. $P(t)$ is the efficiency of the light field irradiating to the surface of the detector:

$$P(t)=\frac{E^2(r,t)A}{Z_0}, \quad (5)$$

Z_0 is the wave impedance in the vacuum. A is the area of the surface detected. By combining Equations (2)-(5) is yielded:

$$\begin{aligned} i(t)=\frac{e\eta}{h\gamma}\frac{A}{Z_0}\frac{1}{2}E_{L0}\left[1+\cos 2(\omega_{L0}t+\varphi_{L0})\right]+\frac{1}{2}E_{M0}^2\left[1+\cos 2(\omega_{M0}t+\varphi_{M0})\right]+\frac{1}{2}E_{M0}^2\left[1+\cos 2(\omega_{M0}t+\phi_{M0})\right]+ \\ E_{L0}E_{M0}\cos\left[(\omega_{M0}-\omega_{L0})t+(\phi_{M0}-\phi_{L0})t\right]+E_{L0}E_{M0}\cos\left[(\omega_{M0}-\omega_{L0})t+(\varphi_{M0}-\varphi_{L0})t\right]. \end{aligned} \quad (6)$$

Since ω_{M0}, ω_{L0}, and the combined frequency $\omega_{M0}+\omega_{L0}$ echo with the optical frequency, the detector shows no response and can be neglected. Thus Equation (6) transforms into Equation (7) finally [10].

$$\begin{aligned} i(t)=i_{L0}+i_{M0}+2\sqrt{i_{L0}i_{M0}}\cos\left[(\omega_{M0}-\omega_{L0})t+(\varphi_{M0}-\varphi_{L0})t\right]= \\ i_{L0}+i_{M0}+2\sqrt{i_{L0}+i_{M0}}\cos(\omega_{if}t+\Delta\varphi), \end{aligned} \quad (7)$$

where, i_{L0} and i_{M0} are DC terms and calculated by:

$$i_{L0}=\frac{e^{\eta}A}{2hYZ_0}E_{L0}^2, \quad (8)$$

$$i_{M0}=\frac{e^{\eta}A}{2hYZ_0}E_{M0}^2, \quad (9)$$

$\omega_{M0}-\omega_{L0}=\omega_{if}$ is intermediate frequency, $\omega_{M0}-\omega_{L0}=\Delta\varphi$ is initial phase difference. Since general modulated signal is far smaller than the optical frequency, there is $\omega_{M0}<<\omega_{L0}$. Thus the light current varying with ω_{if} is detectable. It is given by:

$$i_{if}=2\sqrt{i_{L0}i_{M0}}\cos(\omega_{if}t+\Delta\varphi). \quad (10)$$

By detecting the variations of the light current, it is able to perceive the variations of the pre-measured object.

2.2 THE SENSING PRINCIPLE OF THE DISTURBANCE DETECTION INTERFERMETRIC OPTICAL FIBRE

Figure 2 shows the sensing principle of the disturbance detection interfermetric optical fibre. The principle is indicated as that: basing on the M-Z interferometer, the two single-mode fibres in the central tube of a 60 m long cable are used as the reference arm and sensing arm of the M-Z interferometer respectively. Fibre coupler Y1 divides the light emitted from the laser source into two beams. Through the two single-mode fibres in the centre tube of the cable, the two beams were transmitted to the optical fibre coupler Y2. The optical fibre coupler Y2 combines the two beams into one and interfere the beam. The interfered beam develops into light current in the photo detector, Meanwhile, the optical signals are transformed into weak electric signals and then analysed under the amplification of the photoelectric detection circuit.

The disturbance detection interferometric fibre optic sensor system is based on M-Z interferometer. Since the interferometer arms are two single-mode fibres of a 60 m long optic cable, the light paths of the interferometer are basically symmetric. However, affected the uncertainties in the links of the production process of the two arms, such as the welding of light path and the processing of the end surface of fibre etc., the two arms are not completely symmetric in fact in length and show an error of 4 cm around. Attributing to this error, it is unable to guarantee that the symmetry of the two arms is in the coherent length of the light source. Therefore, the interference fringes produced in the disturbance detection system is not a yield of the coherence of the light source itself.

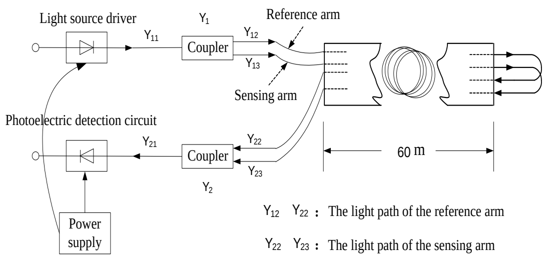


FIGURE 2 Schematic of disturbance detection interferometric fibre optic sensor system

Due to the objective existence of the length error of the two arms, there is light path difference between the two beams of the modulated light emitted from the laser divided by coupler Y_1. We set the lengths of the reference arm and sensing arms as L_1 and L_2 respectively, and the light path difference of the two arms as $\Delta L = c\Delta t$. The Δt therein refers to the time delay caused by the length difference of the two arms. Figure 3 shows the principle of production of the interference signals. The solid and dashed lines refer to the two beams to be interfered respectively. The ordinate represents the light frequency. At time of $t = t_i$, the two beams show minor differences and develops into beat frequency signals. The beat frequency signals generated between t_{si} and t_{xi} keep constant and merely relates to the light path difference.

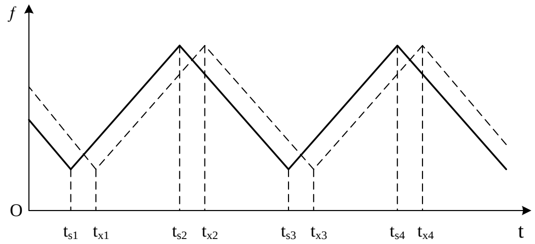


FIGURE 3 The Principle figure of interferometer singles

When the sensing arm is disturbed, the vibration frequencies of the two beams combined by fibre coupler Y_2 generate differences and optical "beat frequency". In the coherent length of the light source, as long as the optical paths of the two arms are suitable, it is prone to yield a series of alternately dark and bright fringes by photosynthesis. The sensing arm located between the two couplers. The fibre of reference arm is independent from the external signals and the optical phase therein keeps constant. When sensing arm fibre is subjected to the disturbance of external signals, the optical phase transmitted in the fibre will generate variations and produce optical phase difference in the case of the minor variations of light path, followed by the obvious variations of signal interference fringes. After the interference singles were then detected by the detection system and applied with signal processing, it is accessible to modulating the phase displacements of the pre-measured signals. When the reference light path and sensing light path are given the same disturbance simultaneously, the interference fringes of the signal basically remain constant. In case of stable disturbance, the interference fringes are supposed to be simple and harmonic vibrations under the influence of external forces, such as vibration [11]. When being applied with external disturbances, the cable generates symmetrical bending on a macro level. However, on the micro level (wavelength magnitude), the two single-mode sensing fibre are significantly asymmetric on bending and thus produce fringes (beat frequency) inevitably. The beat frequencies here, which are random variation frequency instead of regular harmonic frequency now, fluctuate randomly. Normally, the interference fringes vary slowly and stably. However, when there are external disturbance forces on the cable, the interference waves will show significant large fluctuations. Relying on these fluctuations, it is able to judge whether or not there are disturbances.

3 The structure of the system

Figure 4 shows the structure of the disturbance detection interfermetric fibre optical sensor system, which mainly includes the circuit part, light path part, and signal collection part.

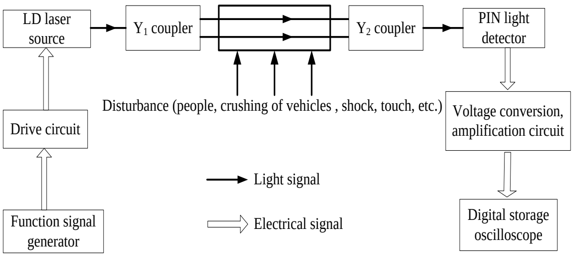


FIGURE 4 Schematic of diagram of experimental device of disturbance detection interferometric fibre optic sensor system

The triangle wave signals produced by the function signal generator are applied to the drive circuit and thus to input the triangle wave-formed current to the LD laser source. The output optical frequency of LD laser is the linear function of the input current. The optical carrier generated by LD laser source transformed the electric signals generated by the function signal generators into optical signals. Optical signals are divided into two beams after reaching to the coupler Y_1. The two beams are transmitted along the two fibres, namely, reference light path and sensing light path. Then the two beam of optical signals are integrated by coupler Y_2 into interference fringes. Since the sensing fibres in the disturbance detection interfermetric fibre optical sensor system are asymmetric in length, the two beams show time delay when reaching to the coupler Y_2 and develop into optical beat frequency.

After the sensing cables are allocated, the interference beat frequency signals is prone to yield significant variations in case of the external disturbances on the fibre. The interference lights are collected by the PIN detector. Related light signals are converted into electrical signals and finally displayed on the oscilloscope after voltage transformation and amplification. In case of no external disturbances, the interference waveforms are stored in the oscilloscope. By simulating the external disturbances, the waveforms under difference disturbances can be recorded for comparison and analysis.

4 Test Results

Figure 5 shows the experimental device. In the device, the waveforms were collected and stored by the digital storage oscilloscope. The characteristics of the oscilloscope are described as follows: bearing bandwidth of 60 MHz, 100 MHz, and 200 MHz; with sampling rate of 2 GS/s; having four 2 or 4 Channel acquisition modes; being applicable to peak detection (12 ns Burr), sampling, averaging and single passing; being capable of setting menu and selecting waveforms automatically; owning waveform and setting memory (two or four 2500 point reference waveform, 10 front panel setting options); being provided with fast Fourier transform (FFT) function. When cable suffers external distribution, the oscilloscope displays the waveform. Basing the memorizing function of the oscilloscope, the waveforms stored can be used for analysis.

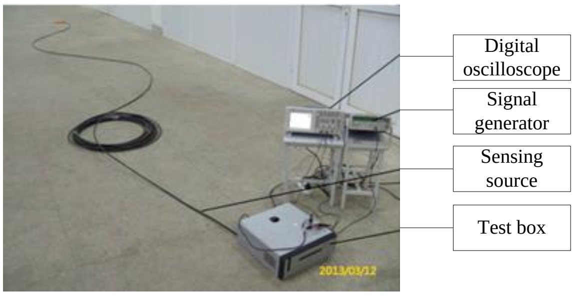


FIGURE 5 The test apparatus

To test the detecting ability of the system to the disturbance signals, the FFT transformation function of the digital oscilloscope was utilized in the test to convert the waveform of the signals into frequency. The frequency of the function signal generator was set at 20 Hz around. Figure 6 shows the frequency spectrum of the system in case of no external disturbance; the frequency spectrum of the interference wave tends to be monodromy and constant beat frequency.

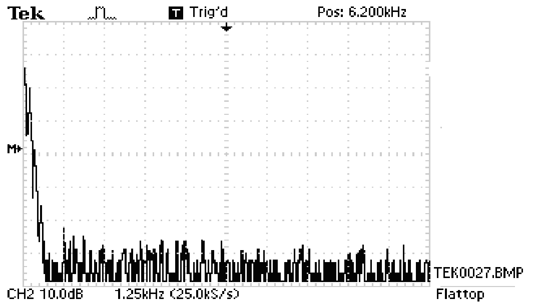
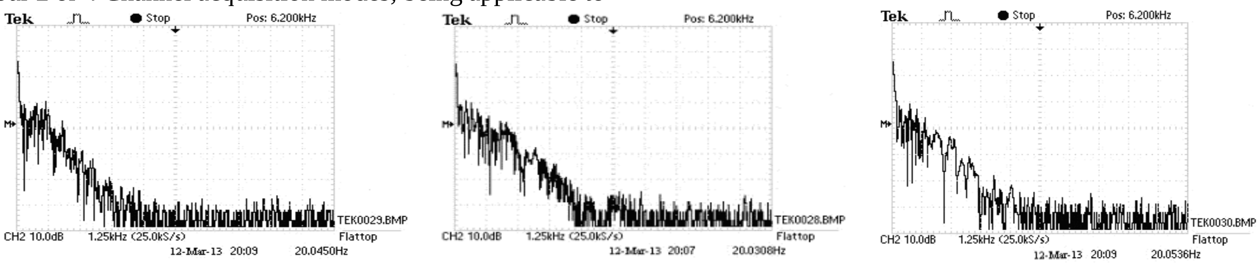


FIGURE 6 The frequency spectrum without continuous perturbation

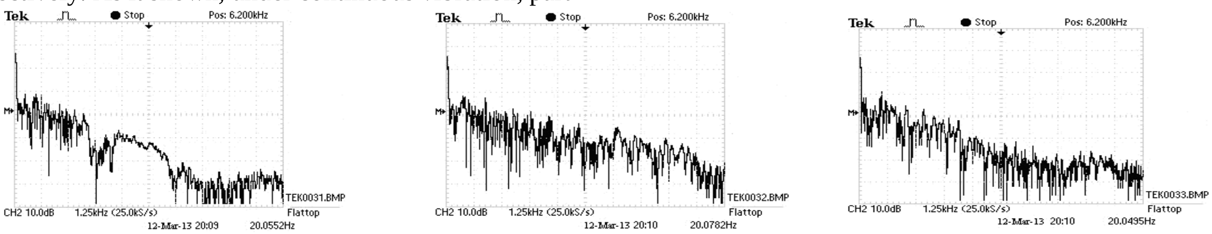
By randomly applying discontinuous equal-amplitude disturbances on three places of the cable respectively, it is observable that the spectrums displayed by the oscilloscope exhibits significant variations in similar amplitude, as shown in Figure 7.



a) b) c)

FIGURE 7 The diagram of three discontinuous disturbance frequency spectrum

Figure 8 shows the frequency spectrum displayed by the oscilloscope after artificially applying continuous disturbances on other three places of the cable respectively. As it shown, under continuous vibration, part of the frequency spectrums shows variations in amplitude. The amplitude variations of the waves on the three positions are similar.



a) b) c)

FIGURE 8 The frequency spectrum of three places at continuous perturbation

By comparing the frequency spectrums in Figures 7 and 8, it is easy to judge whether or not there are external disturbances.

5 Conclusions

This study proposed an M-Z interferometer -based disturbance detection interferometric fibre optic sensor system and analysed the sensing principle of the system. In this system, two single-mode optical fibres passing through the central tube of cable were used as the signal arm and reference arm of the M-Z interferometer. Subsequently, basing on corresponding working circuit, this study developed specific test device. Finally, the system was applied with disturbance test. The test result suggested that this system was very sensitive. Once there were minor disturbance on the cable, could the wave generate vibrations. Thus, it is easy to judge whether or not there are external disturbances using this system.

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