Identification Technique for the Intrusion of Airport Enclosure Based on Double Mach-Zehnder Interferometer

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***Abstract*—In view of the high rate of false alarm problems on the distributed optical fiber sensing technique applied in enclosure, a sensor is proposed based on double Mach-Zehnder interferometer and a method is needed urgently to identify intrusion accurately. This involves eliminating non-intrusion events caused by operating environments from intrusion events. To address the issue, this paper states the tensile strain principle of optical fiber and combines autocorrelation with frequency-energy distribution of signals to extract vibration characteristics. Finally, an identification technique is presented based on vibration theory to distinguish events. The results of simulation show that the algorithm can eliminate vibration characteristic of non-intrusion events so as to minimize the nuisance alarm rate and make prepare for the following recognition of intrusion.**

***Index Terms*—Mach-Zehnder interferometer, Inherent frequency, Stress and strain, Fundamental frequency, Autocorrelation**

I. Introduction

Over the past few decades, subordinate cities have expanded airport scale with the rapid development of civil aviation airports. Airport is a so large area that the intrusion of pedestrians and small animals will be a serious threat to the air transport. The traditional barbed wire and human management are inefficient in outdoor intrusion detection. Although there has been some electrical sensors in the market at present，its ability in anti-interference is poor [1]. Therefore, an efficient and precise alarming fence for great area is badly in need to keep airports in safe. Distributed fiber-optic sensor has been used extensively in outdoor intrusion detection systems as its ability of good reliability and anti-jamming.

The sensor based on double Mach-Zehnder interferometer system has great applied prospect because of its novelty, high sensitivity and low cost. An optical fiber sensor of FFT Secure Fence™ which can eliminate rain-induced nuisance alarm has been put into market, produced by Future Fiber Technologies Corporation of Australia [2, 3]. Many domestic universities have carried on associated experimental researches, such as research team of Tianjin University, they had put forward a recognition method to protect petroleum pipeline based on the same detection system [4, 5], but did not show how to distinguish the signal samples caused by non-intrusion such as wind from the last extracted signals. Beijing University of Aeronautics and Astronautics had done a research about the windy influence on fence-based perimeter system, they concluded that natural wind will make a background noise under 300HZ, similarly it had not put forward any method to eliminate the influence from operating environment [6, 7].

In sum, although most researches focus on the recognition method, all of them have not shown how to distinguish the non-intrusion from signals. To solve these issues, vibration theory is applied to double Mach-Zehnder interferometer and autocorrelation combined with power spectrum estimate is proposed to distinguish vibration type. The final extracted intrusion signals are recognized and discriminated so as to identify the valid intrusion precisely. The simulation verifies the feasibility of identification technique for extracting the event of interest from the event of non-interest.

II. Theory of Mach-Zehnder System

The double Mach-Zehnder fiber optic interferometer is different from the traditional optical fiber sensor, it extracts jamming signals by detecting the changes of the light interference fringes indirectly. Fig. 1 is a double Mach-Zehnder interferometer system diagram [3], as is shown in Fig. 1, laser L is split by couplers a, b and c. Next, the light propagates in two legs of double Mach-Zehnder interferometer. Outer ring of light which is exported from coupler b interfere with the inner light in coupler c and interference fringes are detected by photo-detector D_2. Similarly, the interference fringes produced

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by the light output from coupler c are detected by photo-detector D_1. If disturbance R effects on the fiber, the phase of interference light will be changed, which makes effect to the terminal interference fringes, we can obtain jamming signals after demodulation.

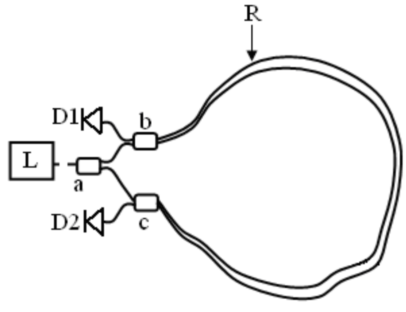


Figure 1. Scheme of fiber fence system based on Mach-Zehnder.

The physical implementation of the sensor as a fence-based perimeter system is achieved by housing the two sensing fibers as well as the insensitive lead-out fiber in a single fiber cable as shown in Fig. 2. The connection of computer and controller can process signals real-timely, so as to achieve the real-time alarm. This can be applied to a range of fence fabrics including chain link, weld mesh and palisade styles [3].

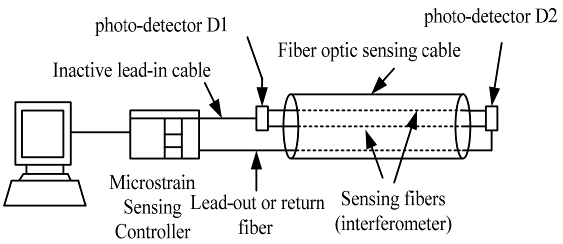


Figure 2. Use of a single fiber cable to implement the Double Mach-Zehnder.

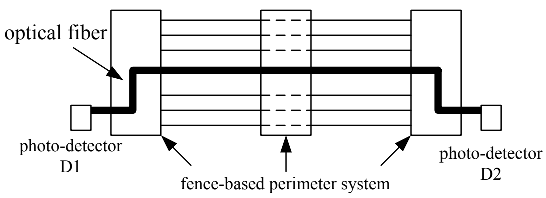


Figure 3. Scheme of fiber fence system based on Mach-Zehnder.

According to the theory, the electric field of two optical rings E_1 and E_2 are [8]

$$E_1 = \sqrt{I_1}\cos(\omega t - \varphi_1) \tag{1}$$

$$E_2 = \sqrt{I_2}\cos(\omega t - \varphi_2) \tag{2}$$

After interfering on optical screen, the intensity of interference fringes received by photodetector is [9]

$$I = (E_1 + E_2)^2 = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\Delta\varphi) \tag{3}$$

In above type, I_1 , I_2 are the intensity of two light beams which occur the interference, $\Delta\varphi$ is the phase difference between them.

Based on strain theory, ignoring the temperature changes of optical fiber, the phase caused by strain can be given by [10]

$$\Delta\varphi = n\frac{2\pi}{\lambda}L\left\{1 - \frac{1}{2}n^2[(1-v)P_{12} - vP_{11}]\right\}\varepsilon_3 \tag{4}$$

$$\text{where } \varepsilon_3 = \frac{\Delta L}{L}. \tag{5}$$

L is the vibration length of optical fiber, ΔL is the measurement of the length difference, n is the refractive index of optical fiber, λ is the optical wavelength, P_{11} and P_{12} are the Pockel's constants, v is Poisson's ratio. Taking these two types into account, we can conclude that phase shift is proportional to the optical fiber strain ε_3. Finally what we want to obtain is $\Delta\varphi$ demodulated from (3) that is the intensity of interference fringes which is used to analyze the disturbance R.

III. Analysis of Signal

A. Analysis based on frequency – energy distribution

As the optical fiber vibration is forced by intrusion, the frequency and amplitude of it are relevant to the force. The frequency-energy distribution of vibration signals are different in nature, thus one of the most reliable methods to judge the events is calculating the frequency and energy of demodulation signals [6]. If the frequency-energy distribution is among the alarm range, the event may be an intrusion to the system, or else, too much width of the distribution will be thought to be caused by non-intrusion.

In order to guarantee the alarm of real-time, the time of sampling signals must be reasonable. We sum up the frequency-energy distribution of demodulation signals included weather and walking intrusion, the relevant data are listed in Tab. 1. Fig. 4 and Fig. 5 are the simulation of wind and walking intrusion.

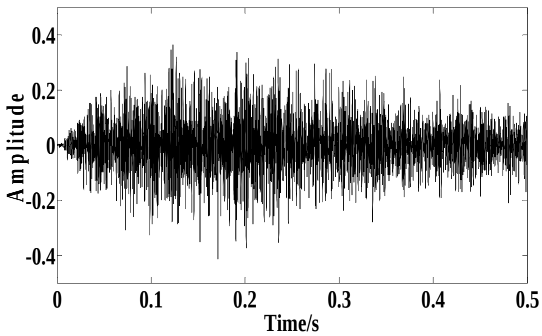


Figure 4. Wind

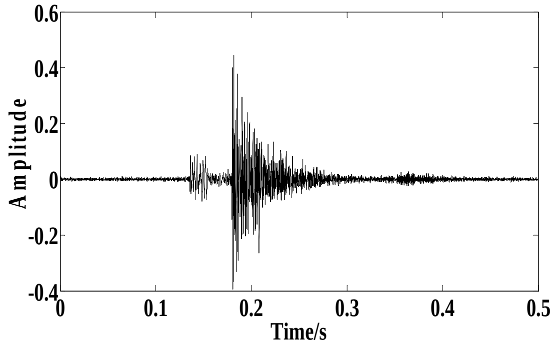


Figure 5. Walking intrusion

TABLE I.
THE FREQUENCY AND ENERGY DISTRIBUTION OF DEMODULATION SIGNAL

Signal type	Band width of frequency	Band width of energy
Environment	0-4KHZ	>100dB
Walking intrusion	0-500HZ	50-100dB

B. Analysis based on vibration theory

Actually, many vibrations on optical fiber are not caused by intrusions. The system is so sensitive that any vibration nearby fiber will affect the demodulation signals. The frequency-energy of non-intrusion is similar to intrusion in a short time. Thus, for the sake of real-time, it is essential for us to eliminate non-intrusion so as to simplify the following recognition.

Fibers in experiment system are generally fixed in subsection, string vibration theory of fiber helps to extract intrusion signals. It is a common phenomenon in nature that vibrating body has a fundamental frequency and several harmonic frequencies. When a string is making free vibration, its displacement regularly changes with times on the track for sine. It also named as simple harmonic vibration, resonant frequency is approximately equal to inherent frequency. According to the answer of free vibration equation solved in method of variable separation, each theoretical harmonic frequency value of string free vibration can be obtained [11].

Thus, non-instrusion can make free vibration of optical fiber, in fact the fiber will pick its resonant frequency and filtrate other frequencies， and it only depends on the inherent nature of optical fiber. Next, this paper will calculate the inherent frequency.

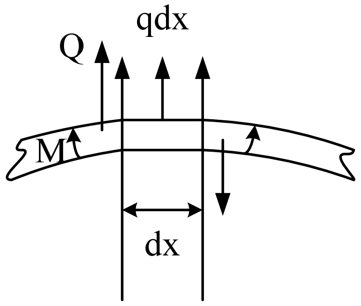


Figure 6. The force on micro part of optical fiber

According to the transverse vibration theory of optical fiber and the force on optical fiber, the equation of motion which shows the micro part moves along the direction y is

$$\rho A dx(\partial^2 y/\partial t^2) = -(\partial Q/\partial x)dx + f(x,t)dx \quad . \quad (6)$$

ρ is the density of optical fiber, A is the cross sectional area, Q is the shearing force, $f(x,t)$ presents the lateral force on the unit length of beam. In terms of free vibration of optical fiber, then $f(x,t) \equiv 0$ .The differential equation of free vibration which optical fiber vibrates in crosswise can be reduced to

$$\rho A \partial^2 y/\partial t^2 = -\partial^2 (EI \partial^2 y/\partial x^2)/\partial x^2 . \quad (7)$$

EI is the bending strength and the inherent frequency of quartz fiber can be given by the method of variable separation of (7) [12]

$$w_r = K_r^2 \sqrt{EI} \Big/ \left(\sqrt{\rho\pi} R l^2\right) . \quad (8)$$

ρ is the density of optical fiber, EI is flexural strength, both of them are constants, R is radius of optical fiber, l is vibration length of optical fiber. K_r is the equation solution of $chK_r \times \cos K_r = -1$.

Predictably, optical fiber have multiple inherent frequencies, thus it can be seen that the inherent frequency of optical fiber is inversely proportional to square of length and diameter. Make quartz fiber for example, the relationship of vibration length and natural frequency can be constructed below

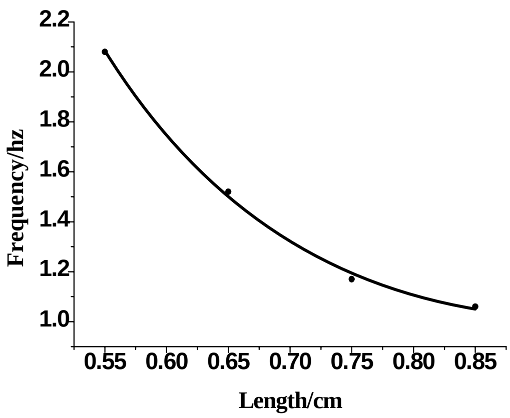
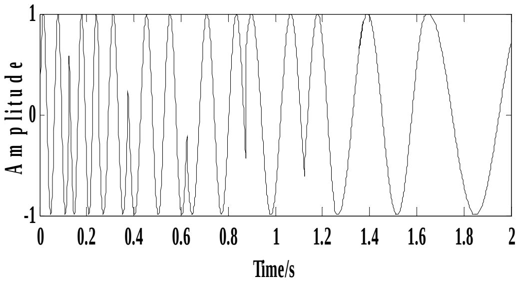


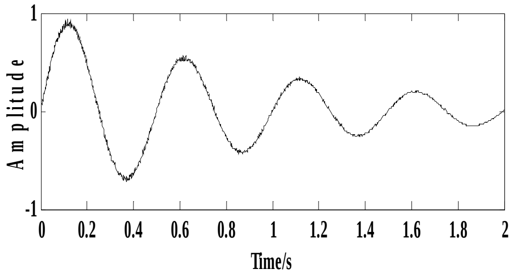
Figure 7. Relation between frequency and length

It can be concluded that the longer librated length of optical fiber, the greater vibration frequency. Combined with the (8), the sharper optical fiber vibrates, the greater phase shifts. It can be informed that the optical fiber translates as rigid body without elongation in the first model. Although the system stays in a resonance, optical fiber can hardly have any response. If it is in the second model, the vibration model of optical fiber layer is swing with a small change of elongation, so there is a mall peak appearing in the curve. In case, it comes into the third model, expansive deformation occurs in the optical fiber causes sharp elongation, a great peak presents on the curve [13].

Inherent frequency of system should be checked in actually used. Fig. 8 is the simulation of interference signals and demodulation signals in case of single-degree-freedom free vibration of optical fiber, the frequency is 2HZ. Fig. 8(a) is the interference signals converted by photoelectric, it presents the light intensity of interference fringes and has been normalized. Fig. 8(b) is the final signals demodulated by hardware or software from Fig. 8(a), these demodulated signals represent disturbance R in some extent [14, 15].



(a) Interferential signal



(b) Demodulation signal

Figure 8. The vibration signal under outside force

The stress and strain of optical fiber is proportional to amplitude according to theoretical analysis on the system. Above simulation shows that the shift of interference fringes reverses as the vibration amplitude reverses. Since there are energy losses in vibration, amplitude of fiber will decrease gradually and the shift of interference fringes are going to slow down.

IV. ALGORITHM

The majority of vibration signals are non-stationary, it should be added window to estimate the power spectrum. The shorter sampling interval we set, the worse evaluation we get. There are two broad approaches to spectral analysis. One of these derives its basic idea directly from definition: The studied signal is applied to a bandpass filter with a narrow bandwidth, which is swept through the frequency band of interest, and the filter output power divided by the filter bandwidth is used as a measure of the spectral content of the input to the filter. The second approach to spectral estimation, called the parametric approach, is to postulate a model for the date, which provides a means of parameterizing the spectrum, and to thereby reduce the spectral estimation problem to that of estimating the parameters in the assumed model. Average periodogram is one of the non-parametric approaches, its basic idea is to smooth or average the periodogram in some way so as to reduce the variances. It can estimate power spectrum effectively, as Blackman-Tukey estimation, its expression is given by [16]

$$\hat{r}_j(k)=\frac{1}{N}\sum_{t=k+1}^{N} y_j(t)y_j^*(t-k) \quad 0\le t\le N-1 \qquad (9)$$

$$\hat{\phi}_j(\omega)=\frac{1}{L}\sum_{j=1}^{L}\sum_{k=-(M-1)}^{M-1}\hat{r}_j(k)e^{-i\omega k} \quad . \qquad (10)$$

$\hat{r}_j(k)$ is the sample covariance sequence of $y_j(t)$ corresponding to the ordinal number j sample. We can get the frequency-energy distribution of non-stationary signals by (9) and (10).

Although power spectrum estimation can reflect spectrum characteristics of signals, the spectrum of non-intrusions are ordinarily similar to intrusion. If the frequency energy distribution of invasion and non-invasion are in the same range, intrusion signals cannot be extracted only by spectrum analysis. Analysis of Mach-Zehnder interferometer system makes us realize that nearby vibration will spread to fiber and affect the alarming effect. After filter of optical fiber, energy redistribution in frequency, part of frequencies strengthened and fundamental frequency will be much stronger than other harmonic frequency, so it decides the main frequency of string. When optical fiber does forced vibration, frequency depends on the characteristic of forced vibration, frequency components of intrusion are more complex. If we consider the rules of optical fiber vibration as intrusion, non-invasion caused by vibration nearby can be reduced in the system.

In order to guarantee the alarm real-timely, another algorithm should be simple and easily to eliminate the non-intrusion characteristics. From the statement on free vibration theory above, we can be informed that there are more than one free vibration frequencies of optical fiber, which include fundamental frequency and some harmonic frequency components. Fundamental frequency is much powerful than other harmonic frequencies, and the harmonic frequencies have multiple relationship with fundamental frequency.

Autocorrelation is an available algorithm to estimate the fundamental frequency, it shows the dependence of instantaneous signals in a moment on another. The function expression of signals $X(m)$ is given by [17]

$$R(k)=\sum_{-\infty}^{\infty} X(m)X(m+k) . \qquad (11)$$

If the signal is random or cyclical, then the definition is

$$R(k) = \lim_{N \to \infty} \frac{1}{2N+1} \sum_{-\infty}^{\infty} X(m) X(m+k) \quad . \qquad (12)$$

For periodic function, the autocorrelation function also presents the cyclical, and there are a lot of peaks in every integer point of fundamental cycle and equivalent to the energy in a special case. It can be proved that autocorrelation of white Gaussian noise has only infinite value in zero, so autocorrelation can detect weak periodic signals and the cycle can be calculated by the interval of two minimums closest to zero [18].

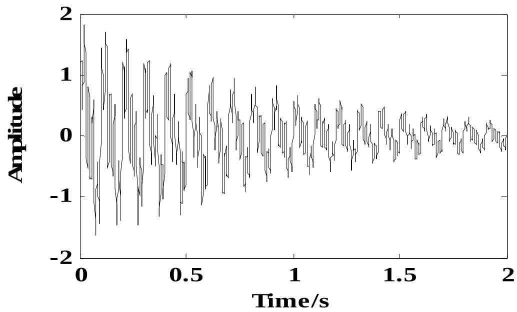
Autocorrelation gives prominence to the amplitude of fundamental frequency and weaken small amplitude as harmonic frequency. When the sampling rate is f_s, sampling length is L, the maximum of autocorrelation function locates in L sampling point, the submaximal value locates in K sampling point, the estimated fundamental frequency is

$$f_0 = \frac{f_s}{|L-K|} \quad . \qquad (13)$$

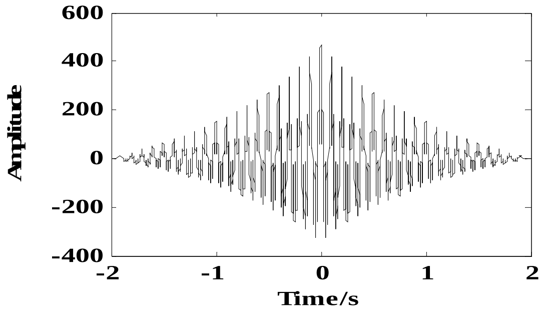
If the autocorrelation and power spectrum estimation of a signal show the frequency and energy distribution which are outside the range of intrusion, or the frequency calculated by autocorrelation is approximate to the inherent frequency of arranged optical fiber, the signal is considered as free vibration caused by non-intrusion.

V. Simulation Experiment

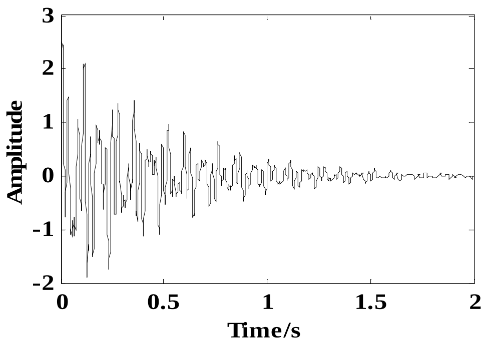
We simulate many signals to verify that the effectiveness of extracting the character of various vibration signals by power spectrum estimation combined autocorrelation. Fundamental frequency is the main frequency components of free vibration of optical fiber and may also contain other harmonic frequencies. Otherwise, the signals of forced vibration depend on external force, so demodulation signals do not have obvious fundamental frequency component as inherence frequency for features. The simulation of non-intrusion and intrusion signals are compounded by sine wave, based on the theory of system. As the frequency-energy distribution of operating environment is unkown, here the simulation experiment which only extracts fundamental frequency from signals has been carried to verify the effectiveness of autocorrelation, then according to the calculated fundamental frequency, we can distinguish the type of vibration which can be used to discriminate intrusion. Fig. 9 shows the autocorrelation of free vibration and forced vibration.



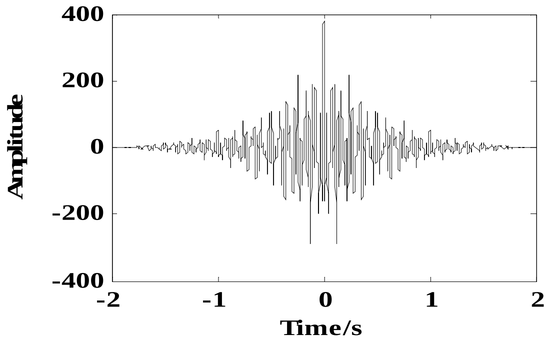
(a) Free vibration of fiber



(b) Autocorrelation of non-intrusion



(c) Forced vibration of fiber



(d) Autocorrelation of intrusion

Figure 9. The signal simulations and autocorrelation of them.

In above figures, the vibration signals (a) and (c) are separately corresponding to the circs of non- invasion and invasion. Free vibration signals of optical fiber caused by the non-intrusion as not crossing the fence include multiple frequency components, but if the forced vibration occurs on optical fiber which is caused by intrusion, its signals will be complex because of various frequency components in it. The results show that autocorrelation efficiently give prominence to the fundamental frequency components of signals. In Fig. 9(b) interval of periodic maximum can be calculated with (13) and contrastively amplitudes in Fig. 9(d) are in confusion. Thus it can theoretically exclude the condition of free vibration caused by non-invasion, so as to reduce nuisance alarm, ensure early alarming real-timely and effectively, and then reduce the complexity of the subsequent recognition.

CONCLUSION

The area of airport may reach to ten thousand square meters, so we can arrange more than one fence based on fiber optic system in order to enhance the validity. The algorithm has distinguished forced vibration and free vibration and simplifies the following recognition, but the texture and arrangement of fiber may be different in practical usage and the criterion of discrimination will be changed. Therefore, it is essential for us to experiment with the vibration of optical fiber. Besides, the condition of multi-points disturbance is more complicated than we commonly suppose. For this reason, algorithm has much room for improvement.

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He undertook the significant national defense project on the signals and images processing of “CO2 active imaging laser radar”, which gained straight A in 2001. In 2004, he hosted the project of National Natural Science Foundation: Research of Algorithm on Laser Radar Image Identification. During the period from 2006 to 2008, he hosted the project of National Natural Science Foundation: Research of wind field retrieval with single Doppler lidar. Now he is the Vice Chairman of graduate faculty of CAUC. His major fields are image processing and pattern recognition, optoelectronic technology and application. His articles “Investigation of Infrared Photonic

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Nowadays, her major field is research on identification methods for the intrusion of fence-based perimeter system based on double Mach-Zehnder interferometer.