Optic Cable Tracking and Positioning Method Based on Distributed Optical Fiber Vibration Sensing

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Abstract: Distributed optical fiber sensing technology developed rapidly in the late 1970s with the development of optical fiber sensing technology and optical fiber communication technology. Distributed optical fiber sensing technology is very suitable for the monitoring of long-distance trunk as it can obtain continuous distributed information along the space and time in the physical field. At present, this technology has become one of the most promising technologies in optical fiber sensing technology. The fiber distributed vibration sensor system put forward in this paper is a new kind of distributed optical fiber sensing system, which can realize real-time extraction of arbitrary vibration signal. It is exerted to the sensing optical fiber and can accurately determine the position of the sensing optical fiber on the vibration signal; it can also be used in the monitoring of long-distance communication lines. This paper analyzes the fiber optic cable tracking and positioning analysis based on distributed fiber vibration sensing.

1. Introduction

Maintaining the security of infrastructure is a basic requirement for social stability and rapid economic development. At present, China's monitoring of infrastructure such as oil and gas pipelines, power grid and communication network mainly relies on some production parameters of the facility itself, manual inspection and reports of passers-by, and other methods. These means commonly have such shortages as low technology content, low efficiency, poor real-time performance, long reaction time, low anti-interference ability, and so on; usually alarms are given after the monitoring facilities have damages, and its practicality is restricted by both natural and human factors. As for the monitoring of long-distance communication lines, especially with the influence of electromagnetic interference, it is impossible to take electrical means to conduct sensing monitoring; optical fiber sensing technology will become the main technical means to implement the safety monitoring of such industries as electric power, communication, and oil and gas pipeline, and to prevent man-made sabotage. However, most optical fiber sensor systems are based on point sensors; thus, for large area or long distance, it needs to be equipped with a large number of sensors, resulting in higher cost and more complexity, with limited application. Distributed optical fiber sensing technology has a better application prospect with its relatively small number of sensors and relatively simple system. Due to the timing requirement of low power short light pulse reverse transmission time, most technologies can only conduct a few static monitoring or some monitoring with small parameter changes, and the application scope of the system is narrow. However, as for the trunk safety monitoring system, the real-time, semi-static or dynamic monitoring information and its location should be obtained. Therefore, a new interferometric distributed optical fiber sensing system is put forward; through the digital signal processing, the system can make accurate positioning of any size of vibration signals on the sensing optical fiber in a real-time and dynamical way. This paper makes the analysis of fiber optic cable tracking and positioning analysis based on distributed fiber vibration sensing.

2. Modeling of distributed optical fiber vibration sensor system

2.1 System modeling method

(1) Theoretical modeling. Theoretical modeling means that people analyzes the internal mechanism according to the characteristics of objective things, based on the basic theory of mechanics, electromagnetism, thermodynamics and chemistry, to clarify the causality; under appropriate simplified assumptions, the analysis and abstraction are made on the measured system; the mathematical model of describing things is obtained through using appropriate mathematical tools, such as differential equation, Laplace transform, transfer function, frequency response function and time domain response curve, etc..

(2) Experimental modeling. When the internal mechanism and characteristics of the things cannot be accurately obtained, we can understand the input and output data of system by using the method of experimental test; measurement data is processed by using the methods of mathematical statistics and a mathematical model of the system is built. The process above is the basic connotation of the experimental modeling method, and it is regarded as “black box” by the measured system; the modeling is only according to its external characteristics.

(3) Finite element modeling. The basic idea of finite element analysis is to use a set of discrete sets of units to replace the continuous body, and this kind of sets of units are called as the mechanical model of the structure. If the forces and displacements of each unit are known, the characteristics of the integrated structure can be derived and the properties of the integrated structure can be studied according to the condition of the deformation continuity of the nodes and the equilibrium conditions of the nodes. The characteristics of finite element is that it always takes the form of matrix as a mathematical expression, easy in programming, and a lot of work is done by computer; as long as the computer capacity is enough, the unit subdivision can be arbitrary, and adaptive to any complicated geometry, various load and any boundary conditions.

2.2 Forced vibration of optical fiber

After the surface impact force is exerted to the soil layer, the vibration wave generated in the vicinity of the surface is mainly transmitted in the form of R wave, which acts on the fiber optic cable and causes the vibration of the optical cable. As is needed, the test optical cable is usually buried in the surface, surrounded by the dense soil layer, and the forced vibration is mainly used in the vertical plane. Therefore, the buried optical cable can be regarded as a single degree-of-freedom linear system, i.e. the number of independent coordinates required by the system in the geometry of the space can be completely determined during the whole vibration process. For the linear damping system, the differential equation of system vibration under the excitation of simple harmonic sine is:

$$m\ddot{x} + c\dot{x} + kx = F_0 \sin \varpi t \tag{1}$$

Formula 1 can be expressed as.

$$p^2 = \frac{k}{m}, X_0 = \frac{F_0}{K}, \xi = \frac{c}{2pm} = \frac{c}{2\sqrt{mk}} = \frac{c}{C_c} \tag{2}$$

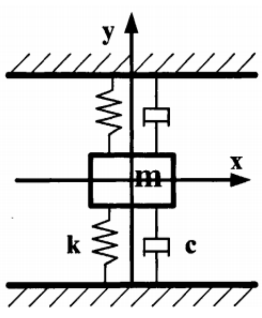

Figure 1 Sketch map of optical cable under the forced damped vibration

The vibration model of the ideal single degree-of-freedom linear system of optical cable is shown in Figure 1.

The model is actually a linear damping system, and the simple harmonic excitation is directly applied to the mass module m in the form of cosine trigonometric functions. The spring stiffness (elastic coefficient) is k, which embodies the elastic property of the system. The equivalent damping coefficient of the system is C.

The amplitude of steady-state solution of forced vibration of the system can be written as:

$$A_1 = \frac{k_Z A_1 N w(z)}{m\sqrt{(k_L - m\varpi^2)^2 + 4\xi_z^2 . m\varpi^2 k_L}}$$

2.3 The forced vibration of optical cable

Optical fiber deformation

Assuming that the two measuring fibers in the optical cable are placed up and down, where the axes are (1) and (3) respectively; two optical fiber closely contact, and the parallel distance between the contact area (2) and the two optical axes are the optical fiber radius a, as shown in Figure 2.

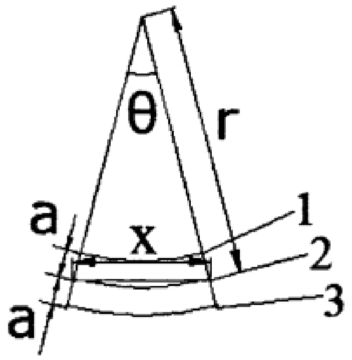

Figure 2 Sketch map of fiber deformation diagram.

The length of the optical cable is x microelement; bending angle is θ and radius is r in the forced longitudinal vibration, and we have:

$$\theta = \frac{x}{r} \qquad \frac{1}{r} = \frac{\partial^2 z(x,t)}{\partial x^2}$$

Assuming the impact range of the force on the optical fiber is %, the total optical fiber deformation caused by longitudinal vibration is:

$$\Delta L(t) = \int_{-xm}^{xm} \Delta l dx = 2\int_0^{xm} \frac{2\alpha x}{r} dx = 4\alpha \int_0^{xm} \left[-\frac{\partial^2 z(x,t)}{\partial x^2} \right] x dx$$

3. Optical cable tracking and positioning based on distributed optical fiber vibration sensing

A. signal analysis

The seal cup of the fiber optical cable is closely connected with the inner wall of the pipe, which causes friction with the pipe wall during operation. At the same time, the seal cup vibrates when it goes across the welding line. The time domain wave form of generated vibration signal when the optical cable goes across the fiber position l has obvious time-variant characteristic (Figure 3); when the optical cable goes across, the amplitude change is obvious and the interval presents some regularity; the time interval of the vibrations is between 2.1 ~ 2.6 s, according to the running speed of the optical cable in the natural gas pipeline, we can conclude that the vibration of the cable is mainly generated by its impact with the pipe welding line.

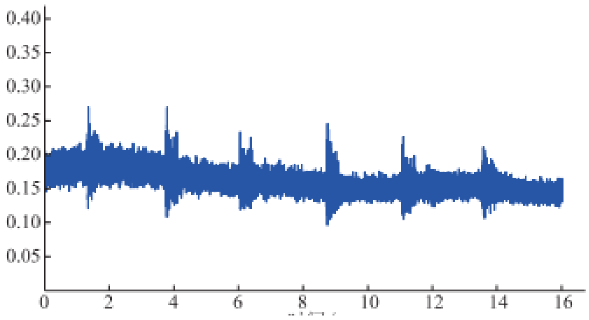

Figure 3 Time domain wave form curve of optical cable vibration signal

According to the time domain characteristics of the vibration signal of the optical cable, through detecting the upper and lower envelope curve of the time domain waveform, the vibration signal is enhanced by means of getting the difference between the upper and lower envelope curves. The fast rising and slow declining curve f (l, t) and the fast declining and slow rising curve g (l, t) at the t moment in the optical fiber position l are as follows:

$$f(l,t) = \begin{cases} f(l,t), iff(l,t) \geq f(l,t-1) \\ \lambda f(l,t-1) + (1-\lambda) f(l,t), else \end{cases}$$

$$g(l,t) = \begin{cases} g(l,t), ifg(l,t) \geq g(l,t-1) \\ \lambda g(l,t-1) + (1-\lambda) g(l,t), else \end{cases}$$

When there is optical cable vibration signal, the difference between the upper and lower envelope curves becomes larger. When there is no vibration signal, the difference between the upper and lower envelope curves is smaller (Figure 4).

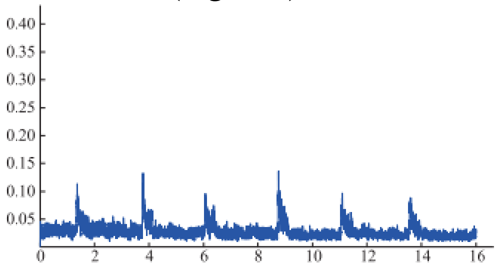

Figure 4 Difference curve between the upper and lower envelope curves of the time domain signal during optical cable vibration.

It can be seen from Figure 4 that the sharp peak signal is visible, and the ratio between the peak amplitude of the difference curve and the background noise amplitude is SNR, i.e., SNR=10log ($|V_{signal}/V_{noise}|$). Take the maximum noise of the range near that point as background noise, it can be concluded that the signal-to-noise ratios of the 6 vibration signals in the time domain wave form curve of vibration signal are: 1.42 dB, 2.54 dB, 1.12 dB, 2.62dB, 1.72dB, and 1.65dB; the signal-to-noise ratios of 6 the 6 vibration signals in the difference curve are: 3.76 dB, 4.36 dB, 3.17 dB, 5.98dB, 3.76dB, and 4.15dB; this method has obvious enhancing effect in the signal-to-noise ratio.

4. Conclusions

This paper proposes the optical cable tracking and positioning method through using a pipe line to run along with the optical cable; based on the principle of Rayleigh scattering, this paper uses one-core fiber in the optical cable which runes along with a pipe line to build distributed optical fiber vibration sensor; when the optical cable runs in the pipe, it causes impact with the pipe welding line and vibration is produced; the vibration effects on the distributed optical fiber vibration sensor, causing sudden changes of light signals; through detecting the changed signals, the real-time tracking and positioning of optical cable can be realized.

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