Time Shifting Deviation Method Enhanced Laser Interferometer for Traffic Monitoring

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***Summary*— Extensive telecommunication cables can be used to construct full coverage sensing network, which is crucial to obtain the information of environmental change and human activities. However, the sensing range, frequency bandwidth and amplitude dynamic range of distributed acoustic sensing restrict each other. The forward interferometer is difficult to locate the vibration source. We show that the vibration event can be monitored and located accurately when combined with the proposed novel time shifting deviation (TSDEV) method. In the lab, vibration localization accuracy of ~2.5 m is realized on the sensing length of 100 km. Furthermore, the traffic vibration events which happen around the urban fiber link are precisely localized and analyzed. The traffic flow of both heavy and light vehicles is obtained respectively. The correlation of light vehicle flow between us and a mobile navigation company reaches 0.96. Applying the proposed technique to the existing telecommunication cables will help to implement a global sensing network for real-time detection of traffic, earthquake and other vibration events.[1]**

Keywords—time shifting deviation; vibration localization; traffic detection; traffic flow; interferometer.

I. INTRODUCTION

Although abundant sensors have been installed, information monitoring method is still lacking in the suburb, mountain and sea, etc. Moreover, even if in the large urban, full coverage sensor network has not been achieved and there are a large number of monitoring blind areas, which limits our ability to observe environmental change and human activities. It is proved that optical fiber can serve as the sensing medium to detect vibration events. Considering the widely distributed telecommunication cables, it has potential to realize large-scale sensing network.

Optical fiber sensing technology, such as distributed acoustic sensing (DAS) [1-4], has been demonstrated in detecting earthquake, traffic, geological structure and leakage of pipeline. However, the sensing range, frequency bandwidth and amplitude dynamic range of DAS restrict each other.

The other scheme, forward-transmission laser interferometer based on the buried cables, can solve these problems [5-7]. It can realize the large dynamic range of more than 100 $\mu\varepsilon$, which is enough to detect urban traffic vibration [5]. On the submarine link with length of 535 km, submarine seismic can be detected [6]. And the wide-band response of more than 10 kHz is demonstrated with the sensing range over 615 km [7]. However, these work utilize the commonly used cross-correlation method to locate vibration events, which is difficult to achieve high-precision location.

In this paper, we propose a novel time shifting deviation (TSDEV) method to locate vibration events which occur along the optical fiber link. A laser interferometer with the sensing length of 100 km is set up in the lab test. The localization accuracy of ~2.5 m is achieved, which is mainly limited by the sampling rate of 40 MS/s. On the urban link, the traffic vibration events are precisely localized and analyzed, whose changing rule is consistent with Beijing traffic regulation. The traffic flow of both heavy and light vehicles is obtained respectively. The correlation of light vehicle flow between our method and a mobile navigation company reaches 0.96. These show great potential of our technology to build the optical fiber sensor network.

II. METHODS/RESULTS

A. Experimental setup of laser interferometer

The experimental setup of laser interferometer is shown in Fig.1. It uses two counter propagating beams to obtain the information along the sensing ring. The laser source we use is form a module NKT Koheras BASIK X15, whose linewidth is <100 Hz with wavelength of 1550.12 nm. It allows us to achieve a long sensing distance. After the module, the laser is divided in signal beam and reference beam. Signal beam gets a frequency shifter 79.9 MHz by an acoustic optical modulator (AOM) to realize heterodyne interference. Then, it is divided into two opposite directions. One travels clockwise (CW beam) and the other travels counter-clockwise (CCW beam). After

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transmitting along the sensing ring, the signal beam of opposite directions will interfere with reference beam at the photodetectors (PD), respectively. Then the data acquisition (DAQ) system is used to obtain the phase information.

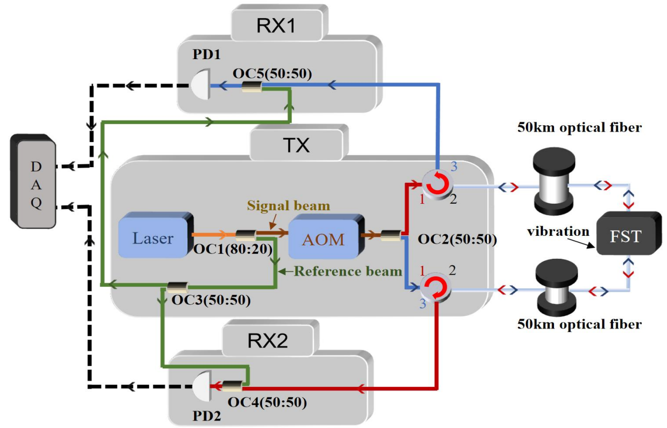

Fig. 1. The experimental setup of the laser interferometer based on the forward transmission scheme.

If vibration occurs along the sensing link at t_0, the optical path length between the vibration point and PD1 is $\Delta 1$, the CCW beam with vibration induced phase change will reach PD1 at $t_1 = t_0 + \Delta 1 / c$, where c is the speed of light. The CW beam with vibration induced phase change will reach PD2 at $t_2 = t_0 + (\Delta - \Delta 1)/c$, where Δ is the overall optical path of the sensing ring. Using the time delay estimation method, we can obtain $\tau_0 = t_2 - t_1 = (\Delta - 2\Delta 1)/c$. Then, we can localize the vibration event by $\Delta 1 = (\Delta - c\tau_0)/2$.

B. *Principle of cross-correlation and TSDEV methods*

According to the principle of positioning vibration events, the accuracy of vibration location depends on the accuracy of time delay estimation. In our case, cross-correlation and TSDEV methods are both used to estimate the time delay between two detected signals $x_1(t)$ and $x_2(t)$.

$$x_1(t) = s(t) + n_1(t), \tag{1}$$

$$x_2(t) = s(t - \tau_0) + n_2(t). \tag{2}$$

Here, $s(t)$ is the vibration event induced phase changing signal. τ_0 is the time delay which need to be estimated. $n_1(t)$ and $n_2(t)$ are the system noise, which are uncorrelated with the vibration signal $s(t)$.

Setting the vibration signal to sinusoidal wave as an example, the cross-correlation function between $s(t)$ and $s(t-\tau_0)$ can be written as:

$$\begin{aligned} R_s(\tau) &= \frac{1}{T_w}\int_{t_0}^{t_0+T_w}\left\{\left[\sin(\omega t)\right]\left[\sin\left[\omega(t-\tau_0+\tau)\right]\right]\right\}dt \\ &= \frac{1}{2}\cos\left[\omega(\tau-\tau_0)\right] - \frac{1}{2\omega T_w}\sin\omega T_w \cdot \cos\left[2\omega t_0 + \omega T_w + \omega(\tau-\tau_0)\right]. \end{aligned} \tag{3}$$

Here, t_0 is the initial time, which represents the initial phase of the intercepted signal segment. T_w is the length of the intercepted window. For arbitrary intercepted length T_w, in addition to the first term $\frac{1}{2}\cos\left[\omega(\tau-\tau_0)\right]$, the second term $\frac{1}{2\omega T_w}\sin\omega T_w \cdot \cos\left[2\omega t_0 + \omega T_w + \omega(\tau-\tau_0)\right]$ will appear. As a result, cross-correlation method will induce errors related to intercepted length in the results of time delay estimation.

For the TSDEV method, the TSDEV value in the same case is given by [5]:

$$\begin{aligned} TSDEV_s^2(\tau) &= \frac{1}{T_w}\int_{t_0}^{t_0+T_w}\{\sin(\omega t) - \sin[\omega(t-\tau_0+\tau)] - C(\tau)\}^2 dt \\ &= A(\tau)\cdot\sin^2\left[\frac{1}{2}\omega(\tau-\tau_0)\right] + B(\tau)\cdot\sin\left[\frac{1}{2}\omega(\tau-\tau_0)\right] + C^2(\tau), \end{aligned} \tag{4}$$

where

$$A(\tau) = \frac{1}{\omega T_w}\left\{2\omega T_w + \sin\left[\omega(2t_0 + 2T_w + \tau - \tau_0)\right] - \sin\left[\omega(2t_0 + \tau - \tau_0)\right]\right\},$$

$$B(\tau) = \frac{4C(\tau)}{\omega T_w}\left\{\sin\left[\omega(t_0 + T_w + \frac{1}{2}\tau - \frac{1}{2}\tau_0)\right] - \sin\left[\omega(t_0 + \frac{1}{2}\tau - \frac{1}{2}\tau_0)\right]\right\},$$

and $C(\tau) = \frac{1}{T_w}\int_{t_0}^{t_0+T_w}\left\{\sin(\omega t_0) - \sin\left[\omega(t_0 - \tau_0 + \tau)\right]\right\}dt$. All these terms will reach 0 at $\tau = \tau_0$. Therefore, the TSDEV method can achieve accurate time delay estimation for arbitrary vibration signal.

C. *In-Lab Test*

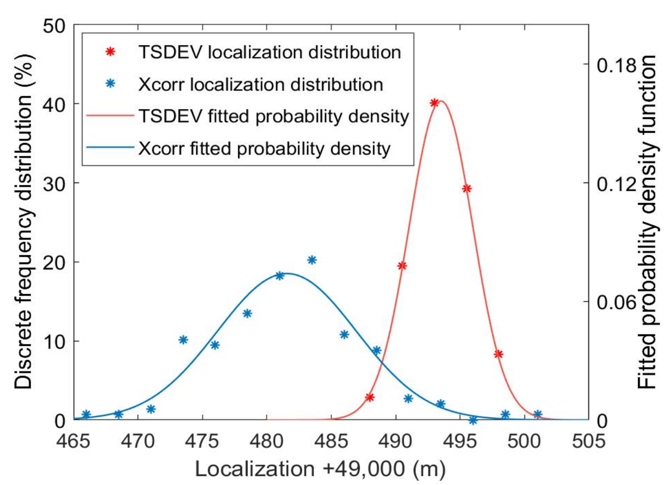

Fig. 2. Localization results using the TSDEV and cross-correlation methods.

First, we carry out an in-lab experiment and compare the localization results of the cross-correlation and TSDEV methods. Two fiber spools around 50 km (one is 49.49 km, the other is 48.22 km) are utilized to form the sensing ring. In the middle of these two spools, a fiber stretcher (FST) is used to generate controllable vibration whose frequency is about 80 Hz. The localization results of different methods are shown in Fig. 2.

For the TSDEV method, the average point is 49,493.3 m away from PD1 and the standard deviation is 2.2 m. In contrast, the result using the cross-correlation method shows that vibration occurs at 49,482.3 m away from PD1, and the standard deviation is 5.7 m. When the intercept length is inappropriate, the localization accuracy of cross-correlation method will deteriorate further. It demonstrates that the TSDEV method can obtain more accurate localization results than cross-correlation for vibrations at different positions on the fiber link.

D. Field Test on the Urban Link

We carry out more experiments on a communication cable with the length of 31.42 km in Beijing. The link passes through Olympic center, green parks, and education zones and has been buried underground deeply. We detect a strong vibration point along this link, which is localized at 15,749.0 m away from Tsinghua University with the standard deviation of 18.5 m. The localization results are shown in Fig. 3. At the location of the vibration source, there is a pedestrian underpass, which enhanced the vibration of vehicles on the ground.

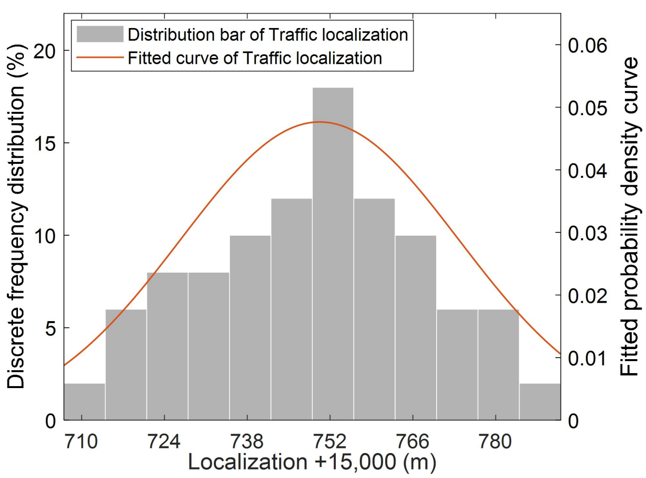

Fig. 3. Localization results of vibration traffic events [5].

We monitor the vibration information of this point for a long time. The phase information shows us an interesting phenomenon of traffic vibration. Before midnight (21:00-23:00), vibrations have low-amplitude and high-frequency (10-20 Hz). After midnight (24:00-3:00), it changes to be high amplitude and low frequency (~4 Hz) vibrations. This phenomenon reflects the vibration information of light and heavy vehicles respectively. It is also consistent with the city's traffic regulations.

We analyzed the signal energy of different frequency bands to obtained the traffic flow of both heavy and light vehicles respectively. We monitor the traffic for 15 days and get the data of corresponding time period from AutoNavi to verify the effect of our method. From Nov. 5th to 20th, the correlation coefficient between two sets of data is 0.83. For the average traffic flow in 15 days, the correlation coefficient reaches 0.96 [9] and show that light vehicles mainly travel during the weekday. During weekends and holidays, light traffic flow is greatly reduced.

We monitor the traffic flow of heavy vehicles for a long time, including the shopping festival and the Winter Olympics. We find the traffic peaks during shopping festivals and concentrated traffic flow during the Winter Olympics. It is consistent with the actual situation.

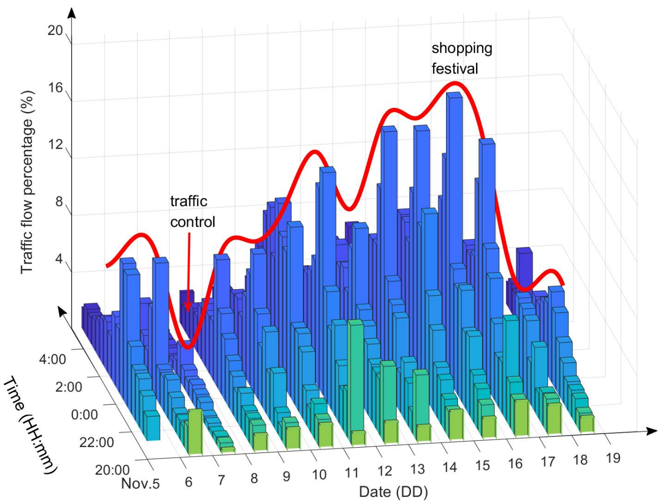

Fig. 4. Traffic flow of heavy vehicles during shopping festival [9].

III. Conclusions

In this paper, we propose a novel TSDEV method. Compared with cross-correlation, the proposed TSDEV method can realize more accurate localization results. We experimentally demonstrate a laser interferometer to detect vibrations along the 100 km fiber link. Vibration localization accuracy of ~2.5 m is realized. Furthermore, the traffic vibration events which happen around the urban fiber link are precisely localized and analyzed. The standard deviation of localization results is 18.5 m. Besides, the traffic flow of both heavy and light vehicles is obtained respectively. The correlation of light vehicle flow between the data of us and a mobile navigation company reaches 0.96.

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