Multi-point distributed optical fiber vibration sensing based on forward transmission

Yaxi Yan*
[1]Department of Electrical Engineering
The Hong Kong Polytechnic University
Hong Kong, China
[2]Hangzhou Institute of Advanced Studies
Zhejiang Normal University
Hangzhou, China
ya.xi.yan@connect.polyu.hk

Yuyao Wang
Department of Electronic and Information Engineering
The Hong Kong Polytechnic University
Hong Kong SAR, China
yuyao.wang@connect.polyu.hk

Liwang Lu
Department of Electronic and Information Engineering
The Hong Kong Polytechnic University
Hong Kong SAR, China
22117728r@connect.polyu.hk

Daru Chen
Hangzhou Institute of Advanced Studies
Zhejiang Normal University
Hangzhou, China
daru@zjnu.cn

Alan Pak Tau Lau
Department of Electrical Engineering,
The Hong Kong Polytechnic University
Hong Kong SAR, China
alan.pt.lau@polyu.edu.hk

Chao Lu
School of Electronics and Information Technology
Sun Yat-sen University
Guangzhou, China
lvchao@mail.sysu.edu.cn

***Abstract*—We demonstrate multi-point vibrations detection and localization by using a forward transmission based-distributed fiber sensor with cascaded structures of frequency-shifted optical delay lines. A positioning accuracy of 120 m over 197.9 km distance is achieved.**

Keywords—forward transmission, long haul vibration sensing, multi-point detection

I. Introduction

Distributed optical fiber vibration sensing (DOFVS) has attracted great attention due to its wide applications, including pipeline monitoring, seismic activity detection, optical network monitoring and so on. Typical backscattering-based DOFVS often measures the external disturbances by detecting the Rayleigh [1] or Brillouin [2] backscattering light in fiber but the sensing range is limited due to the weak signal power. Traditional fiber interferometers can be used for distributed vibration sensing as well [3], but Rayleigh backscattering noise degrades the sensing performance especially in ultra-long-distance scenarios since two light beams are bidirectionally transmitted in one fiber [4]. Recently, a unidirectional forward transmission based DOFVS using frequency shifted optical delay line (FSODL) was proposed to achieve ultralong haul vibration sensing. However, multi-point detection cannot be achieved except for some special circumstances e.g. uncorrelated vibrations occur far away and the power difference between different vibration signals is not very big [5,6]. Although the null frequency analysis algorithm [6] was proposed to solve the multi-point detection problem, it fails to work if the spectrum of the disturbance is not wide enough to cover the null points.

In this paper, we propose to apply multiple cascaded structures of FSODL to forward transmission based-DOFVS to achieve detection and localization of multi-point vibrations through calculating the delays between demodulated phase profiles at different frequencies and cross correlating them. We successfully demonstrate the simultaneous measurements of multiple vibrations on an optical fiber with total length of 395.8 km (corresponding to a sensing distance of 197.9 km) with positioning accuracy of 120 m.

II. Principle of Multi-point Vibration Sensing

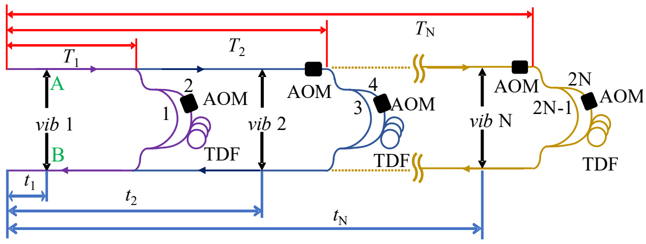

Fig. 1: Principle of multi-point vibration measurement. AOM: acoustic-optic modulator, TDF: time delay fiber.

The operating principle of multi-point vibration sensing using the proposed forward transmission sensing system is shown in Fig. 1. An FSODL is used to connect two equal length optical fibers that are placed close to each other at the far end. Such a loopback configuration is referred to as a basic unit. Several basic units are cascaded to form a long-haul sensing chain and the number of vibrations that can be measured simultaneously is determined by the number of basic units. At each unit except the first one, an AOM will be used before the FSODL structure to shift the frequency of the sensing light. In that case, after coherent detection, we will have a series of frequency lines corresponding to different optical paths and the phase of each frequency line can be demodulated. The sensing of external vibrations is based on the measurement of phase variations of the propagating signal. Obviously, vibration at a given location will affect the phase of light beams twice (e.g. points A and B in Fig.1). Assuming N vibrations simultaneously occur at N different points as shown in Fig.1 and ignoring the systematic phase noise by assuming the use of ultra-narrow laser and ideal FSODL [5], the phases of optical paths 1, 3, …, 2N-1 can be written as

$$\varphi_{2k-1}(t)=\sum_{m=1}^{k}\phi_m(t)+\sum_{m=1}^{k}\phi_m\left(t-2\left(T_k-t_m\right)\right), k=1,2,\ldots,N \tag{1}$$

and the phases of optical paths 2, 4, …, 2N can be written as

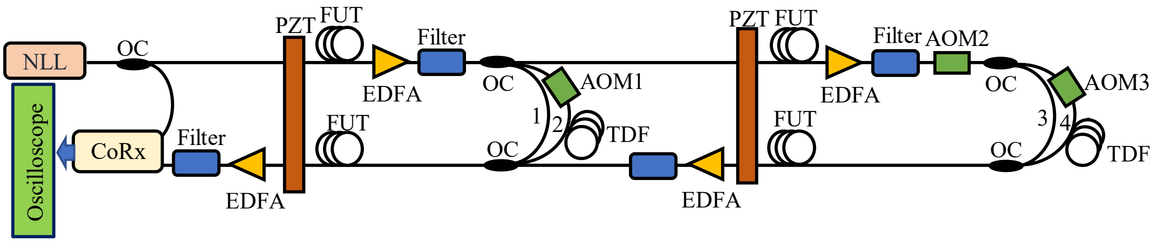

Fig.2 Experimental setup for two vibrations measurements. NLL: narrow linewidth laser; OC: optical coupler; PZT: piezoelectric ceramics; FUT: fiber under test; EDFA: erbium-doped fiber amplifier; AOM: acoustic-optic modulator; TDF: time delay fiber; CoRx: Coherent Receiver.

$$\varphi_{2k}(t)=\sum_{m=1}^{k}\phi_m(t)+\sum_{m=1}^{k}\phi_m\left(t-2\left(T_k-t_m\right)-\Delta\tau_k\right),k=1,2,...,N \tag{2}$$

where $\phi_k(t),k=1,...,N$ is the phase variation induced by k^{th} vibration, $2T_k$ is the propagation time for light passing through path $2k$-1, t_k is the propagation time from transmitter to the k^{th} vibration point and $\Delta\tau$ is the time delay between path $2k$-1 and path $2k$ which is the same for each cascaded structure. Then from Eq. (1) and (2), we can construct the phase differences of first type as

$$\begin{aligned}\Delta\varphi_{k,1}(t)&=\varphi_{2k-1}(t)-\varphi_{2k}(t)\\&=\sum_{m=1}^{k}\left(\phi_m\left(t-2\left(T_k-t_m\right)\right)-\phi_m\left(t-2\left(T_k-t_m\right)-\Delta\tau\right)\right)\\&=\Delta\varphi_{k-1,1}\left(t+2\left(T_k-T_{k-1}\right)\right)\\&\quad+\phi_k\left(t-2\left(T_k-t_k\right)\right)-\phi_k\left(t-2\left(T_k-t_k\right)-\Delta\tau\right)\end{aligned} \tag{3}$$

$$\begin{aligned}\Delta\varphi_{k,2}(t)&=\varphi_{2k}(t+\Delta\tau)-\varphi_{2k-1}(t)\\&=\sum_{m=1}^{k}\left(\phi_m(t+\Delta\tau)-\phi_m(t)\right)\\&=\Delta\varphi_{k-1,2}(t)+\phi_k(t+\Delta\tau)-\phi_k(t)\end{aligned} \tag{4}$$

Here we define $\Delta\varphi_{0,1}(t)=\Delta\varphi_{0,2}(t)=0$. To localize the k^{th} vibration, we use the phase differences in Eq.(3) and (4) to construct the second-type phase differential signals as follows:

Here we define $\varphi_{-1}(t)=\varphi_0(t)=0$. Now, note that

$$\begin{aligned}\Delta\phi_{k,1}(t)&=\phi_k\left(t-2\left(T_k-t_k\right)\right)-\phi_k\left(t-2\left(T_k-t_k\right)-\Delta\tau\right)\\&=\Delta\varphi_{k,1}(t)-\Delta\varphi_{k-1,1}\left(t+2\left(T_k-T_{k-1}\right)\right)\\&=\varphi_{2k-1}(t)-\varphi_{2k}(t)\\&\quad-\left(\varphi_{2k-3}\left(t+2\left(T_k-T_{k-1}\right)\right)-\varphi_{2k-2}\left(t+2\left(T_k-T_{k-1}\right)\right)\right)\end{aligned} \tag{5}$$

$$\begin{aligned}\Delta\phi_{k,2}(t)&=\phi_k(t+\Delta\tau)-\phi_k(t)=\Delta\varphi_{k,2}(t)-\Delta\varphi_{k-1,2}(t)\\&=\varphi_{2k}(t+\Delta\tau)-\varphi_{2k-1}(t)-\left(\varphi_{2k-2}(t+\Delta\tau)-\varphi_{2k-3}(t)\right)\end{aligned} \tag{6}$$

$$\Delta\phi_{k,1}(t)=\Delta\phi_{k,2}\left(t-\left(2\left(T_k-t_k\right)+\Delta\tau\right)\right) \tag{7}$$

Since T_k and $\Delta\tau$ are already known, the parameter t_k and hence the location of the k^{th} vibration can be calculated through estimating the time delay by cross-correlating $\Delta\phi_{k,1}(t)$ and $\Delta\phi_{k,2}(t)$.

III. *EXPERIMENTAL SETUP AND RESULTS*

A forward transmitting sensing system with two cascaded basic units is experimentally implemented. A narrow linewidth (100 Hz) laser is used as the light source and the delay fibers are set to be 5 km. The lengths of fibers under test in unit 1 and 2 are 197.797 km and 198.033 km, corresponding to a sensing distance of 98.8985 km and 99.0165 km, respectively. To separate the signals of path 1-4, AOM1 (80 MHz), AOM2 (100 MHz) and AOM3 (80 MHz) are used. Two piezoelectric ceramics (PZTs) are placed at the front of two units to simulate vibrations. The split ratios of optical couplers and the gains of EDFAs are specifically chosen to ensure equal power at each frequency. To guarantee a good SNR, the power of LO is set to be 15 dB higher than each frequency signal. Finally, signals are coherently received and acquired by an oscilloscope with a sampling rate of 625 MSa/s.

To test the performance of the proposed scheme, we first simultaneously apply two low-frequency vibration signals of around 600 Hz to the PZTs followed by two high frequency vibration signals of around 22.36 kHz. The spectra of the vibration signals are shown in Fig.3 (a) and Fig.4 (a). The upper graphs of Fig.3 (b) and (c) show the demodulated $\Delta\varphi_{2,1}$ and $\Delta\varphi_{2,2}$. The correlation of $\Delta\varphi_{2,1}$ and $\Delta\varphi_{2,2}$ is used in [5] for locating the vibration. However, we can see from the upper graphs of Fig.4(c) that the correlation peaks are not distinguishable for multiple positioning of high frequency vibrations and even worse, only one correlation peak appears in the upper graphs of Fig.3(c) for low-frequency vibrations.

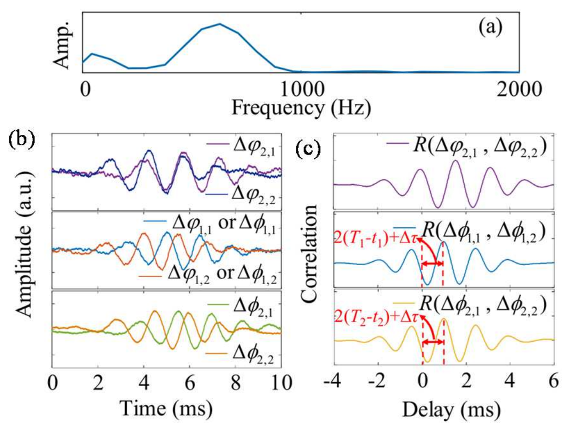

Fig.3 (a) Spectrum of the applied low frequency; (b) and (c) demodulated differential phase signals and their corresponding correlation signals for low-frequency vibrations.

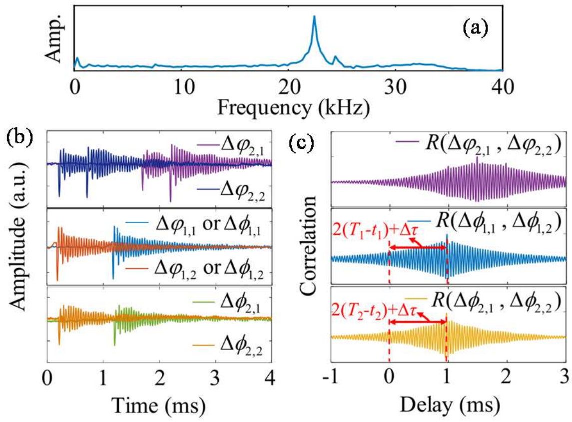

Fig.4 (a) Spectrum of the applied high frequency vibrations; (b) and (c) demodulated differential phase signals and their corresponding correlation signals for high-frequency vibrations

These results show the inability of the previously proposed scheme [5] for multi-point vibration detection. However, through cascading the proposed sensing units and calculating the second-type phase differences $\Delta\phi_{2,1}$ and $\Delta\phi_{2,2}$, the influence of the first vibration can be eliminated, which can be seen in lower graphs of Fig.3 (b) and Fig.4 (b). The locations of the first and second vibrations can be obtained through cross-correlating ($\Delta\phi_{1,1}$, $\Delta\phi_{1,2}$) and ($\Delta\phi_{2,1}$, $\Delta\phi_{2,2}$) respectively. To characterize the localization accuracy, 70 independent sets of phase profiles are acquired for each type of vibrations we studied and the standard deviations of the estimated vibration locations are shown in Table 1. The high frequency signals have better localization accuracy than the low frequency signals as laser phase noise and the external environment perturbations to the fiber are both at low frequency, which will decrease the positioning accuracy of the low-frequency signals but not high frequency vibrations. A positioning accuracy of around than 120.2 m is achieved in this experiment. In order to improve the positioning accuracy of low frequency signals, the length of time delay fiber can be extended. The longer time delay fiber can increase the SNR of the differential phase signals, thereby improving the location accuracy.

IV. Conclusions

We proposed and demonstrated a forward transmission based-DOFVS with multiple cascaded structures for multi-point vibrations detection and localization. A positioning accuracy of around 120 m is achieved over a sensing distance of 197.915 km. Since the possibility of simultaneous vibrations along a sensing link increase with the sensing distance, we anticipate that the proposed scheme will be useful in ultralong haul vibration sensing applications.

TABLE I. Localization Accuracies

	Low frequency		**High frequency**	
	Vibration 1	***Vibration 2***	***Vibration 1***	***Vibration 2***
Standard deviation (m)	120.2	120.1	2.4	9.4

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