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Remote audio signals detection using a partial-fiber laser Doppler vibrometer

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ABSTRACT

All-fiber laser Doppler vibrometer (LDV) systems have great potential in the application of remote acoustic detection. However, the system performance is impaired due to the serious intermediate frequency (IF) crosstalk signal, which is caused by the fiber circulator. In this paper, a system adopting a partial-fiber structure is proposed and analyzed. Simulative and experimental analysis indicate that the IF crosstalk signal is mainly caused by the fiber circulator, and it damages demodulation signal. In order to reduce the IF crosstalk signal, a polarization prism is employed to substitute the circulator. Experimental results reveal that the IF crosstalk signal can be eliminated by the partial-fiber LDV effectively. The comprehensible speech signals within the range of 50m can be obtained.

1. Introduction

LDV has the characteristics of long distance, non-contact and high sensitivity. It has been widely used in industry and military field [1,2]. On the one hand, LDV can detect and measure extremely tiny vibration of a target at a long distance; on the other hand, the acoustic pressure can vibrate the objects near the audio sources. Therefore, the voice signals of a human could be acquired by capturing the vibration of a target's surface. Li and Wang [3–7] have presented their researches in detecting and processing voice signals of people from large distances using a LDV from Polytec. However, the sensor heads are usually bulky and heavy because of the inner separated structure of the commercial LDV systems (e.g., the Polytec OFV 505 system has dimensions of 120 mm × 80 mm × 345 mm and weight of 3.4 kg). An all-fiber LDV system has the advantages in smaller size, lightweight design, and more robust structure, therefore it is less prone to structural vibrations and more suitable for remote speech detection [8]. In previous study [9,10], we have established an all-fiber LDV to detect remote voice signals. Although this system can acquire more than 120 m comprehensible voice signals, the serious IF crosstalk signal impairs system performance. In this paper, a partial-fiber LDV is developed by employing a polarization prism to eliminate the IF crosstalk signal. A series of experiments are carried out to verify the capability of partial-fiber LDV system. Experimental results indicate that the IF crosstalk signal can be eliminated by the partial-fiber LDV efficiently. Besides, the comprehensible speech signals within the range of 50 m can be obtained.

2. Experimental setup

The schematic diagram of a traditional LDV is illustrated in Fig. 1. The LDV is composed of optical unit and electrical unit. A 20-mW single mode CW laser with the line-width less than 10 kHz at wavelength of 1550 nm is adopted as a transmitter. The output laser beam is divided into two beams by an optical fiber splitter. One beam is taken as the local-oscillator (LO) beam after passing through the acousto-optic frequency shifter (AOFS), which shifts the frequency of the LO beam by ω_{AO}. Meanwhile, the other beam is focused on the detected target after passing through a fiber circulator and a telescope. The Doppler frequency shift of the received beam is generated due to the vibration of the target, which can be expressed as

$$\varphi(t) = 4\pi \frac{S(t)}{\lambda} \tag{1}$$

where $S(t)$ is the vibration displacement, λ is the wavelength. Being received through the telescope and coupled into the fiber circulator, the reflected beam is mixed with the LO beam in a polarization-maintaining fiber coupler to produce a beat signal, which is converted into a voltage signal by a photoelectric balanced detector. The IF signal is emerged when the voltage signal passes a bandpass filter. The LO signal, echo

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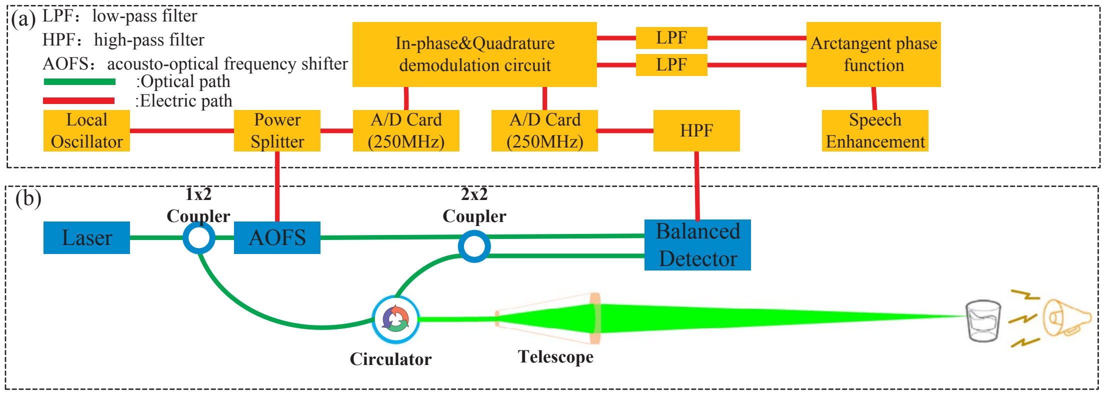

Fig. 1. Schematic diagram of the LDV (a) electrical unit (b) optical unit.

signal and IF signal are expressed as follows:

$$I_{LO} = A_{LO}\cos[(\omega_c+\omega_{AO})t+\varphi_1] I_S = A_S\cos[\omega_c t+\varphi(t)+\varphi_2] u_{IF} = \alpha A_{LO}A_S\cos[\omega_{AO}t+\varphi(t)+\varphi_1-\varphi_2] \tag{2}$$

where A_{LO}, A_S are the amplitude of local-oscillator and signal beam respectively, ω_{AO} is the frequency shift caused by AOFS, φ_1 and φ_2 are random phases, α is the photoelectric conversion efficiency, $\varphi(t)$ is the Doppler shift.

In order to obtain the characteristic of the vibrating target, it's a classical method to demodulate the beat signal using quadrature demodulation and arctangent phase algorithm [11]. This method has been analyzed and tested in recent years, enabling the realization of high-accuracy heterodyne signal processing in commercial LDV.

The demodulation and arctangent phase algorithm block diagram is depicted as Fig. 2.

The IF signal is divided into two equal parts by the power splitter. One is mixed with half of the LO beam, transformed into the baseband signal u_I after passing through a low-pass filter. While the other is mixed with a 90° phase shift of the rest LO beam and changed into the baseband signal u_Q after passing through a same low-pass filter. The expression of the baseband signal is given as follows:

$$u_I \approx \alpha A_{LO}A_S\cos[\varphi(t)+\varphi_1-\varphi_2] u_Q \approx \alpha A_{LO}A_S\sin[\varphi(t)+\varphi_1-\varphi_2] \tag{3}$$

It is simple to get the Doppler frequency shift $\varphi(t)$ using arctangent phase algorithm. Once the Doppler frequency shift $\varphi(t)$ is calculated, the speech signal can be reconstructed. The ambiguity of the arctangent function can be removed by phase unwrapping algorithm. The Doppler frequency shift $\varphi(t)$ can be simplified as:

$$\varphi(t) = \arctan(u_Q/u_I) + m\pi + \Delta\varphi \tag{4}$$

There is a channel crosstalk in the fiber circulator due to structural defects of the fiber circulator in the above typical diagram of LDV. Because of the existence of channel crosstalk, the echo beam and LO beam change their expressions:

$$I_{LO} = A_{LO}\cos[(\omega_c+\omega_{AO})t+\varphi_1] I_S = A_S\cos[\omega_c t+\varphi(t)+\varphi_2] + A_c\cos[\omega_c t+\varphi_3] \tag{5}$$

Therefore, baseband signal u_I and u_Q become the following expressions:

$$u_I \approx \alpha A_{LO}A_S\cos[\varphi(t)+\varphi_1-\varphi_2-\varphi_3] + \alpha A_{LO}A_c\cos[\varphi_1-\varphi_2-\varphi_3] u_Q \approx \alpha A_{LO}A_S\sin[\varphi(t)+\varphi_1-\varphi_2-\varphi_3] + \alpha A_{LO}A_c\sin[\varphi_1-\varphi_2-\varphi_3] \tag{6}$$

Assuming the phase difference $\varphi_1-\varphi_2-\varphi_3$ is equal to 0, the Doppler frequency shift is obtained by adopting arctangent phase algorithm.

$$\varphi(t) = \arctan\left(\frac{u_Q}{u_I}\right) = \arctan\left(\frac{\sin(\varphi(t))}{\cos(\varphi(t)) + \frac{A_c}{A_S}}\right) = \arctan\left(\tan(\varphi(t))\left(1 + (-1)^n\sum_{n=1}^{\infty}\left(\frac{A_c}{A_S}\right)^n\left(\frac{1}{\cos(\varphi(t))}\right)^n\right)\right) \tag{7}$$

The crosstalk of the fiber circulator is negligible when the intensity of crosstalk signal is much less than the one of echo signal, ie $Ac \ll A_S$. However, when the two are comparable in magnitude or the intensity of crosstalk is greater than the one of echo, the crosstalk of the fiber circulator affects the measurement accuracy of Doppler frequency shift directly.

3. Simulation

According to laser radar range equation, the power of echo signal P_S is derived as follows:

$$P_S = \frac{P_T}{4\pi R^2} \times \frac{\sigma}{4\pi R^2} \times \frac{\pi D^2}{4} \times \eta_{atm}\eta_{sys} \tag{8}$$

where P_T is the power of transmitted laser, σ is the radar cross section of target, D is the receiving aperture, R is the distance between laser transmitter and target, η_{atm} is atmospheric transmission coefficient, η_{sys} is transmission coefficient of the optical system. Since the laser is focused on the target through focusing system, all of the radiant energy near the spot can be reflected. Therefore, the target can be taken as an expansion target. The area of the irradiation is expressed as:

$$dA = \frac{\pi R^2\theta_T^2}{4} \tag{9}$$

where θ_T is the diffraction limit angle of the laser beam. For extended Lambert scattering targets, there are:

$$\sigma_{ext} = 4\rho_{ext}R^2\theta_T^2 \tag{10}$$

The power of echo signal P_S can be simplified as:

$$P_S = \frac{\pi P_T\rho_{ext}D^2}{(4R)^2}\eta_{atm}\eta_{sys} \tag{11}$$

where ρ_{ext} is the average reflective coefficient of target.

Assuming the measured target is file folder, the received echo beam power P_S equals 0.318 nW theoretically with the condition of P_T = 18 mW, R = 30 m, D = 1.5 cm, $\eta_{atm} = 0.9$, $\eta_{sys} = 0.8$, $\rho_{ext} \approx 0.5$. In the system, the channel crosstalk level of the fiber circulator is about 60 dB and the power of the crosstalk equals 18 nW. Supposing that movement of target is a simple harmonic vibration ($S(t) = 50 \times 10^{-6} \times \cos(2\pi \times 500\,t)$), simulation is carried out based on the following parameters in Table 1.

Compared Fig. 3 with Fig. 4, it is obvious that the IF crosstalk can directly affect the accuracy of measurement when the intensity of