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Development of a variable and broad speed range all-fiber laser vibration measurement technology

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ABSTRACT

This paper realizes a variable and broad speed range all-fiber heterodyne laser vibration measurement system. The system employs a dual-parallel Mach-Zehnder modulator to generate a carrier-suppressed single-sideband signal and facilitates non-contact vibration measurements based on the optical Doppler shift principle. The maximum speed can be measured is much higher than the general vibrometer. This technology has the advantages of high precision, dynamically adjustable measuring range, full-frequency modulation etc. In this paper, a prototype has been built, and Hilbert Transform is used to extract the vibration signal from the frequency shift signal. Laboratory experiment result shows the ability of mutative and expansive measuring range.

1. Introduction

Vibration analysis is widely used in machinery diagnostics, and the demand for vibration testing is increasing substantially. Performing vibration measurements can test the strength and stiffness of mechanical structure, can estimate the performance of aircraft structure such as aircraft wings and also assess the safety of the building [1]. In these applications, the vibration speed varies greatly and is quite high in some cases. However, the measurement range of the general vibrometer is not sufficient to cope with these situations. For instance, average speed of the racing engine piston is about 30 m/s, while the hurricane wind speed is 50 m/s [2], and the instantaneous impact speed of explosive experiment is greater than or equals to 400 m/s, and the instantaneous speed of mechanical impact test is about 1000 m/s. Since the maximum speed that the current high-speed vibration meter can measure only reaches 40 m/s, it cannot meet all the requirements of these tests. Therefore this paper will present a mutative and expansive speed range laser vibration measurement system which is able to measure hugely distinct and high speed vibration.

Speed and vibration measurement is often based on the optical Doppler Effect, whose principle is that the optical frequency shifts due to the relative motion between light source and target [3]. The state of movement is resolved from the frequency shift of optical lights reflected back from the target. This method has the advantage of non-contact measurement that does not disturb the operation of the object under measurement.

At present, the common structure of laser Doppler vibration measurement technology is heterodyne structure. The key of the heterodyne structure is the optical frequency shifters with the capacity to generate frequency shift. Nowadays, many optical elements can act as optical frequency shifters, such as optical Bragg grating [4] and integrated optical waveguide [5]. However, those devices are generally bulky and require precise optical alignment. Fortunately, all-fiber frequency shifters can avoid those defects. B. Y. Kim has developed the first all-fiber acousto-optic frequency shifter constructed by spreading acoustic wave in a two-mode fiber (TMF) [6]. Currently, most heterodyne laser Doppler vibration measurement systems have used acousto-optic modulators as frequency shifters. However, the shift frequency of acousto-optic shifter limits from dozens of MHz to hundreds of MHz [7], and one acousto-optic modulator produces only one fixed frequency shift. Thus it is difficult to reach accurate and adaptive measurement for all vibration conditions.

Considering the limitation of acousto-optic modulator, this paper proposes a novel heterodyne laser Doppler vibration measurement system by employing a dual-parallel Mach-Zehnder modulator (DPMZM). Two same RF signals with a phase difference of 90°are loaded in the upper and lower arm of the DPMZM respectively to perform carrier-suppressed single-sideband (CS-SSB) modulation. The value of Doppler frequency shift is measured by combining the CS-SSB reference beam with the reflected measurement beam. Dozens of GHz adjustable frequency shift can be produced by adjusting the frequency of RF signals fed to DPMZM, which results in broader and dynamic

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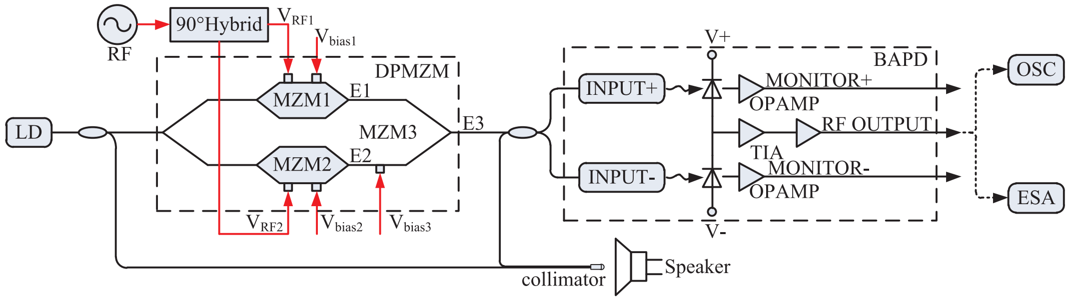

Fig. 1. The structure diagram of laser vibration measurement system. LD: laser source; DPMZM: dual-parallel Mach-Zehnder modulator; BAPD: balance amplified photodetector; Speaker: acting as a vibration target; OSC: oscilloscope; ESA: electrical spectrum analyzer.

bandwidth. Large shift frequency is capable of facilitating accurate measurement when the target vibrates at a high speed, but it needs an expensive data acquisition module designed for capturing high frequency electronic signals. Since a low shift frequency satisfies the measurement of a low speed vibration, the cheaper data acquisition module can be used to reduce the cost of the whole system. Furthermore, the driving power of the RF signals for DPMZM is much lower than acousto-optic modulator, leading to low power consumption and low cost.

2. Principle

2.1. Principle of heterodyne laser vibration measurement

The structure diagram of the proposed system is given in Fig. 1.

A 1550 nm laser beam is divided into reference and probe beam by a splitter. The reference beam is injected into the DPMZM to generate the CS-SSB signal which is shifted in optical frequency domain from the original optical frequency f_c to $f_c + f_{RF}$. The probe beam propagates along the fiber and is led out by a collimator to collect vibration information of the vibrating target. Then the reflected beam is combined with the reference beam by a coupler. Thus, two beams beat each other during the process of photoelectric conversion by a photodiode and recorded by the oscilloscope or data acquisition module. The frequency of the beat signal detected by the balance amplified photodetector is $f_{RF} - \Delta f$:

$$|f_c + f_{RF} - (f_c + \Delta f)| = f_{RF} - \Delta f \tag{1}$$

where $f_c + \Delta f$ is the frequency of the reflected beam, f_{RF} is the frequency of the RF signal fed to the DPMZM, and Δf is the optical Doppler shift frequency generated by the vibrating target (Δf is a vector). Note that $f_{RF} > \Delta f$. If $f_{RF} = 0$, irrespective of whether the frequency of reflected beam becomes higher or lower, the different frequency of reflected beam and reference beam is always positive, then the system cannot discriminate the vibration direction. When $f_{RF} \leqslant \Delta f$, the different frequency of two beams is meaningless because of the negative frequency. Only when $f_{RF} > \Delta f$, the negative frequency can be avoided. Then the vibration direction can be distinguished, and the random vibration measurement is achieved. Thus, when the target is vibrating at a high speed and Δf is huge, we need a vast frequency shift f_{RF} to guarantee the precise probe of motion pattern. And as reported by the introduction, the frequency shift of acousto-optic modulate approach is too cramped to match high speed vibration measurement.

Moreover, the higher measurement accuracy of displacement and speed claim the higher frequency resolution of data acquisition module. And, the frequency resolution F_0 of a data acquisition module is proportional to sampling rate f_s and inversely proportional to sampling number N:

$$F_0 = \frac{f_s}{N} \tag{2}$$

According to the Nyquist's sampling theorem, the sampling rate f_s must be more than two times of the highest frequency of a continues-time signal. Hence, when the target is vibrating at a high speed and Δf is huge, a high sampling rate data acquisition module should be employed and its acquisition memory should be enormous enough to ensure high frequency resolution. When the vibration speed of the target is low and Δf is little, the optical frequency shift obtained by RF signals with lower frequency is high enough to cover the Doppler shift frequency Δf. According to Nyquist's sampling theorem, since the frequency of RF signals is low, the data acquisition module with low sampling rate can recovery the signal. Then we can utilize a more economical data acquisition module with small sample rate and guarantee the high frequency resolution concurrently.

2.2. Control principle of dual-parallel Mach-Zehnder modulator

The dual-parallel Mach-Zehnder modulator is an integrated optical component comprising two Mach-Zehnder modulators (MZM1 and MZM2) embedded in a large Mach-Zehnder modulator (MZM3) [8]. The DPMZM working on the state of CS-SSB modulation acts as a frequency shifter, and we have to set the RF signals and three bias voltages accurately.

The schematic diagram of the CS-SSB signal generated by the DPMZM is shown in Fig. 2. Where $E1$, $E2$ and $E3$ are the optical field output from MZM1, MZM2 and MZM3 respectively. $E3$ is equal to E_{CS-SSB} in Eq. (6).

The optical field of the input optical carrier from the LD can be expressed as:

$$E_{Laser} = E_0 \cos(\omega_0 t) \tag{3}$$

where E_0 and ω_0 denote the amplitude and angular frequency of the input optical carrier respectively. The 90° hybrid splits the input RF signal into in-phase and quadrature components. Therefore, the RF drive signals respectively fed to MZM1 and MZM2 can be expressed as:

$$V_{RF1} = V_{RF} \sin(\omega_{RF} t) \tag{4}$$

$$V_{RF2} = V_{RF} \sin\left(\omega_{RF} t + \frac{\pi}{2}\right) \tag{5}$$

where V_{RF} and ω_{RF} denote the amplitude and angular frequency of the input RF signal respectively. We set the bias voltages of MZM1 and

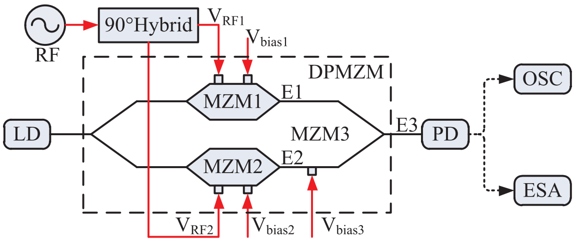

Fig. 2. The schematic diagram of CS-SSB signal generation using DPMZM. PD: photodetector.