Design of new seismometer based on laser Doppler effect

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In order to improve the resolution of seismic acquisition, a new seismic acquisition system based on tangential laser Doppler effect with an optimized differential optical configuration is proposed. The relative movement of the inertia object and the immobile frame is measured by laser Doppler effect, which can avoid the electromagnetic and thermometric interference, and the adoption of frequency-modulated (FM) transmission can improve the ability of anti-jamming. The frequency bandwidth is properly determined by analyzing the frequency of the Doppler signal. The velocity, displacement, acceleration, and frequency to be measured can be real-time acquired by frequency/velocity (F/V) converting the FM Doppler signal. A 100-dB dynamic range and the linear frequency range of 1.0 to 1000 Hz are realized.

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The performance of the electromagnetic geophone has become the bottleneck of the development of high-resolution seismic acquisition. Scientists and engineers have paid great attention to the development of new seismic geophone[1,2]. Laser Doppler technique is characteristic of high precision, fine linearity, swift dynamic response, wide measuring range, and non-contiguity, so it has been widely used in the diversified kinds of movement measurements[3-5]. In this paper, a new method of seismic acquisition based on tangential laser Doppler effect with an optimized differential optical configuration is proposed.

In the differential laser Doppler measurement system[3], the received interferential signal is generated by the backscattered light that undergone the Doppler frequency shift. Two laser beams I and II, whose frequencies are f_0 and $f_0 + f_c$ respectively, are focused on the measured object whose velocity is V. The backscattered light is focused to the photodiode (PD) through object lens, and the detected AC current signal is

$$i(t) = kE_1E_2\cos\left[2\pi\Delta f t + \Delta\phi\right]. \tag{1}$$

And owing to $f_c \ll f_0$ and $V \ll c$, we can deduce

$$\Delta f \approx f_c + \frac{2V}{\lambda}\sin\frac{\theta}{2}, \tag{2}$$

$$V = \frac{\lambda}{2\sin(\theta/2)}(\Delta f - f_c), \tag{3}$$

where $\theta = \theta_2 - \theta_1$, $\lambda = c/f_0$ is the laser wavelength.

The Doppler frequency shift contains the information of the measured velocity, which is proportional to the frequency difference $(\Delta f - f_c)$. There is no nonlinear relation between them and the data acquisition will not be affected by the electromagnetic and thermometric variation.

The velocity of sinusoidal vibration is denoted as

$$\dot{x}(t) = A_0\omega_x\cos(\omega_x t + \phi_{\dot{x}}), \tag{4}$$

where ω_x is the frequency of vibration, A_0 is the amplitude, and $\phi_{\dot{x}}$ is the initial phase of the velocity waves.

From Eqs. (1), (2), and (4), the beat signal detected by the PD is

$$i(t) = K\cos\left\{[\omega_c + m_p\omega_x\cos(\omega_x t + \phi_{\dot{x}})]t + \Delta\phi\right\}, \tag{5}$$

where $m_p = \frac{4\pi A_0\sin(\theta/2)}{\lambda}$, $\omega_c = 2\pi f_c$, and K is a constant coefficient relating to the system.

As shown by Eq. (5), the detected beat signal is of angle modulation with the carrier frequency w_c and the frequency of the modulation signal w_x. The modulation ratio is lied on the measured amplitude and frequency w_x. As angle modulation signal performs better anti-jamming ability than traditional base band signal during the transmission, which can improve the signal-to-noise ratio (SNR) effectively, the seismometer based on laser Doppler effect essentially has high performance.

In order to determine the bandwidth of the transmission channels and the signal-processing unit, it is necessary to analyze the spectrum of the beat signal. After Fourier series expansion, Eq. (5) is transformed into

$$\begin{aligned} i(t) &= K[\cos(m_p\omega_x\cos(\omega_x t + \phi_{\dot{x}})t)\cos(\omega_c t + \Delta\phi) \\ &\quad - \sin(m_p\omega_x\cos(\omega_x t + \phi_{\dot{x}})t)\sin(\omega_c t + \Delta\phi)] \\ &= K\sum_{-\infty}^{+\infty} J_n(m_p)\cos[(\omega_c + n\omega_x)t + \Delta\phi], \end{aligned} \tag{6}$$

where $J_n(m_p)$ is nth order Bessel function. So the spectrum of the beat signal is

$$\begin{aligned} &I_{PM}(\omega) \\ &= \pi S_0\sum_{n=-\infty}^{+\infty} J_n(m_p)\left\{\delta\left[\omega - (\omega_c + n\omega_x + \Delta\phi)\right]\right. \\ &\quad \left.+\delta[\omega + (\omega_c + n\omega_x + \Delta\phi)\,]\right\}. \end{aligned} \tag{7}$$

Theoretically, the beat signal contains infinite frequency spectrum monomials. But the value of the Bessel function $J_n(m_p)$ will decrease sharply with the increase of the order n. Practically, the distribution of spectra is still relatively concentrated. Considering the required dynamic range in the Doppler seismometer, the design of bandwidth may follow the principle of "wide band modulation" as

$$W_{PM} \approx 2m_p\omega_{\max} = \frac{8\pi A_0\omega_{\max}\sin(\theta/2)}{\lambda}, \tag{8}$$

where $\omega_{\max} = 2\pi f_{\max}$, $f_{\max}$ is the maximum of measured seismic frequency, A_0 is the amplitude, λ is the laser wavelength, and θ is the included angle between the two beams. According to Eq. (8), when $f_{\max} = 200$ Hz, $A_0 = 1.0$ mm, $\lambda = 632.8$ nm, and $\theta = 14°$, the bandwidth of the transmission channel and the signal-processing unit is about 6.08 MHz.

Figure 1 is the schematic diagram of seismic acquisition system based on laser Doppler effect. It comprises the laser source, acousto-optic (AO) modulator, lenses, and PD. The Doppler beat signals are picked up and transferred into current signal by the PD. After pre-amplification, they are transmitted to the signal-processing unit where the signals are amplified, filtered, limited, frequency modulated (FM), and frequency/velocity (F/V) transited.

The laser beam, with the frequency of f_0, enters with the Bragg diffraction angle into the AO modulator (modulating frequency f_c = 40 MHz) to form the 0 order diffracted light of frequency f_0 and the +1 order diffracted light of frequency (f_0 + 40 MHz). The +1 order light and the 0 order light are converged on the object through lens. The backscattered light is collected by the lens1, and then reflected and converged on the PD to convert into current signal. It is FM signal that contains the Doppler signal associated with the measured velocity, and the sub-carrier frequency is 40 MHz. The modulated signals are pre-amplified and transmitted to the signal-processing unit.

As shown in Fig. 2, the transmitted radio frequency (RF) signals are amplified and filtered by the bandpass filter, whose effective bandwidth is related with the dynamic range determined by Eq. (8), then the signals pass through the amplitude limiter and enter the phase demodulator. A moiety of signal from the output of the AO modulator is used as the reference signal of FM demodulation. The outputs of the phase demodulator are filtered by the low-pass filter to gain the signal ($\Delta f - f_c$). As Eq. (3) shows, the frequency difference is proportional to the measured velocity, and then the signal passes the F/V circuit to get the real-time velocity of measured inertia object. Through the differential coefficient of the signal, we can get the acceleration signal, and through the integral of the signal, we can get the displacement signal, the changing circuit is responding to the circuit of the vibration.

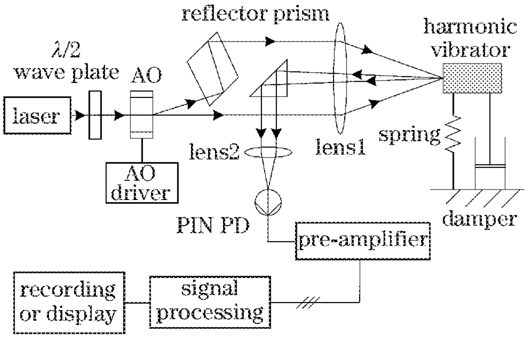

Fig. 1. Diagram of seismic acquisition system based on laser Doppler effect.

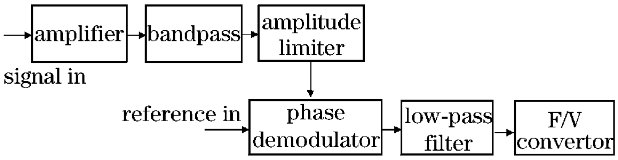

Fig. 2. Block diagram of the signal processing.

Figure 3 shows the measured amplitude value varying linearly with the output voltage of the oscillator when the oscillator's frequency output is fixed at 20.0 Hz. The vibration amplitude has a fine linear relation with the voltage signal.

Figure 4 shows the measured amplitude value when the output frequency is changed from 0.8 to 1000 Hz under the fixed oscillator's voltage output of 3.0 mV. Under some given excitation power, the typical linear range measured by this system is 20 nm – 2.0 mm, corresponding to a 100-dB dynamic range.

Theoretical analysis and the experimental results indicate that measuring the micro-vibration by differential laser Doppler technique can improve the resolution of displacement; reasonably designing the bandwidth can improve the system's dynamic range effectively.

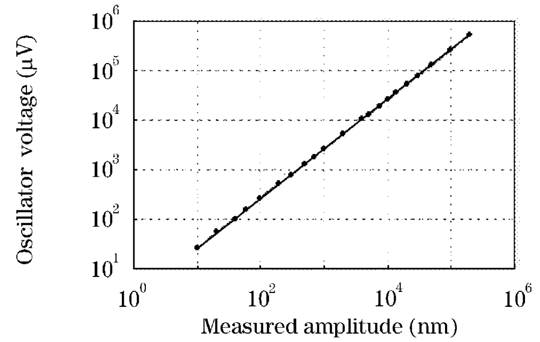

Fig. 3. Linearity of the output voltage of oscillator to the measured amplitude.

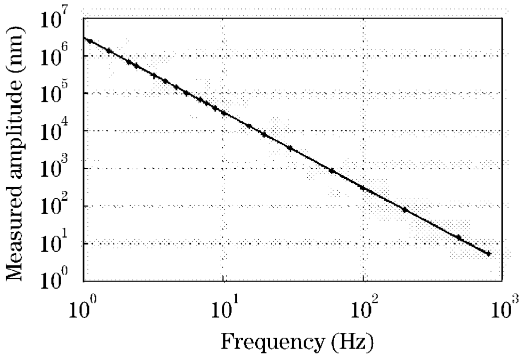

Fig. 4. Measured dynamic range.

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