Study on the Signal of Laser Doppler Differential Demodulation System*

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Abstract The differential technology of Laser Doppler and the frequency-tracking technology of PLL are studied and a Laser Doppler differential demodulation system with high accuracy and broad dynamic range is designed. The system has the characters of tight structure, convenience on fixing and tuning and can make full use of laser energy. Furthermore, by focusing the waists of two Gauss beams on the object measured, the smallest speckle and the superposition of plane waves are obtained to enhance the resolving power, SNR and the intensity of signal. It tracks the frequency automatically to resolve the dropout of signal and to restrain all kinds of noises and disturbances. It is proved by simulation experiment that the measure accuracy of amplitude and frequency respectively are 1% and 0.6% and the resolving power is 50nm, so the technology indexes are satisfactory.

Keywords Laser Doppler differential demodulation; Frequency-tracking of PLL; Frequency-voltage transition; Measurement on simulative oscillation

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0 Introduction

The seism detection is a measurement in which the reflected wave of man-made seism is the measured signal. Because of high accuracy, high resolving power and great penetration depth, presently it is used widely in all kinds of detection methods in physical geography. It mainly serves to detect the stratum construction and to find the mineral resources, such as petroleum, gas resource, and so on. The technology of seismic wave demodulation and machines relevant have a history of decades. The demodulator of electromagnetic moving ring which dynamic range is ≤60 dB is used frequently before 90's. Later, super electromagnetic demodulator is invented abroad to meet require of high resolving power, such as SM-24 of Holand[1], G3-32CT of Japan, UM-2 of America, which are improved distinctly in technology, such as dynamic range achieves 70dB, the aberration achieves 0.05% (UM-2). But their frequency range (≤ 100 Hz), dynamic range of amplitude, resolving power and the accuracy etc. are not satisfactory. Especially, working outdoors, the quality of signal is bad (because of random fluctuation of amplitude), such as signal dropout, which affects the measure accuracy and dynamic range. To solve it, seismic demodulation technology with high accuracy and broad dynamic range and theories relevant, especially Laser Doppler measurement and signal-processing technology[2,4-6], are researched in this paper, and the backward-scattered light is detected with high intensity, high SNR, and high resolving power by focusing the waists of Gauss beams[3] with a differential Laser Doppler system and the frequency is tracked automatically without odd frequency difference with PLL frequency-tracker to restrain all kinds of noises and to overcome the dropout of signal, etc.. It proved by the result of experiment that the technical parameters are satisfactory.

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1 Principle

1.1 Frequency displacement of differential Laser Doppler system

Laser Doppler measurement has developed greatly for its high accuracy, quick dynamic response, good linearity, great measured range and contactlessness. Because the frequency displacement of differential optical system is irrelevant to the value of angle receiving the scatter light, receiving lens with big diameter is used to obtain intense signal of Laser Doppler[2].

When the object moves with a velocity v, the corresponding frequency displacement Δf of the scatter light is

$$\Delta f = (2v/\lambda)\sin(\theta/2) \tag{1}$$

Count the number N of corresponding pulse, and then the displacement x of moving object is

$$x = N\frac{\lambda}{2\sin(\theta/2)} \tag{2}$$

Obviously, measuring accuracy of the displacement is only relevant to the value of angle between the two differential beams and its variation, but irrelevant to the value of v and its variation. Therefore, Laser Doppler technique also can be used to measure oscillation displacements of oscillation and seismic wave.

1.2 Measurement signal of oscillation

If the oscillation platform which is prompted by sinusoidal signal and made in Danmark is used to simulate seismic measure, the oscillation displacement and velocity of the object can be respectively expressed i. e.

$$x = x_{max}\sin 2\pi f_x t = x_{max}\sin \omega_x t \quad (3)$$

$$v = \dot{x} = x_{max}2\pi f_x \cos 2\pi f_x t = x_{max}\omega_x \cos \omega_x t \quad (4)$$

f_x is driving frequency, and x_{max} is the biggest displacement or oscillation amplitude. It is obvious that the object moves with a variable velocity when oscillating as sinusoid. Therefore, it is got from expressions (1), (4)

$$(\Delta f)_{max} = \frac{2}{\lambda}v_{max}\sin\frac{\theta}{2} = \frac{4\pi}{\lambda}x_{max}f_x\sin\frac{\theta}{2}$$

or

$$x_{max} = \frac{\lambda}{4\pi}\frac{(\Delta f)_{max}}{f_x\sin(\theta/2)} = q\frac{\lambda}{2} \quad (5)$$

q that expresses the number of the object' s displacements that contain $\lambda/2$ is the number of Laser Doppler waves. Thus it can be seen that the object's displacement of λ brings about two Laser Doppler changes, i. e. every oscillation cycle contains two Laser Doppler waves(shown as Fig. 3). Therefore, we can get the oscillation displacement by counting the number of Laser Doppler waves.

When the differential beams are focused on the oscillating object, the scatter light can be demodulated. Thus, the output voltage signal of the photoelectric receiver is

$$V = V_{max}\cos[\omega_c t - (M\omega_x \cos\omega_x t)t] \quad (6)$$

In expression (6), $M = 2kx_{max}\sin(\theta/2)$, is the index of phase modulated. It's value depends on the value of the amplitude measured. It can be seen that the oscillating beat wave is phase-modulated signal, and it's carrier frequency and modulation frequency respectively are f_c, f_x.

1.3 Signal processing

Expand expression (6) with the triangle formula and Fourie series, and then have it Fourie transformed, the beat signal can be got

$$V(\omega) = \pi V_{max}\sum_{n=-\infty}^{\infty} J_n(M)\{\delta[\omega - (\omega_c + n\omega_x)] + \delta[\omega + (\omega_c + n\omega_x)]\} \quad (7)$$

So the beat wave has infinite spectrum. But, because the biggest value of $J_n(M)$ reduces gradually with the increasing of n, it's spectrum is finite and convergent. Considering all kinds of measure conditions, the bandwidth B of the Dopller measurement system should be designed according to the principle of phase modulating to broad band, i. e.

$$B \approx 2M\omega_x \quad (8)$$

2 Measurement system of oscillation

As shown in Fig. 1, the schema of measurement system of oscillation is differential, composed of laser L, acoustoopic modulator A, reflective prism R, mirrors M_1 and M_2, extender and collimating lenses $L_1 \sim L_2$, $L_3 \sim L_4$, collective lenses L_5, L_6, photoelectric receiver D. And it's signal processing system is made up of signal amplifying, filtering, frequency tracking with PPL, converting with F/V convertor , data acquisition and processing and so on.

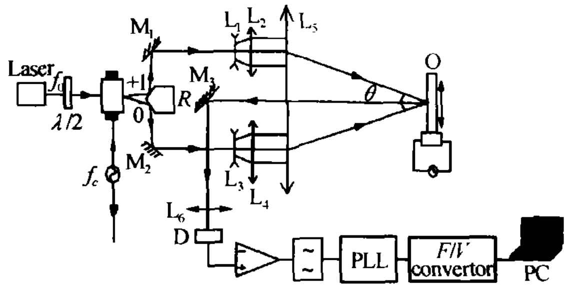

Fig. 1 Differential demodulation system

The biggest strongpoint of the system is that the smallest speckle and the superposition of plane waves are obtained, by means of making the waists of two beams pass the extender and collimating lenses composed of $L_1 \sim L_2$, $L_3 \sim L_4$, and image on the L_5 lying on the focal plane of L_2 and L_4, and then be focused on the surface of the oscillating object by L_5, which enhances the intensity of Doppler signal, SNR, and the measure accuracy greatly[3].

Backward-scattered receiving structure is adopted for tight structure, however, which brings about bad Dopller signal (i. e. dropout of signals because of random wave of the amplitude), low SNR and so on. Therefore, frequency tracker of PLL shown in Fig. 2 is adopted. It is made up of frequency mixer, intermediate-frequency amplifier, amplitude limiter, loop filter, voltage-controlled oscillator (VCO) and drop-out detecter. The output signal of photoelectric receiver is forward-placed amplified and in the frequency mixer is mixed with the output signal of VCO to produce frequency-invariable intermediate-frequency signal. And the intermediate-frequency signal is amplified and amplitude limited, and then is phase compared with reference signal in the phase demodulator to export the voltage signal having direct ratio to the phase displacement, and then it is filtered to control the output signal's frequency of VCO in order to make it track the input signal's frequency. When Doppler signals drop out, turn off the gate of integral circuit controlling phase demodulator to make the voltage value of the integral capacitor keep the value before dropout till next normal Doppler signal comes, and then open the gate.

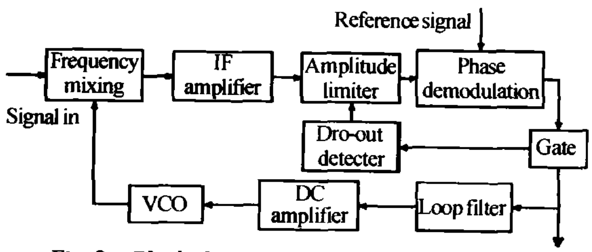

Fig. 2 Block diagram of PLL frequency tracker

The modulated signal exporting from PPL whose frequency contains information of the velocity about the measured object is converted into Doppler frequency wave by F/V convertor, i. e. the wave shape of the measured object's velocity, and then the wave shape of the displacement is obtained after integral.

3 Experiment and conclusion

The oscillation measurement system shown in Fig. 1 is adopted to conduct simulation experiment of oscillation. The source is He-Ne laser whose power is 2 ~ 3 mW. The oscillation platform is Brüel & Kjær (Br) Sine Random Generator, Type 1027, Power Amplifier Type 2706; the measured oscillating object is aluminum film. Data acquisition and processing are done based on LabVIEW of NI firm, and the DAQ is PCI6023E.

The beat wave shape shown in Fig. 3 is obtained by the experiment. The phase-modulated Doppler tracking signal of PLL is shown in Fig. 3 (a); the measured displacement wave shape is shown in Fig. 3 (b); and the output voltage of F/V convertor, i. e. the measured wave shape is shown in Fig. 3 (c). Besides, the simulation contrast value of frequency and amplitude can be obtained, and the average values of 10 data

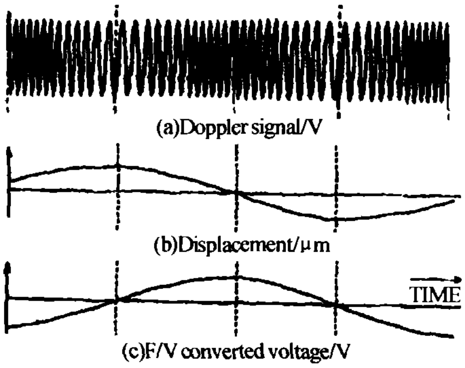

Fig. 3 Waveshape diagram showing an example of vibration measurement

obtained by means of being measured for every parameter are shown in table 1.

Table 1 Measured data of frequency and amplitude

Number	Frequency/Hz		Amplitude/μm	
	Comparable value	Measured value	Comparable value	Measured value
1	0.3	0.3	4900.00	4887.25
2	3	3	3600	3602.21
3	10	10	2000	2010.82
4	20	19.9	1500.5	1514.04
5	40	40.2	280.81	282.86
6	80	80.5	110.20	109.31
7	400	401.5	20.30	20.22
8	1000	1005.2	4.52	4.48

4 Conclusion

It can be got from above data that the measurement accuracies of frequency and amplitude about the demodulation system respectively are 0.6%, 1%. And the power of distinguishability is 50nm. Obviously, the technological parameters are satisfactory, and the system can be used to explore on physical geography.

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激光多普勒差动检波装置的信号研究

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摘　要　研究了差动多普勒技术和锁相放大器的频率跟踪技术，设计了一种精度高、动态范围大的激光多普勒差动检波系统．此系统结构紧凑，安装调节方便，可以充分利用激光光能．而且，它把两束高斯光束的束腰聚焦在被测物体上，获得了最小光斑和平面波的叠加，提高了分辨力、信噪比和信号强度．采用频率自动跟踪技术来解决信号丢失问题，抑制了各种噪声和干扰．模拟实验证明，振幅测量精度为 1%，频率为 0.6%；分辨力为 50 nm，技术指标是令人满意的．

关键词　激光多普勒差动检波；锁相放大器频率跟踪；频率-电压转换；模拟振动测量

He Shunzhong was born in Hunan Province, in 1945. In 1970, he graduated from Changchun Institute of Optics and Fine Mechanics and got the Bachelor Degree. In August of the same year, he went to work in the Precise Instruments Department of Tianjin University. Now, he is an associate professor and director of graduate students. He is mainly engaged in the teaching and research of engineering and metering optics, technology and application of laser, optoelectronics, photoelectric sensing, nonlinear optics and physical optics. He has finished six research projects and published more than twenty papers, and he is studying the project and applications about laser Doppler technique now.