Simultaneous Vibration Measurements of Two Separate Objects Using a Wavelength-Swept Optical Heterodyne Method

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Abstract

In this study, a new laser Doppler velocimeter (LDV) is proposed for multipoint vibration measurements in complicated ultrasonic vibration systems. Separate vibrating objects distributed in-line are discriminated from each other using the wavelength-swept optical heterodyne method based on the phenomenon that the beat frequency is proportional to the optical path difference. A continuous optical frequency sweep over several GHz can be made easily with laser diode (LD) using the injection current modulation, and in the pseudo-heterodyne system, we can eliminate an expensive and large acousto-optic modulator used in conventional LDVs. However, it is impossible to demodulate the vibration with a conventional FM demodulator. The authors designed a quadrature demodulator with a tunable local oscillator in order to utilize the principle for multipoint vibration measurements and were able to measure the two separate vibrations.

1. Introduction

Recently, laser Doppler velocimeters (LDV) have been used for multipoint vibration measurements in ultrasonic vibration systems. We need a complicated and expensive mechanical scanning system for measuring the vibration distribution. Moreover, the conventional LDV is a large and expensive instrument because it is typically constructed with a Helium-Neon laser as a light source and an acousto-optic modulator (AOM) as a frequency shifter for heterodyne interferometry. The authors have proposed a method for vibration measurement with spatial resolution capability using a single laser beam. Using this method, several separate vibrating objects distributed in-line are measured at the same time with the wavelength-swept optical heterodyne method[1)] based on the phenomenon that the beat frequency is proportional to the optical path difference. A continuous optical frequency sweep over several GHz can be made easily by a popular Fabry-Perot laser diode (LD) using injection current modulation[2)] . By utilizing the pseudo-heterodyne system, we can eliminate an expensive and large acousto-optic modulator used in conventional LDVs. However, it is impossible to demodulate the vibration signal with conventional FM demodulator, since the output of the pseudo-heterodyne interferometer is a cyclic signal repeated within the LD modulation frequency. We designed a quadrature demodulator suitable for the present system using a burst driven local oscillator. By tuning the local oscillator frequency, we could measure the two separate vibrations with the signal discrimination of over 15 dB for two vibrating objects with a spacing of 45 mm. In this report, we describe the present principle and prototyped the system. The spatial resolution capability and considered is examined.

2. Pseudo-heterodyne Methods

First, we describe the wavelength-swept optical heterodyne system. A Michelson interferometer shown in **Fig.1** with an appropriate path difference using a Fabry-Perot LD at 670 nm is used in our experiments. An f_m (kHz) saw-like waveform of Δi mA is added to the injection current. This results in the optical frequency sweep of $\Delta\nu$ (Hz) as shown in **Fig.2.** The LD output is divided by a half-mirror into two beams. One is reflected by a reference mirror and a vibration object reflects the other. They are combined by a half mirror and continue to a photodiode. Here, because there is a path-length difference l between the reference light and the measurement light, an optical frequency change occurs because the reference light has a time delay Δt with respect to the measurement light. A beat signal of the frequency f_b equivalent to the delay shown in Fig.3 can be observed. The frequency of the beat signal (beat frequency) is calculated

$$f_b = \frac{\Delta\nu \cdot l}{c} f_m , \quad \textbf{(1)}$$

where c is the light velocity. The beat frequency is proportional to the path-length difference, and we can estimate the position of the vibration object by measuring the beat frequency. The light reflected by the vibration object is shifted in its frequency by the Doppler effect. Therefore, the beat frequency observed at the photodiode would be an FM signal. By calculating the Doppler shift magnitude, we can get the vibration velocity.

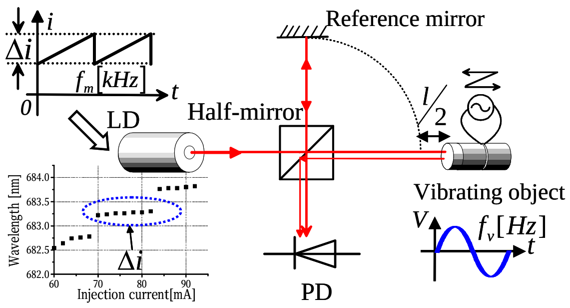

Fig.1 Pseudo-heterodyne interferometer.

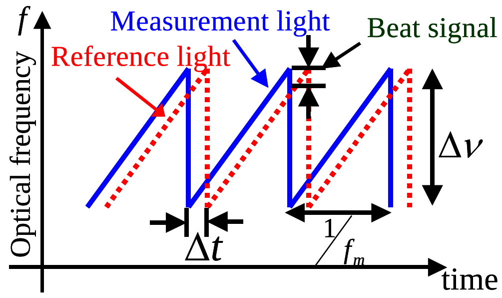

Fig.2 Principle of the pseudo-heterodyne system.

If there are some vibration objects distributed in the depth direction along the measurement light the beat contains the same number of frequency components, and each frequency is oscillated due to the vibration. The vibration waveforms of each object can be measured using an FM demodulator turned to the target frequency. However, it is impossible to demodulate the vibration with a conventional FM demodulator, since this FM signal, shown in **Fig.3,** is a cyclic signal repeated within the LD modulation frequency. Thus, we newly designed a special FM demodulation for the present system.

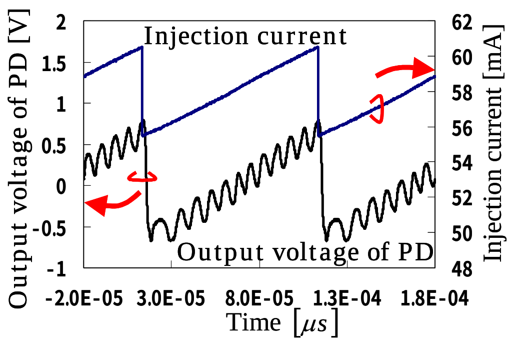

Fig.3 Injection current and the beat signal.

2. Discussion about the demodulation method

2.1 Quadrature demodulator[3)]

We developed a quadrature demodulator to extract the Doppler shift component from the FM signal received at the photodiode in Fig.1 as shown in Fig.4. First, the beat signal is digitized with a comparator after the high-pass filtering. A sine-cosine local oscillator triggered by the LD modulation signal is also equipped in the system. The results of Exclusive-OR operations between the beat and the local oscillator are the inputs of low-pass-filters as shown in the figure. Since these signals have frequency sum $2f_b+f_d$ and frequency difference component f_d, they are low-pass filtered to remove the component at $2f_b$ leaving only the Doppler shift component f_d. By using the two outputs I and Q, the vibration waveform is demodulated with the following equation:

$$\omega = \frac{\phi_2 - \phi_1}{t_2 - t_1} = \frac{1}{\Delta t} \cdot \tan^{-1} \frac{I_2 Q_1 - I_1 Q_2}{I_1 I_2 + Q_1 Q_2} \quad (2)$$

2.2 Operating condition of the quadrature demodulator

The authors examine the conditions for the local oscillator signal such as the burst number and frequency, and the modulation frequency of the LD to operate the quadrature demodulator effectively. Here, a Fabry-Perot LD (DL-3149-056, SANYO, 670 nm) was used as a light source, and the operation temperature was kept constant at 23 ℃, and the current was 39 mA. The current modulation width Δi was 2 mA_{pp} and the optical frequency deviation $\Delta\nu$ was approximately 8.9 GHz. Since the path difference l in the Michelson interferometer in Fig.1 was 430 mm the wave number f_b/f_m in a modulation cycle was approximately 12. A mirror on a piezo-actuator was used as vibration object and was oscillated at 10Hz. The LD modulation frequency was set at 15 kHz which was much higher than the vibration frequency. First, the local oscillator frequency was held constant at 193 kHz which was equal to the beat frequency. The cut-off frequencies of the HPF and LPF were 35 kHz and 16 Hz, respectively. As shown in Fig.5, when the local oscillator was operated continuously, no output signal was obtained. Next, the burst number is changed from 1 to 12, and the demodulated wave amplitude was observed as shown in Fig.6. From the result, the burst number needs to be equal to be the wave number of the beat signal. Next, the burst number was constant at 12, the local oscillator frequency was swept from 175 kHz to 210 kHz. The results are shown in Fig.7. From the result, the local oscillator frequency needs to be tuned at the beat frequency within a few percent error. The result means that the target vibration can be chosen among several vibrations by selecting an appropriate frequency for the local oscillator. The output signal to noise ratio is plotted in Fig.8 as a function of the frequency of the vibration, where the burst frequency and number were 193 kHz and 12, respectively. If the vibration frequency is higher, the saw-like modulation signal of LD leaked into the output signal. If the vibration was lower than 7.5 kHz, the output signal to noise ratio was over 20 dB. We can conclude that the LD modulation frequency should be at least twice the vibration frequency to be measured.

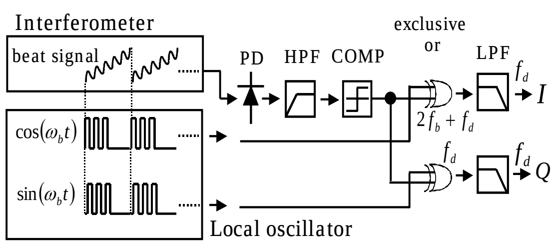

Fig.4 Demodulation of vibration waveform.

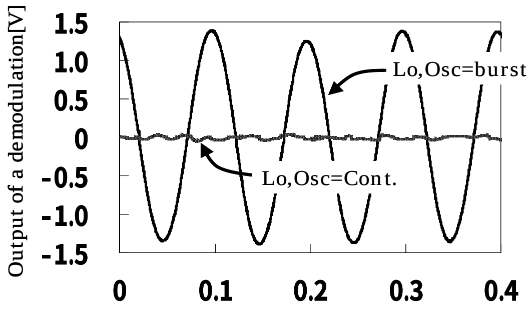

Fig.5 Demodulated waveforms.

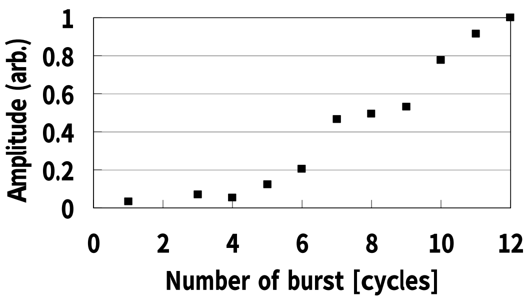

Fig.6 Amplitude of the demodulated signal as a function of the number of the burst.

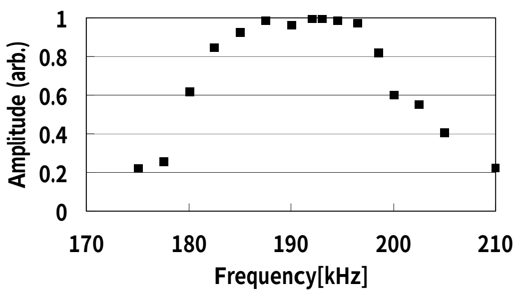

Fig.7 Amplitude of the demodulated signal vs. the frequency of the local oscillator.

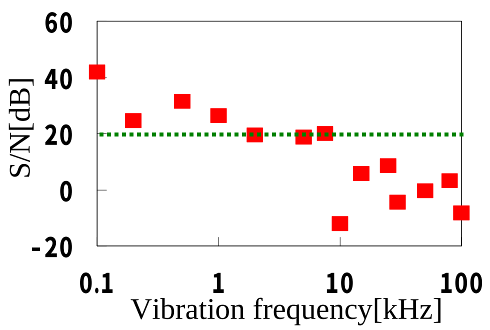

Fig.8 The signal to noise ratio vs. frequency of the measurement object

3. Simultaneous vibration measurement of two separate objects

3.1 Spatial resolution [3)]

The wave number f_b/f_m in the beat signal is the expressed as

$$\frac{f_b}{f_m} = \frac{\Delta\nu}{c} l \quad (3)$$

by rewriting Eq.(1). If the minimum detectable change in the wave number is only 1, the spatial resolution Δl is

$$\Delta l = \frac{c}{\Delta\nu} . \quad (4)$$

If we have a larger optical frequency modulation deviation $\Delta\nu$, a higher spatial resolution Δl can be achieved.

3.2 Experimental setup

We placed another vibrating half mirror (HM) between the vibrating mirror (M) and the beam –dividing half mirror. It has a transparent mirror, and reflects a part of the measurement beam. The output beat signal contained the two components corresponding to each path difference. The waveform observed at the photodiode and its spectrum are shown in Fig.10 and 11, respectively. Here, the interference signal caused by the reflection between the two vibrating objects is removed with HPF. The authors examined the capability of the system to make a simultaneous vibration measurement of HM and M. The LD temperature was kept constant at 23 ℃ to avoid wavelength drift. The optical frequency modulation deviation $\Delta\nu$ was set approximately at 12.7 GHz. Each path length in Fig.9 was l_1=45 mm、l_2=345 mm and l_3=445 mm. It should be noted that l_2 and l_3 were set larger than l_1 to make the beat generated by the interference between HM and M was much lower in frequency. Beat frequencies caused by HM and M are calculated to be f_{b2}=315 kHz and f_{b3}=415 kHz by Eq. (1). Two beat signal components are observed if two objects HM and M exist. The frequency error to the calculated value was about 1 kHz. This corresponds to 0.12 mm in position error.

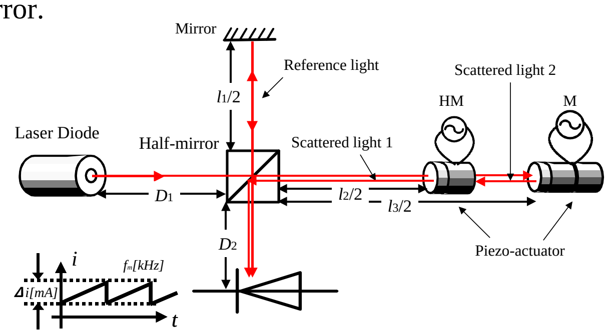

Fig.9 Pseudo-heterodyne interferometer with two reflection objects.

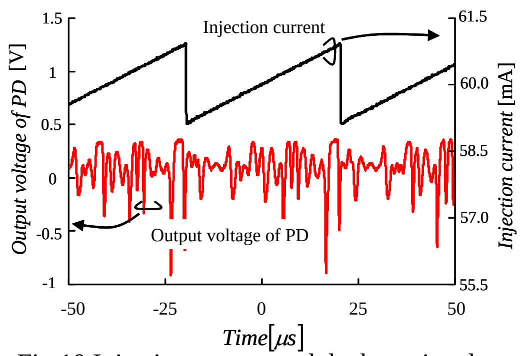

Fig.10 Injection current and the beat signal.

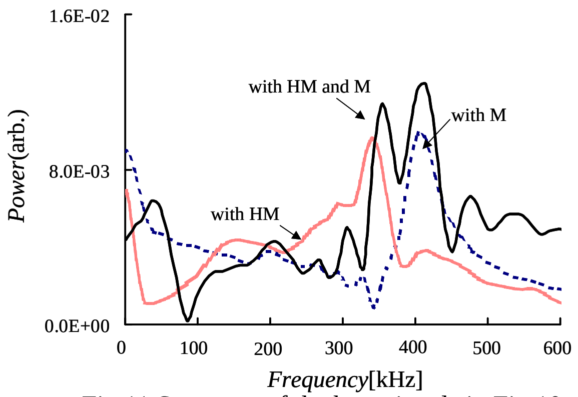

Fig.11 Spectrum of the beat signals in Fig.10.

3.3 Experiments

In the next set of experiments, a double-balanced mixer instead of an Exclusive-OR circuit in Fig.4 was used. The demodulation method is the same. When there are some measurement objects and some beat signals, if the frequency of the local oscillator signal is adapted to the beat frequency, vibration of a measurement object corresponding to the beat frequency should be selectively detected. HM and M are vibrated at different frequencies 750 Hz and 1kHz respectively. The cut-off frequency of the HPF is 100 kHz to remove the beat generated by the interference between HM and M, and one of the LPF is 1.1 kHz to pass the vibration component. Here, the frequency of the local oscillator was swept from 0 to 600 kHz with a 5 kHz step. At every local oscillator frequency, we calculated the spectrum of the output signal using FFT, and plotted the components at 750 Hz and 1kHz in Fig.12. Each result is normalized to the maximum value. The burst number of the local oscillator was adjusted to the optimum value at every plot. The 750 Hz vibration component had a peak at 320 kHz, while the 1kHz vibration component at 415 kHz. The result shows that it is possible to demodulate each vibration only when the local oscillator frequency is adapted to each beat frequency.

Next, the authors measured the spatial resolution capability of the system using the setup shown in Fig.9. The position of M was fixed at l_3=445 mm and the local oscillator frequency was held constant at 415 kHz which is the optimum for measuring the vibration of M. The distance between M and HM was increased from 35 mm to 75 mm by 5 mm steps. The modulation depth gives a 15 dB suppression of the signal by HM. The experimental results agreed with the theoretical curve; the spatial resolution is inversely proportional to the modulation depth.

4.Conclusion

A new LDV to measure vibration of objects distributed in-line by an optical pseudo-heterodyne system using a semi-conductor laser was examined. The quadrature demodulator that detects the Doppler component in an FM signal was designed, and the operating conditions were examined. Furthermore, in the case that there are some vibration objects, by tuning the local oscillator frequency, we were able to separately demodulate the two vibrations. We also examined the spatial resolution.

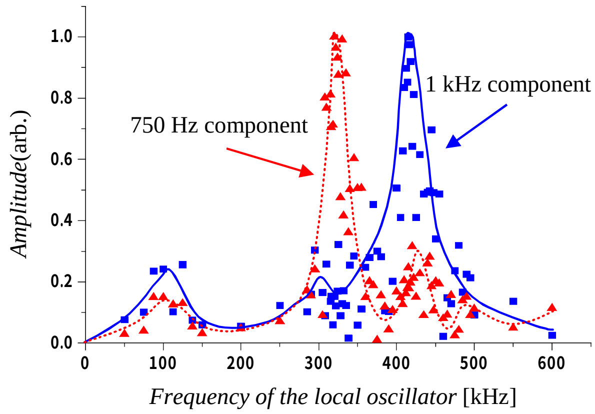

Fig.12 Amplitude of the demodulated signals as functions of the local oscillator frequency.

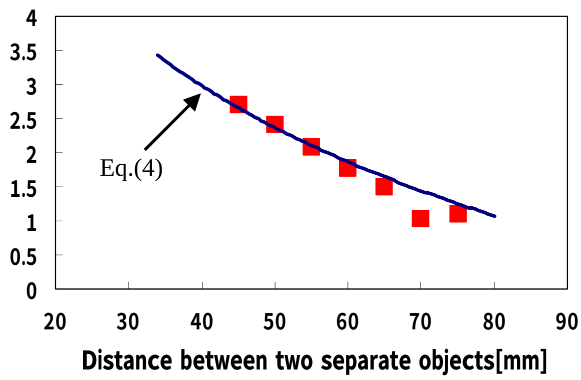

Fig.13 Modulation width vs. a distance between two separate objects.

5. References

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[2] A.Dandridge and L.Goldberg, "Current-induced frequency modulation in diode lasers," Electrum.Lett., Vol.18, No.7. pp.302-304,1982.

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