Performance Limit of Digital Vibrometer Using Self-Mixing Type LDV

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Abstract Recently, we proposed a compact digital vibrometer using a self-mixing laser Doppler velocimeter (SM-LDV).
In this paper, we theoretically obtained formulas giving lower and upper limit of measurable velocity. In the prototype digital vibrometer, the theoretical value was 6.7mm/s and 162.8mm/s, respectively, which agreed well with the measured value. The upper limit of measurable displacement amplitude was 1200μm at 10Hz, and 250μm at 100Hz. Furthermore, the measurement accuracy of the displacement amplitude was within -3% and average error -1.3%, when the shape of the sawtooth contained in the Doppler beat signal is clear and sharp. The measurement accuracy is found to depend on a degree of sawtooth asymmetry (DSA).

1. INTRODUCTION

Previously we proposed a laser Doppler velocimeter using the self-mixing effect of a semiconductor laser diode[1][2].

Recently, we proposed a digital vibrometer using a self-mixing laser Doppler velocimeter (SM-LDV)[3][4]. In the SM-LDV, the Doppler beat wave becomes sawtooth and its inclination is reversed in accordance with the direction of the velocity. Therefore, in the vibrometer, by using a binary up-down counter, the number of the each sawtooth contained in the beat signal can be accumulated, which is proportional to the vibrational displacement of an object under measurement. The up or down count pulse is produced by a directional counting circuit, which identifies the positive or negative sign of the half wavelength displacement due to each sawtooth.

In this paper, we investigated a performance limit of the digital vibrometer using self-mixing type LDV. In the prototype digital vibrometer, the theoretical value of the lower and upper limit of measurable velocity is 6.7mm/s and 162.8mm/s, respectively, which are compared with the measured value of 6.9mm/s and 150mm/s, respectively. The upper limit of measurable displacement amplitude, and the measurement accuracy of the displacement amplitude are measured. The relation between the measurement accuracy and the sharpness of the sawtooth is investigated. A new figure of merit representing the sharpness of the sawtooth is introduced, which is called a degree of sawtooth asymmetry (DSA). Those measured performance show that the prototype digital vibrometer can be further improved for practical application.

2. EXPERIMENTAL SYSTEM

Figure 1 shows a schematic configuration of the experimental system for digital displacement measurement. The laser diode

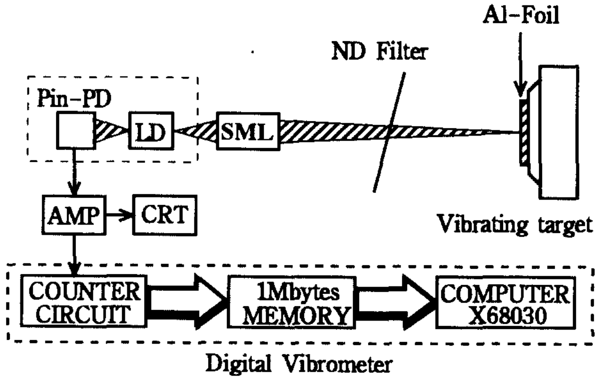

Fig. 1 Experimental setup.

(LD) operates at a current I=55mA, and the laser wavelength is equal to 0.78μm. The laser light emitted from the LD is focused and illuminated to a vibrating target with a sheet of aluminum foil. A part of the scattered light returning into the LD is mixed with the original light, and a beat signal is produced. The beat signal obtained from the pin-photodiode is counted by using a counter circuit. The counted number of the waves contained in the Doppler beat signal is stored in the memory (1024bytes) at a various sampling rate. The data in the memory circuit are transported to the computer (Personal Workstation X68030/SHARP), which calculates the amplitude of the displacement and the frequency characteristics of the vibration and so on. In this system, we change the apparent reflectance of the object surface, by adjusting the transmittance of an ND filter.

3. MEASUREMENT PRINCIPLE

3.1 Degree of Sawtooth Asymmetry (DSA)

When the returning light from the vibrating surface decreases, an amplitude of Doppler beat signal decreases and the shape of the sawtooth degrades. Thereupon, we define a degree of sawtooth asymmetry (DSA) γ in order to estimate the degradation of the sawtooth wave. Figure 2 shows a sawtooth waveform to introduce the degree of sawtooth asymmetry. When a is positive-edge time and b is negative-edge time, the degree of sawtooth asymmetry is given by

$$\gamma = -\frac{a-b}{a+b} \tag{1}$$

In case of positive velocity

$$0 \leqq \gamma \leqq 1$$

,while in case of negative velocity

$$-1 \leqq \gamma \leqq 0$$

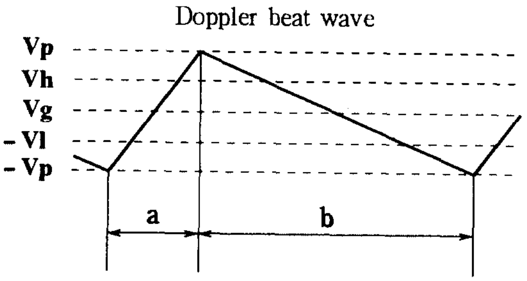

Fig. 2. A sawtooth waveform to introduce degree of sawtooth asymmetry.

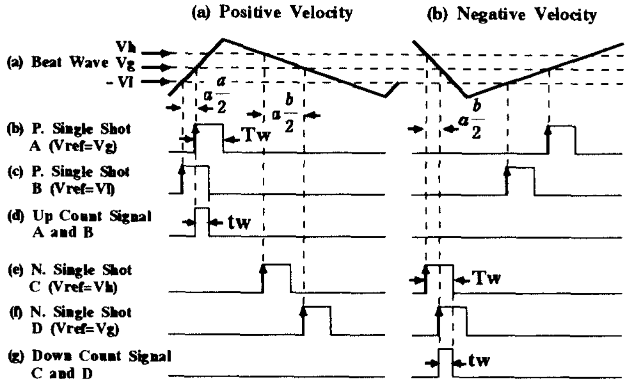

Fig. 3. Time chart of counter control signals in case of (a) positive velocity and (b) negative velocity.

3.2 Theoretical Limit of Doppler Frequency

Figure 3 shows a time chart of counter control signals. Let an average of the maximum level and the minimum level of the sawtooth be V_g. The Doppler beat wave is compared with three levels ($V_l<V_g<V_h$) which are different from each other shown in Fig. 2. Let the amplitude of the plus and minus of Doppler beat wave be $+V_p$, $-V_p$, respectively, then its ratio α is given by

$$\alpha = \frac{V_h}{V_p} = \frac{-V_l}{-V_p} \tag{2}$$

This α shows a relative reference level with which the beat signal compares.

First, we consider the case of positive velocity when the sawtooth wave rises quickly and falls slowly.

At a lower limit of Doppler frequency f_d (=1/(a+b)) as shown in Fig. 3 (a), during the positive slope, an up count pulse (d) with width t_w is produced as a product of two positive single shot pulses(b) and (c) with width T_w. While, during the negative slope, a down count pulse is not produced because the negative single shot pulses (e) and (f) do not overlap. Thus the counter circuit operates properly.

At an upper limit of Doppler frequency, the duration time a and b reach certain small values, which satisfy the equation

$$T_w = \alpha\frac{b}{2} + t_w \tag{3}$$

At this time, an unwanted down count pules is produced, which causes a miscount of the up count pulse. Therefore, the upper limit of f_d is obtained from

$$T_w < \alpha\frac{b}{2} + t_w \tag{4}$$

Where t_w is the pulse width required to be counted by a TTL counter. By substituting equation (1) into equation (4), and rewriting a+b=1/f_d we obtain

$$f_d < \alpha\frac{1+\gamma}{4(T_w - t_w)} \tag{5}$$

As can be seen from Fig. 3 (a)-(d), the lower limit of Doppler beat frequency is obtained from

$$T_w > \alpha\frac{a}{2} + t_w \tag{6}$$

This equation reduces to the following equation by the similar manipulation

$$f_d > \alpha\frac{1-\gamma}{4(T_w - t_w)} \tag{7}$$

Therefore, the measurable range of Doppler frequency f_d is given by

$$a\frac{1-\gamma}{4(T_w - t_w)} < f_d < a\frac{1+\gamma}{4(T_w - t_w)} \tag{8}$$

Furthermore, the measurable range of velocity is given by multiplying λ/2cosθ to the above equation

$$0 \le a\frac{\lambda(1-\gamma)}{8(T_w - t_w)\cos\theta} < v < a\frac{\lambda(1+\gamma)}{8(T_w - t_w)\cos\theta} \tag{9}$$

,where λ is the light wavelength and θ is the angle between the velocity vector and incident light wave vector. In case of negative velocity

$$a\frac{-\lambda(1+|\gamma|)}{8(T_w - t_w)\cos\theta} < v < a\frac{-\lambda(1-|\gamma|)}{8(T_w - t_w)\cos\theta} \le 0 \tag{10}$$

4. MEASUREMENT RESULTS

4.1 Theoretical and Measured Results of Measurable Limit

Table 1 shows results of measurable limit of Doppler frequency and velocity. These theoretical values agree well with the corresponding measured values. The theoretical values are obtained by substituting T_w=250ns, α=0.20, γ=0.920, t_w=20ns, λ=780nm and θ=0 into equations (8). And by obtaining the values of γ, α and T_w in advance, we can estimate the measurable range. The reason of the non-zero lower limit velocity is that the degree of sawtooth asymmetry (DSA) is not ± 1, which means that the shape of the actually measured sawtooth wave produced by self-mixing LD is not ideal one.

Table 1. Measurable limit of Doppler frequency and velocity.

	Max. Doppler Frequency (Max. Velocity)	Min. Doppler Frequency (Min. Velocity)
Theoretical Value	417kHz (162.8mm/s)	17.4kHz (6.7mm/s)
Measurement Value	390kHz (150mm/s)	17.8kHz (6.9mm/s)

T_w=250ns, α=0.20, γ=0.92

4.2 Lower and Upper Limit of Measurable Velocity

Figure 4 (a) shows a counted number waveform which is affected by the upper limit Doppler frequency. As seen from Fig. 4, this waveform which should have been analogous to sinusoidal displacement becomes flat at fast velocity part. This is because the Doppler beat frequency of the flat part is higher than the upper limit frequency in equation (8). Figure 4 (b) shows a velocity waveform obtained by differentiating the waveform in

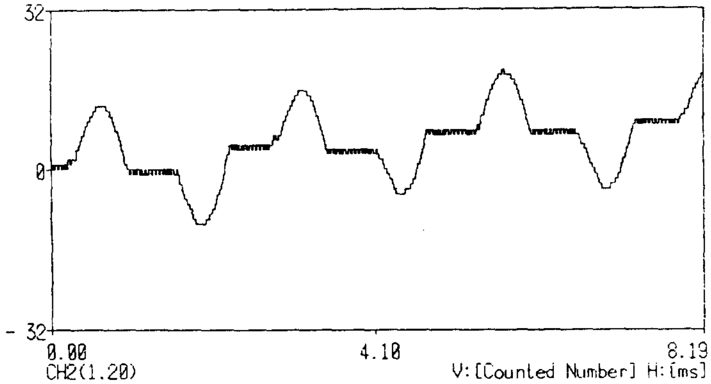

Fig. 4 (a). A counted number waveform which should have been analogous to a sinusoidal displacement, however the waveform is deformed by the upper limit Doppler frequency.

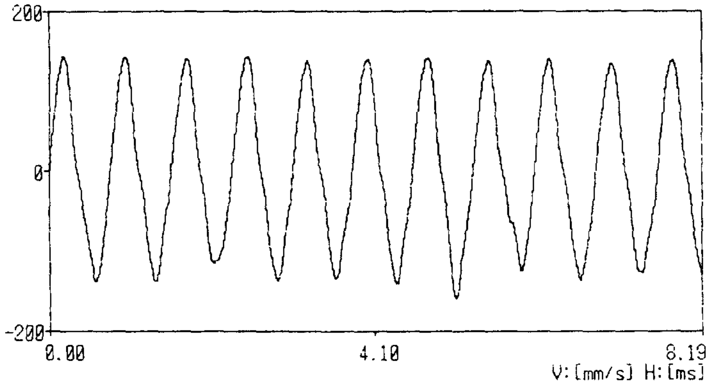

Fig. 4 (b). Velocity waveform obtained from Fig. 4 (a). The waveform is effected by the upper limit Doppler frequency.

Fig. 4 (a). According to this, a measured maximum velocity is about 150mm/s. The measured maximum velocity 150mm/s coincides well with a maximum Doppler frequency 390kHz, which is obtained from a frequency spectra of the Doppler beat signal.

Figure 5(a) shows a Doppler beat frequency spectrum which has a frequency band restricted below the lower limit of Doppler frequency. From this figure, the lower limit of Doppler beat frequency is estimated about 17.8kHz, which corresponds to a velocity about 6.9mm/s. Figure 5(b) shows a counted number waveform at that time, which is affected by the lower limit Doppler frequency. We can barely count the number of beat wave.

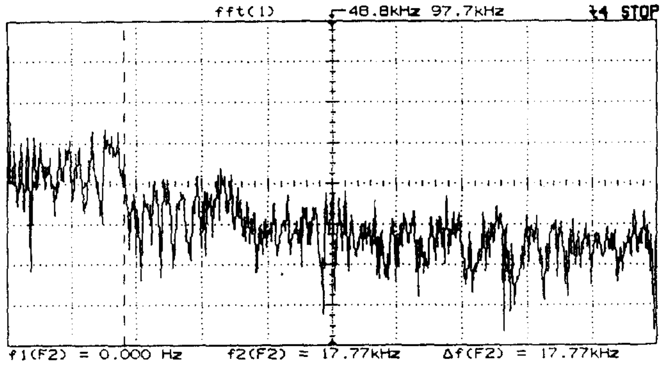

Fig. 5 (a). Frequency spectrum of a Doppler beat wave of which frequency band is restricted below the lower limit of Doppler frequency.

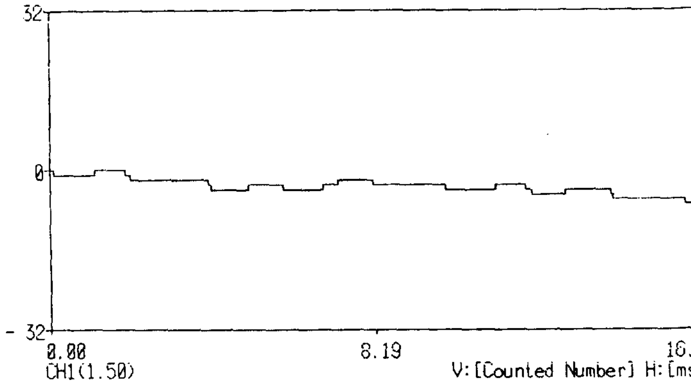

Fig. 5 (b) Counted number waveform of the Doppler beat wave with relation to Fig. (a).

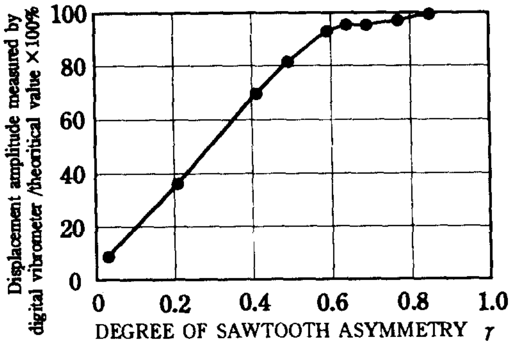

Fig. 6 Normalized displacement amplitude versus degree of sawtooth asymmetry.

4.3 Measurement Accuracy of Displacement

Figure 6 shows a relations hip between a normalized displacement amplitude and the degree of sawtooth asymmetry. The vertical axis is a displacement amplitude measured by the digital vibrometer divided by the theoretical value, and its full scale is 100%. When γ is 0~0.6, the normalized measured displacement increases in approximate proportion to the DSA and approaches about 90% of the theoretical value. When γ is 0.6~0.85 the measurement error becomes within 10%, and for γ more than 0.85, the error is reduced to within 1%.

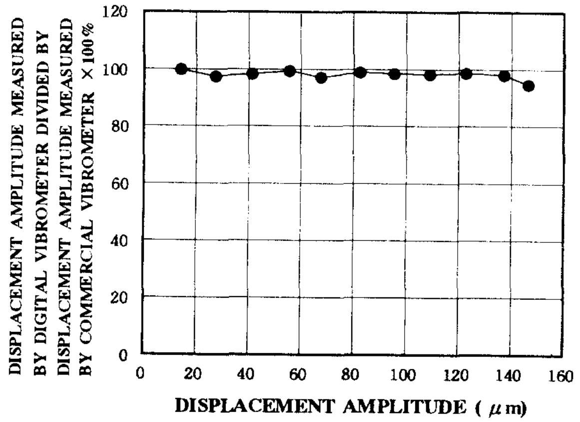

Fig. 7 Displacement amplitude measured by the digital vibrometer is compared with that measured by a commercially available vibrometer.

Figure 7 shows measurement accuracy of the proposed digital vibrometer. The vertical axis is a displacement amplitude measured by the digital vibrometer which is divided by that measured by a commercially available vibrometer. The vibrating target is driven by a sinusoidal voltage of 200Hz, and λ=0.782nm, γ=0.89. The measurement accuracy of the displacement amplitude was within -3% and average error -1.3% when the displacement amplitude was adjusted in a range of 15μm~140μm.

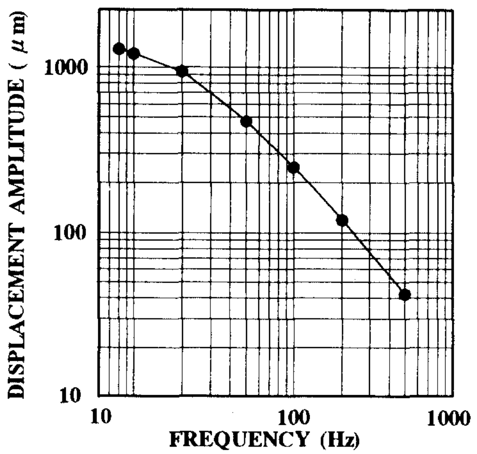

Fig. 8 Upper limit of displacement amplitude versus vibration frequency, which is measurable by the digital vibrometer.

Frequency characteristics of an upper limit of a displacement amplitude is shown in Fig. 8 . The upper limit of a measurable displacement amplitude was 1200μm at 10Hz, and 250μm at 100Hz, and the lower limit was about 4mm.

5. CONCLUSION

It is confirmed by experiments that the measured performance limit of digital vibrometer using self-mixing type LDV agrees well with the theoretical value. The measurable velocity range is 6-7mm/s through 162-8mm/s, which corresponds to the Doppler frequency of 17.4kHz through 417kHz.

The measurement accuracy of the displacement amplitude was within -3% and average error -1.3%, when the shape of the sawtooth is clear and sharp. The degradation of the measurement accuracy is also shown due to a degradation of the sharpness of the sawtooth, which is represented by a degree of sawtooth asymmetry (DSA).

Those measured performance show that the prototype digital vibrometer can be further improved for practical application.

REFERENCE

[1] S. Shinohara et al., "Laser Doppler Velocimeter Using the Self-Mixing Effect of a Semiconductor Laser Diode", Applied Optics, vol. 25, no. 9, pp. 1417-1419, 1986.

[2] S. Shinohara, H. Naito, H. Yoshida, H. Ikeda and M.Sumi, "Compact and Versatile Self-Mixing Type Semiconductor Laser Doppler Velocimeter with Direction Discrimination Circuit", IEEE Trans. on Inst. and Meas., vol. 38, no. 2, pp. 574-577, Apr. 1989.

[3] S. Shinohara, M. Toyoshima, H. Yoshida, T. Sawaki, H. Ikeda and M. Sumi, "Novel Method of Digital Displacement for Vibrating Object Using Self-Mixing Type LDV", Proc. of SICE'93, pp. 1021-1024, 1993.

[4] M. Toyoshima et al., "New Digital Displacement Measuring Circuit for Aperiodic Vibration Using Self-Mixing Type LDV", Conference Record of IEEE Instrumentation and Measurement Technology Conference, vol. 1, pp. 336-339, May, 1994.