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VELOCITY AND ITS DIRECTION MEASUREMENT OF SCATTERER WITH DIFFERENT VELOCITIES USING SELF-MIXING SEMICONDUCTOR LDV

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ABSTRACT

The self-mixing type semiconductor laser Doppler velocimeter (SM-LDV) is applied to measure two simultaneously moving targets with different velocities in the same direction as a prototype target for multiscatterers. The measured beat waveform is found to be a composite wave of each beat waveform measured from each of only moving target.

In the composite waveform, each one-cycle wave has a feature of the sawtooth wave. This fact shows a possibility to discriminate the flow direction of fluid containing multiscatterers with distributed velocities by cooperating an improved version of the direction discrimination circuit already devised by the authors.

1. INTRODUCTION

When measuring turbulent flow or fluid flow containing multiscatterers with time-varying flow direction, it is necessary to measure not only velocity distribution but flow direction. Kajiya et al. demonstrated a new laser Doppler velocimeter (LDV) with an optical fiber to measure blood flow velocity profiles in coronary arteries.(1) Although Doppler shift frequency spectra corresponding to velocity distribution are successfully observed by a spectral analyzer, the LDV system is not compact because it requires an optical frequency shifter and some other optics.

On the other hand, Shinohara et al. proposed the compact self-mixing type semiconductor laser Doppler velocimeter (SM-LDV), which can discriminate the velocity direction without using the frequency bias.(2) The velocity discrimination was performed using the direction-discrimination circuit (DDC), which processes the sawtooth-like beat waveform obtained from a photodiode (PD) packaged in a laser diode (LD). The DDC produces a high or low dc voltage according to the velocity direction.

In this paper, a feature of a composite beat waveform to be produced in a laser diode by two targets moving with different velocities in the same direction is investigated theoretically and experimentally. The obtained results show that each one-cycle wave in the composite beat waveform has a feature of the sawtooth wave. Therefore, if we devise an improved direction discrimination circuit it will be possible to discriminate the flow direction of fluid with distributed velocities.

2. THEORY

According to the theoretical analysis of the Doppler beat waveform produced in a self-mixing type laser diode (LD)(3), the normalized beat signal Z(t) obtained from a PD packaged in the LD becomes sawtooth-like, and given by

$$Z(t)=Z_{01}+\sum_{k=1}^{5} Z_{k1}\sin(k\,\Omega_D t+\theta_{k1}) \quad (1)$$

where Z_{k1} is the normalized amplitude of the k-th harmonics, z_{01} the dc component nearly equal to 1, Ω_D the Doppler angular frequency and θ_{k1} the phase angle of the k-th harmonics. We assume that the beat wave obtained from two moving targets is a composite of each beat wave obtained from each only moving target with a definite velocity. The amplitudes of the two component beats are set equal, and the amplitudes of the 2nd, 3rd, 4th and 5th harmonics are set 1/4, 1/8, 1/16 and 1/32 times the fundamental amplitude, respectively. The phase angles θ_{k1} for all k's are set zero for an approaching target ($\Omega_D>0$), while π radians for a departing target ($\Omega_D<0$).

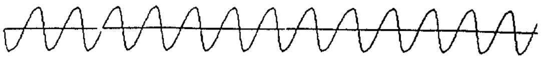
The simulation results of the beat waveforms are shown in Fig.1. The beat waveforms (A) and (B) correspond to each target departing from an LD, resulting each Doppler frequency shift of f_{d1}=-4.5kHz and f_{d2}=-13.1kHz, respectively. The lower beat waveform (C) represents the composite wave of both (A) and (B). Each one-cycle wave in the composite wave has a feature of the sawtooth wave.

When the Doppler frequency difference is relatively small, the theoretically synthesized beat waveforms became as shown in Fig.2 and Fig.3. The feature of the sawtooth wave holds in the case of small Doppler frequency difference such as 5% - 20%.

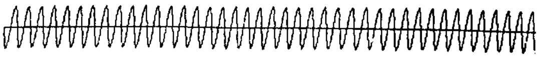
3. MEASUREMENT PRINCIPLE

The velocity direction of the moving targets can be discriminated using the direction discrimination circuit (DDC) shown in Fig.4. The DDC gives a high or low dc voltage in accordance with the velocity direction.

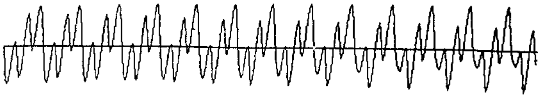
The measurement principle of the velocity direction is described making reference to the theoretical waveforms of the signals at the respective check points of the DDC. Figure 5 shows the theoretical waveforms in the case of



(A) Beat waveform, f_{d1}=-4.5kHz.

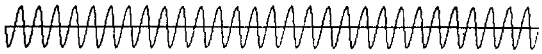


(B) Beat waveform, f_{d2}=-13.1kHz.

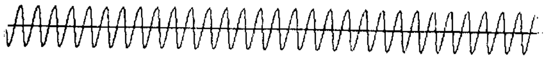


(C) Composite wave of (A) and (B).

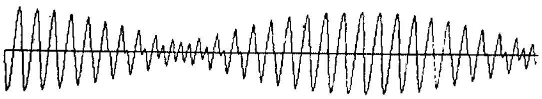
Fig.1 Simulated results for the beat waveforms. (A) for a departing target 1 resulting Doppler frequency shift f_{d1}=-4.5kHz, (B) for another target 2 resulting f_{d2}=-13.1kHz, and (C) for the both targets departing simultaneously.



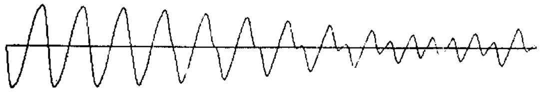
(A) Beat waveform, f_{d1}=-10kHz.



(B) Beat waveform, f_{d2}=-10.5kHz.

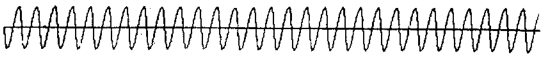


(C) Composite wave of (A) and (B).

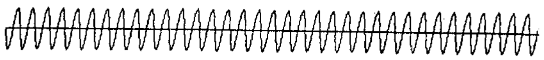


(D) Waveform (C) with its time axis expanded into 2.4 times.

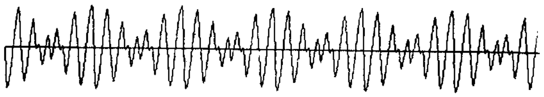
Fig.2 Theoretically synthesized beat waveforms (C) and its time-axis expanded one (D). The difference of Doppler frequencies of the two component beats is 5%.



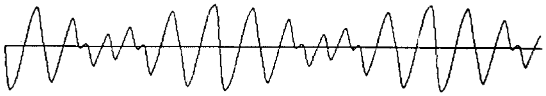
(A) Beat waveform, f_{d1}=-10kHz.



(B) Beat waveform, f_{d2}=-12kHz.



(C) Composite wave of (A) and (B).



(D) Waveform (C) with its time axis expanded into 2.4 times.

Fig.3 Theoretically synthesized beat waveforms (C) and its time-axis expanded one (D). The difference of Doppler frequencies of the two component beats is 20%.

one target departing from an LD at a constant speed.

The beat signal obtained from the PD is fed, through an amplifier, to a differentiator having a time constant of $1/6|f_d|$ for the beat signals at frequencies less than $|f_d|$. The differentiator output (2) branches into two paths: one is directly fed to the positive-slope-sense comparator, and the other through an inverter to the negative-slope-sense comparator. Both comparator outputs (3) and (6) are, respectively, fed through the corresponding low pass filter (LPF), each having a cutoff frequency of 10Hz, to the noninverted and inverted input terminals of the direction-sense comparator. The LPF output (4) is higher than the LPF output (7), because the pulse width of the comparator output (3) is wider than that of the comparator output (6) due to the slow rise and the quick fall of the beat signal (1). The final output level (8) is high (H) for the departing target ($f_d<0$), and low (L) for the approaching target ($f_d>0$). Therefore, a light emitting diode (LED) is turned on indicating that the target is departing as in the case of Fig.5. While the LED is turned off when the target is approaching.

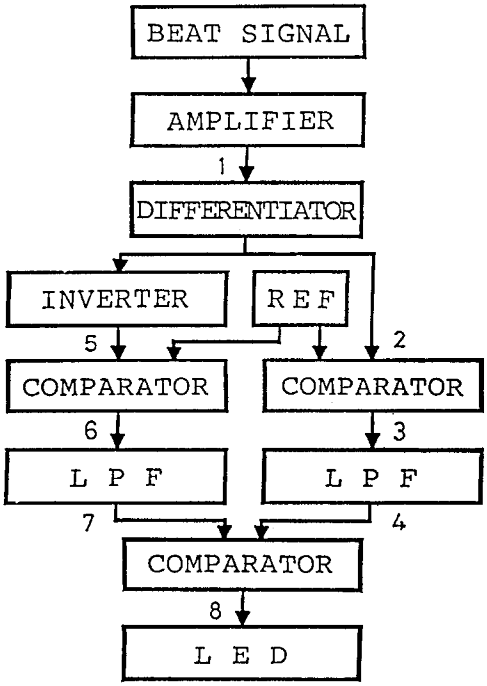


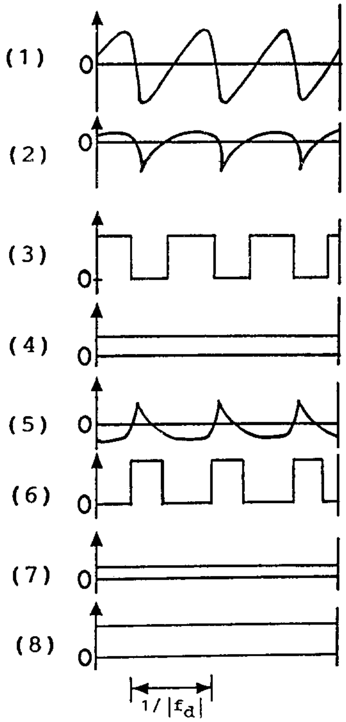
Fig.4 Block diagram of the direction discrimination circuit (DDC).

In the case of two moving targets, the composite beat signal has a feature of the saw-tooth wave in each one-cycle wave as shown in Figures 1 through 3, despite the change of both amplitude and periodicity. Therefore, the DDC with a slight modification will discriminate the velocity direction.

4. EXPERIMENT

Figure 6 shows schematic configuration of an experimental setup of a self-mixing type laser Doppler velocimeter (SM-LDV). Targets 1 and 2 made of plastics plate are carried on each separate X-Y recorder. The both targets can move along the same straight line with different velocities.

The emitted light from an LD is focussed by a selfoc microlens (SML) and illuminates the



Output (8) is L level for $f_d>0$, and H level for $f_d<0$.

Fig.5 Theoretical waveform of the signals at the respective check points in the DDC shown in Fig.4, in the case of one target departing from a laser diode at a constant speed.

target 2 departing at a definite velocity V_2. A part of the light is reflected from the target 2 back to the LD, and the transmitted light illuminates the target 1 covered with an aluminium foil, departing at a velocity V_1. A part of the reflected light from the target 1 also returns to the LD. The both returned lights with different Doppler frequency shifts are mixed with the original light in the LD to produce a beat signal, which is detected by a pin photodiode packaged in the LD.

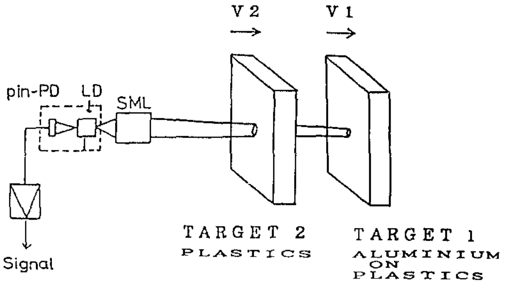


Fig.6 Schematic configuration of an experimental setup of a self-mixing type laser Doppler velocimeter (LDV).

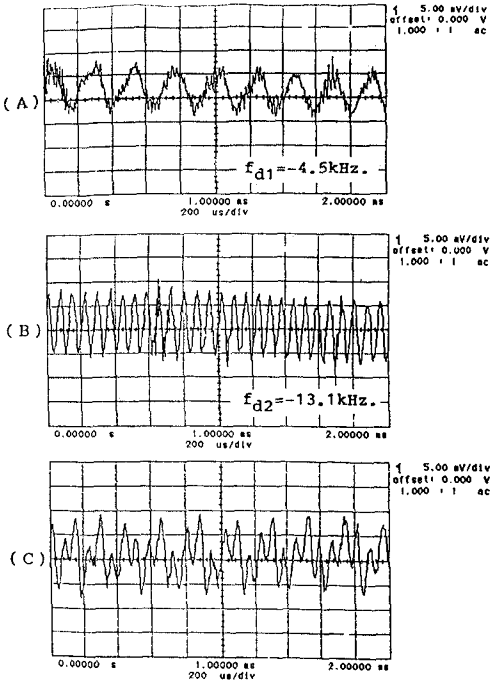


Fig.7 Experimental results of the beat waveforms obtained by the SM-LDV system when targets 1 and 2 are departing. (A) for an only moving target 1 at 2mm/s, (B) for an only moving target 2 at 5mm/s, and (C) for the simultaneously moving targets 1 and 2 at 2mm/s and 5mm/s, respectively.

5. EXPERIMENTAL RESULTS

Figure 7 shows the experimental results of the beat waveform obtained by the SM-LDV system. Figure 7 (A) and (B) are the beat waveforms obtained from an only moving target 1 or 2, respectively, when the other target keeps still. The velocity of the target 1 and 2 is kept constant at 2mm/s and 5mm/s, which approximately coincides with the measured Doppler shift frequency f_{d1}= -4.5kHz and f_{d2}=-13.1 kHz, respectively. Both the beat waveforms of (A) and (B) have the feature of a sawtooth wave, i.e., the slow rise and the quick fall in case of departing.

Figure 7 (C) shows the beat waveform obtained from the simultaneously moving targets 1 and 2 with the each preset velocity. The waveform of Fig.7 (C) is very similar to the simulated waveform shown in Fig.1 (C). Consequently, the assumption proved to be valid, i.e., the linear superposition of each beat waveform ob-

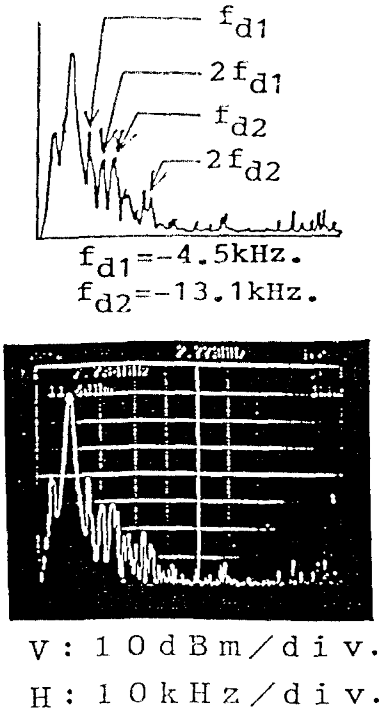


Fig.8 Frequency spectrum of the beat waveform shown in Fig.7 (C).

tained from each target can be applicable to express the beat waveform obtained from the both targets. In the measured beat waveform (C), each one-cycle wave has the feature of the sawtooth. Therefore, it will be possible to discriminate the flow direction of fluid with distributed velocities by improving the direction discrimination circuit shown in Fig.4.

Figure 8 shows the frequency spectrum of the beat waveform shown in Fig.7 (C). The fundamental frequencies f_{d1} and f_{d2}, as well as its second harmonics are clearly seen.

6. CONCLUSION

The self-mixing type semiconductor laser Doppler velocimeter (SM-LDV) is applied to measure two simultaneously moving targets with different velocities in the same direction. The beat waveform produced in the laser diode (LD) has been investigated theoretically and experimentally.

The beat waveform measured from the both moving targets are found to be a composite wave of each beat waveform measured from each only moving target. The fact agrees with the theoretically simulated results. In the measured composite beat waveform, each one-cycle wave has a feature of the sawtooth wave. Therefore, it will be possible to discriminate the flow direction of fluid with distributed velocities by improving the direction discrimination circuit already devised by the authors.

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