On the Mechanism of Generation of Detected Sound in Ultrasonic Flow Meter

By

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Synopsis

In the equipment to inspect a state of blood flow in blood vessel by means of ultrasonic waves, which was invented by the late Prof. Satomura, it was explained by the inventor that the output voltage of the equipment was caused by reflection of ultrasonic waves occurring in liquid being in a state of turbulent flow. But from the point of view of speed of blood flow in blood vessel, it must be considered that the output voltages are produced by another origin than the turbulent flow. In this paper, it was confirmed that the origin of the output is blood corpuscles and not its turbulent flow.

Introduction

The late Professor Satomura discovered a phenomenon, that is, we radiate ultrasonic waves to a blood vessel and detect the combined waves of the incident and reflected ones, we get a noisy output (hereafter we denote it as detected sound) synchronized with the pulsation of heart.

Applying this phenomenon, he succeeded in observing states of the flowing blood in vessels without seeing blood itself. As the mechanism of generation of the detected sound is not yet clear, it is necessary to elucidate the phenomenon in order not only to evaluate the experimental results properly but also to improve the equipment. Professor Satomura presumed the phenomenon followingly; in a state of turbulent flow, there are many portions with different speed of flow, consequently the reflected waves from the layers among different speeds are suffered from frequency modulation by Doppler Effect, so the detected sound can be obtained by beat occuring between the incident and reflected waves. He confirmed experimentarily that the detected sounds are produced in water which is in a state of turbulent flow. From this experiment, he inferred that the blood flow in blood vessel is in a state of turbulent flow. Blood flow in blood vessels, however, has been considered as being in a stste of laminar flow. Since the detected sound can be heard even at the fine blood vessels of the top of fingers, the flow velocity in the fine blood vessels such as the one at the

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top of fingers must be very high, supposed the detected sound be generated only in turbulent flow. For example, if we assume that the diameter of the blood vessel at the top of a finger is 50×10^{-3}mm and the turbulent flow occurs beyond 2000 of Raynold's number, the flow velocity must be more than 70 meters per second (in this calculation, coefficient of blood viscousity is assumed to be the same as water, i.e. 0.018 poises). Contrary to the above calculation, observed speed is several centimeters per second at the most. Therefore, it must be considered that the detected sounds are produced by another origin than the turbulent flow. In this paper, expreimental and theoretical confirmation of an idea, assumed by the authours, that the origin of the detected sounds is blood corpuscles rather than its turbulent flow, is presented.

Outline of Experimental Equipment

The block diagram of the experimental equipment is as shown in Fig. 1. The energy supplied by the high frequency oscillator is conducted to a sending barium titanate transducer T. The reflected wave is received by a receiving transducer R and is conducted to the demodulator together with part of the direct wave. The high

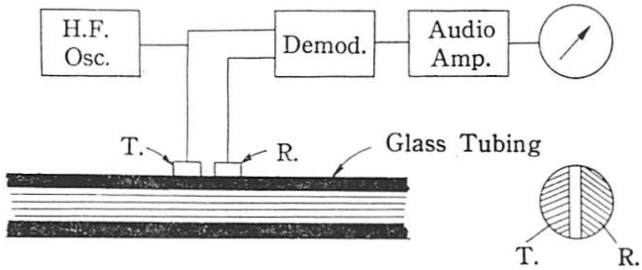

Fig. 1. Block Diagram of the Equipment.
T—Sending Transducer,
R—Receiving Transducer.

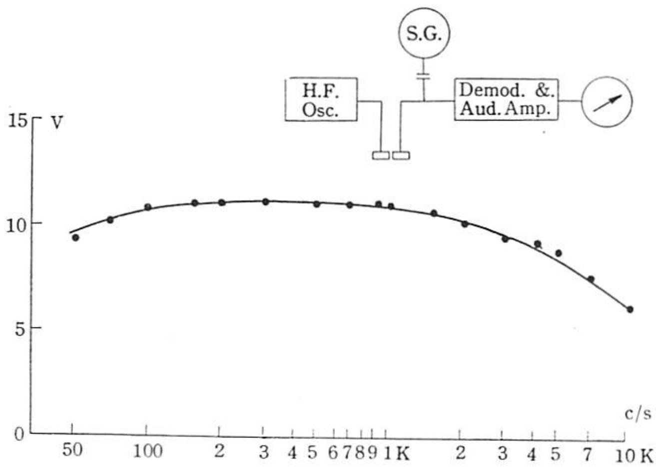

Fig. 2. Overall Frequency Characteristics.

frequency oscillator has a power of 1∼2 watts and operates at 5 Mc. The amplification of audio amplifier is about 80 db. The overall frequency characteristics is nearly flat from 50 to 2000 cps as shown in Fig. 2.

Experiments

a) Relations between frequencies of the detected sound and the speed of flow

Experiments were carried out using the equipment shown in Fig. 1 in which a glass tubing with outer diameter of 6 mm and inner one of 3.9 mm was used. An aqueous solution of commercially available wheat starch paste is made to resemble blood in having many particles in it and used instead of blood. The starch solution was used throughout the experiments except the last one in which the blood of cow was used and was confirmed to produce the same results as those by the starch solution. The water used in these experiments must be very clean and degassed, so that dusts or gass bubbles in water do not become sources of the detected sounds. The detected sound is a kind of noise like hiss sound. The frequency distribution, shown in Fig. 3, of the detected sound was obtained by passing the starch solution through the glass

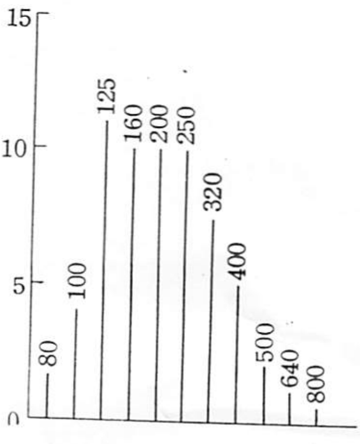

Fig. 3. Frequency Distribution of the Detected Sound

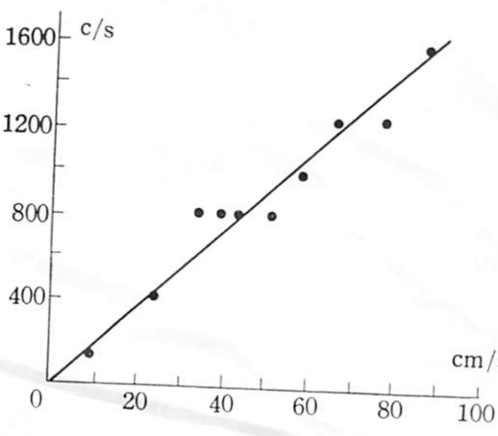

Fig. 4. Relation between Frequency and Flow Speed.

tubing with a speed of 9.3 cm/s. The lengths of vertical lines indicate output voltages of successive filters with a band width of 1/3 octave and the figures noted on the vertical lines show center frequencies of respective filter. Since the frequencies of the detected sound distribute over a wide range of frequency, we regard the frequency with maximam output as a representative frequency of the detected sound. Fig. 4 indicates the relationship between flow speed and representative frequency of the detected sound measured as above mentioned. This figure shows that frequencies of the detected sounds are proportional to flow speed.

b) Relations between outputs of the detected sound and speed of flow

Fig. 5 shows a dependence of output voltage of the detected sound on the speed of the solution, in which the density of starch particles was taken as parameter.

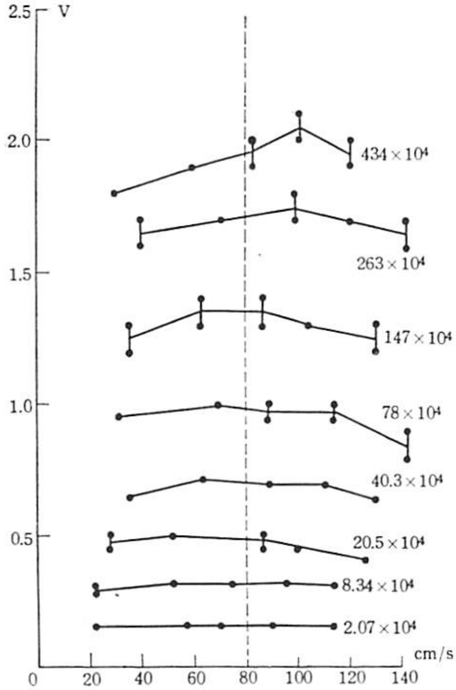

Fig. 5. Relation between Output Voltage and Flow Speed. Parameter indicates Number of Starch Particles in 1 cc.

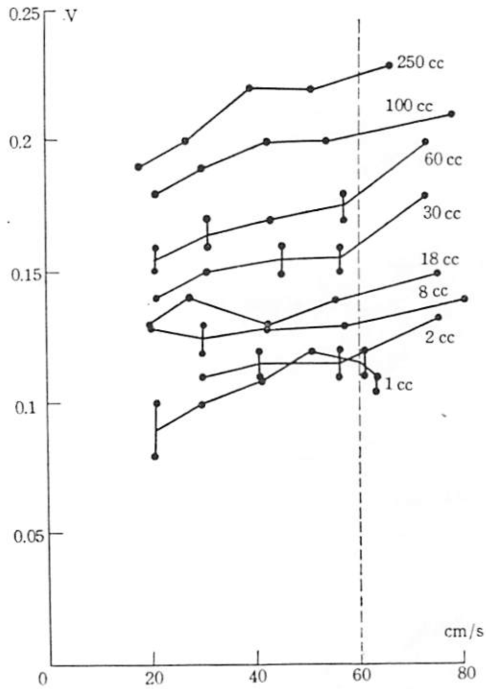

Fig. 6. Relation between Output Voltage and Flow Speed. (Blood of Cow)

Ordinate and abscissa indicate output voltage and flow speed respectively. From the figures it can be found that output voltages are constant and almost independent of flow speed. Experimental results shown in Fig. 6 were obtained using blood of cow. Figures adherent to the curves indicate concentrations of blood in physiological saline solution. For example, 100 or 30 means that 100 or 30 cc of blood is diluted with a fixed amount, 600 cc, of saline. In the case of blood, experimental results are not so accurate as the one by starch solution, since the output voltage is very low compaired with the latter case. Still the output voltage is essencially constant and independent of flow speed.

c) Relations between outputs and number of particles

From the above experiments, it was found that the output voltages increase with the number of particles or blood corpuscles. From Fig. 5 output voltages at certain speed versus square root of the number of particles were plotted and a straight line was obtained as shown in fig. 7. Fig. 8 was drawn from Fig. 6 in similar way to Fig. 7 and was found to be straight too. From these facts, it was confirmed that the outputs of the de-

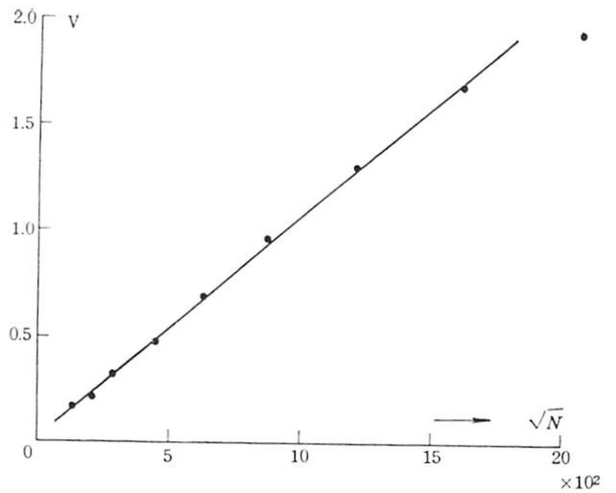

Fig. 7. Relation between Output Voltage and Number of Particles. (Starch Solution)

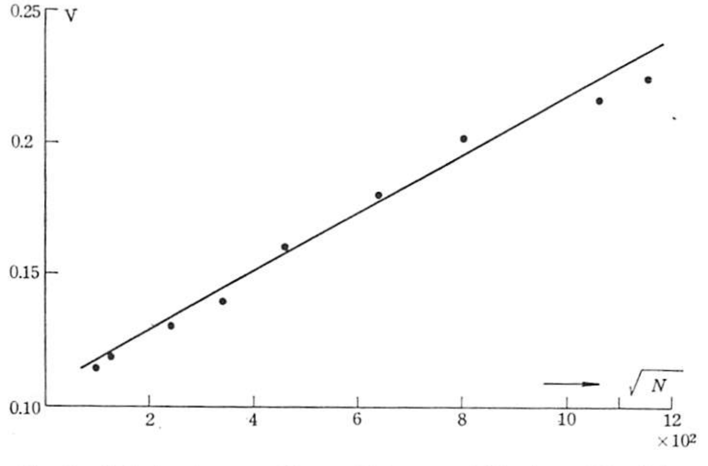

Fig. 8. Relation between Output Voltage and Number of Particles. (Blood of Cow)

tected sounds are proportional to the square root of the number of particles in solution.

Theoretical Considerations

Now we assume that the detected sound is caused by the reflected waves from particles contained in a solution flowing in a pipe.

The power of reflected waves from one particle is $(\gamma p)^2/\varrho c$, provided the length of pipe radiated with ultrasonic waves be l, the sound pressure in the part l be constant P, and the other notations are defined as follows;

γ .... coefficient of reflection of a particle,
n .... number of particles in cubic cm,
s .... internal area of cross section of pipe,
v .... speed of flow,
ϱc .... specific acoustic impeeance of the liquid.

The energy reflected by one particle in an interval of passing through l is $\frac{(\gamma p)^2}{\varrho c}\frac{l}{v}$ and the power of reflected waves (W) is as follows, since the total number of particles passing through in unit of time is nsv.

$$W = snv\frac{(\gamma p)^2}{\varrho c}\frac{l}{v} = snl\frac{(\gamma p)^2}{\varrho c}.$$

If a reflected sound pressure and power of i'th frequency are denoted to be P_i and W_i respectively from the reason that the frequencies of reflected waves extend over a wide range. We get a formula, that is,

$$W = \sum_i W_i = \frac{1}{\varrho c}\sum_i P_i^2.$$

An induced voltage (V_i) at the receiving transducer by sound pressure (P_i) can be expressed as follows,

$$V_i = kP_i$$

where k is constant.
From the above relations a formula can be obtained as follows;

$$W = \frac{1}{\varrho c}\frac{1}{k^2}\sum_i V_i^2.$$

As the effective value of total induced voltage V is $(\sum V_i^2)^{\frac{1}{2}}$, then a formula advanced as follows;

$$V = k^2\gamma P\sqrt{snl}.$$

This formula indicates that the output voltage is independent of flow speed and proportional to square root of the number of particles contained in unit volume. These facts agree perfectly with the above described experimental results.

Conclusion

It is clear from these demonstrations both by experiments and theoretical considerations that the detected sound caught by an ultrasonic flow meter is produced by reflected waves, having been subjected to frequency change due to Doppler Effect, from moving particles.

In the above considerations, for the sake of simplisity, we assumed that the sound pressure is constant over a length l of pipe, though actually it is not constant but rather complex, because the sound field is very close to the sound source. If particles pass through such complex field, reflected waves get modulation not only in frequency but in amplitude. This phenomenon can be also an origin of the detected sounds. In any case, the detected sounds obtained by ultrasonic flow meter is attributed to reflection of sound wave by corpuscles in blood.

References

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2) S. Satomura, Z. Kaneko, *Proceedings of Third International Conference on Medical Electroncs, London*, 1960