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Measurement of Pipe Flow with Cross-Sectional Speed Distribution using an Orthogonally Radiated Ultrasonic Beam
直交入射超音波ビームを用いる断面流速分布をもつ管流計測

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1. Introduction

A detection method of flowing object speed using a transverse ultrasonic beam based on the spectrum bandwidth expansion has been suggested and studied[1-4]. It has been indicated that the method can be applied to a pipe flow speed measurement by proving effectiveness of the method for variation of location of particle paths in a pipe assuming all particles move with an uniform speed[4]. This paper suggests a method of pipe flow rate measurement using an ultrasonic beam radiated orthogonally to the flow direction even when there is a cross-sectional flow speed distribution. The results of numerical simulations for several different flow distribution models show possibilities that the maximum local flow speed is measurable with the spectrum bandwidth and a relative flow rate can be estimated by the spectrum profile analysis.

2. Pipe flow with speed distribution

With a geometry shown in **Fig. 1**, an ultrasonic beam is assumed to be radiated by a circular planar transducer and plural particles which scatter the ultrasonic wave are passing across the beam along with the line parallel to x axis with speed v. Locations of the particle paths have variations in terms of offsets in y and z axes from y=0 and z=z_p, respectively with a finite amount.

Here we consider the case that the fluid flow has a flow speed distribution in a cross section of the pipe to investigate the influence of the distribution to the spectrum of the detected signal. We made the simulation model of the different speed distribution patterns assuming that the flow speed in a pipe is distributed radially as shown in **Fig. 2**. The horizontal axis represents the location in the pipe as radial distance from the center of the pipe and the veritical axis represents the local flow speed. The flow distribution pattern models introduced here are designed to contain the same maximum flow speed while the distribution patterns that determine the rate of lower local flow speed occurence are changed. Thus, the different distribution patterns are supposed to have different total volumetric flow rate.

We run numerical simulations of the detected signal while removing carrier frequency, as simulating a synchronous detection, for each pattern based on eq. (1).

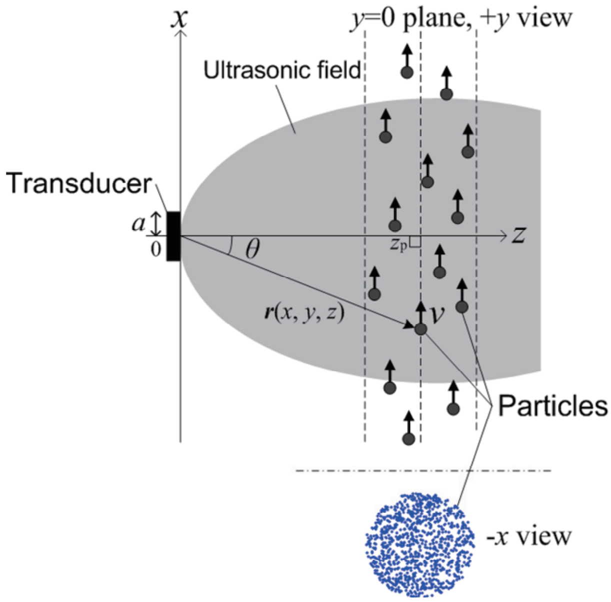

Fig. 1 Schematic diagram of the measurement setup

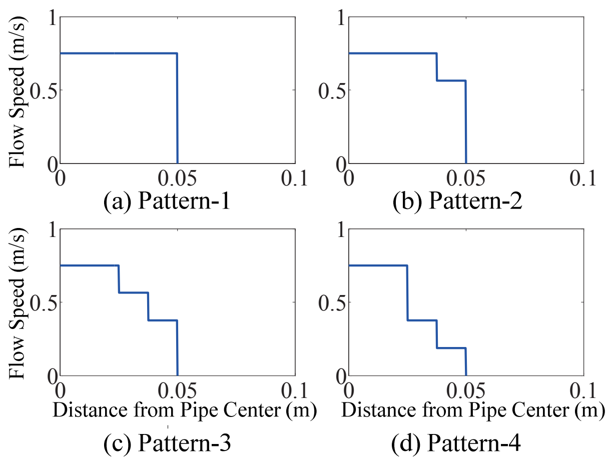

Fig. 2 Created simulation model patterns of the cross-sectional flow speed distribution. Horizontal axis represents Distance from center (m) and Vertical axis represents Flow speed (m/s).

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$$e_s(\boldsymbol{r},t) = A \cdot \left(\frac{D(\theta)}{2\pi r}\right)^2 \cdot \exp\left\{ j2\pi f_0 \left(-\frac{2r}{c} - \varphi \right) \right\}, \qquad (1)$$

where $e_s(\boldsymbol{r}, t)$ is the detected signal, $\boldsymbol{r}$ is vector of a particle location referring the center of transducer, r is magnitude of $\boldsymbol{r}$, f_0 and φ are frequency and arbitrary phase of the transducer vibration, respectively, c is sound velocity and A is an arbitrary amplitude coefficient. $D(\theta)$ represents the ultrasonic beam directivity function of a circular planer piston described as

$$D(\theta) = \frac{2 \cdot J_1(ka \cdot \sin\theta)}{ka \cdot \sin\theta}, \qquad (2)$$

where k is wavenumber, a is radius of circular transducer, and J_1 is Bessel function of the first kind. The following parameter values are used in the simulation; c: 1500 m/s, f_0: 2 MHz, $2a/\lambda$: 1, y: ±50 mm, z_p: 75 mm, z: z_p±50 mm.

Fig. 3 shows the normalized amplitude spectra of the simulated signals. It is observed that the bandwidth that is defined with width between the spectrum zero drops is consistent while the maximum local flow speed is constant regardless the distribution pattern. It is also found that the amplitude spectrum profiles depend on the flow distribution patterns. The relative amplitude of the slope in the spectrum becomes low as the fraction of low-velocity particle increases. It is supposed that the Doppler effect occurs on a particle that flows with the maximum speed determines the bottom width of the slope and that occurs on a relatively low speed particle contributes to the amplitude around the center frequencies of the profile. Thus, the spectrum profile may characterize the flow speed distribution. **Fig. 4** shows the relationship between the total flow rate and the integration of the normalized amplitude spectra calculated for each simulation model. A marked linear correlation is observed. It implies that the volumetric flow rate may be estimated by analyzing the detected signal spectrum profile even there is a flow speed distribution in the pipe cross section in conjunction with the detection of the maximum flow speed using the spectrum bandwidth.

3. Conclusions

Considered a geometry with a flow in a pipe containing particles that scatter ultrasonic wave is flowing perpendicular to an ultrasonic beam radiated with a circular planar transducer. We run numerical simulations of the scattered waves received with the transducer in case there is a distribution of the local flow speed in terms of the pipe cross section. It was found that the bandwidth of the amplitude spectrum of the detected signal was determined by the maximum flow speed and the spectrum profile varied depending on the flow speed distribution. Besides, a remarkable correlation between the total flow rate and the integration of the normalized spectrum was observed. These results imply a pipe flow rate measurement using a transverse ultrasonic beam radiated by a simple transducer even if the flow has a cross-sectional distribution. It may be achieved by a combination of the maximum flow speed detection with the spectrum bandwidth and the relative flow rate estimation with the spectrum profile.

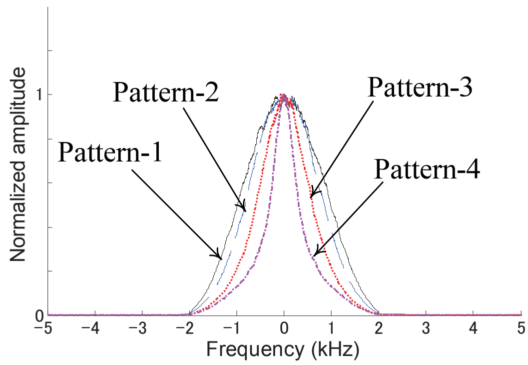

Fig. 3 Normalized amplitude spectra for different flow speed distribution patterns

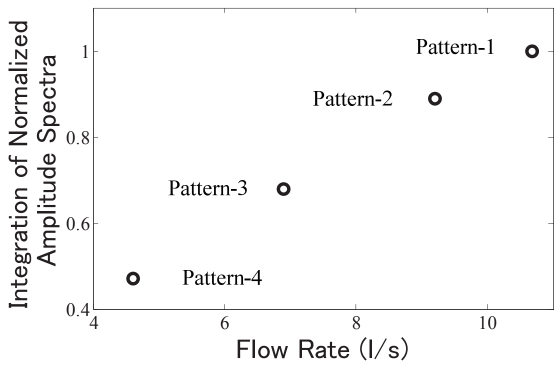

Fig. 4 Correlation between pipe flow rate and integration of the normalized amplitude spectra

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