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Transverse Velocity Measurement of Particle Flow Passing across an Ultrasonic Beam

超音波ビームを通過する粒子流の横方向流速測定

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1. Introduction

A method to measure the transverse velocity of particle flow passing across the ultrasonic beam is discussed. Despite the fact that Doppler effect is known to occur only on the velocity components parallel to the wave propagation, Doppler-spectra has been suggested as a method to measure the transverse velocity of an object moving across the ultrasonic field using the spectrum bandwidth[1]. We have validated the method using a planer transducer assuming a single moving object[2,3]. Here we attempt to validate it for the case multiple objects flowing continuously to expand the applications of the method to the flowmetries such as blood or pipelines. We run the numerical simulations of the ultrasonic wave scattered by particle(s) and received at the transducer when particle(s) flow perpendicular to the axis of the circular planer transducer which is creating an ultrasonic beam.

2. Numerical simulations and discussions

Assume a circular planer transducer is generating an ultrasonic beam with the geometry shown in **Fig. 1** and particles which scatter the ultrasonic wave are passing across the beam along with the line parallel to x axis and perpendicular to z axis with velocity $\boldsymbol{v}$. If a particle scatters the wave when it is at the position $\boldsymbol{r}(x, 0, zp)$, the output signal of the transducer which has received the scattered wave $e(\boldsymbol{r},t)$ is given by

$$e(\boldsymbol{r},t) = A \cdot \left(\frac{D(\theta)}{2\pi r}\right)^2 \cdot s\left(t - \frac{2r}{c}\right), \tag{1}$$

where c is speed of sound and $D(\theta)$ represents the ultrasonic beam directionality function of a circular planer piston described as

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

where k is wavenumber, a is radius of circular transducer and J_1 is Bessel function of order one. And the transducer vibrates with velocity $s(t)$.

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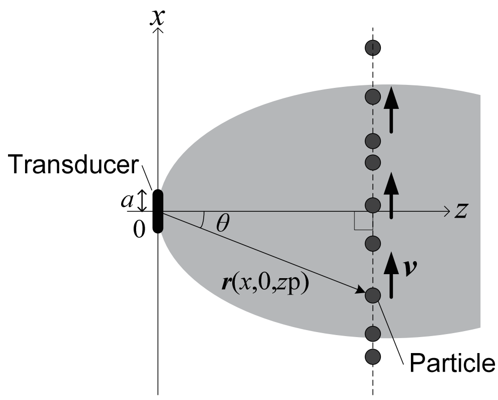

Fig. 1 Geometry of the problem

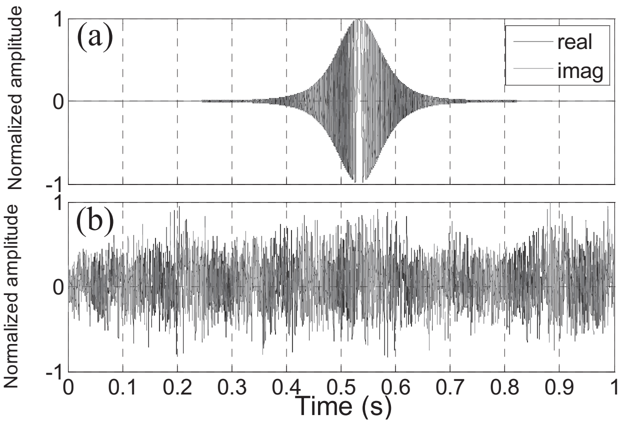

Fig. 2 Calculated signal for synchronous detection of scattered waves from particles passing across ultrasonic beam.
(a) Single particle case (b) Multiple particle case.

When $s(t)$ is

$$s(t) = A \cdot \exp\{j2\pi f_0 (t - \varphi)\}, \tag{3}$$

the signal detected with removing carrier frequency, i.e. that simulates the synchronous detection, $e_s(\boldsymbol{r}, t)$ is derived as

$$e_s(\boldsymbol{r},t) = A \cdot \left(\frac{D(\theta)}{2\pi r}\right)^2 \cdot \exp\left\{j2\pi f_0 \left(-\frac{2r}{c} - \varphi\right)\right\}. \tag{4}$$

Examples of the calculated signal are plotted in time domain in **Fig. 2** with the parameters listed as

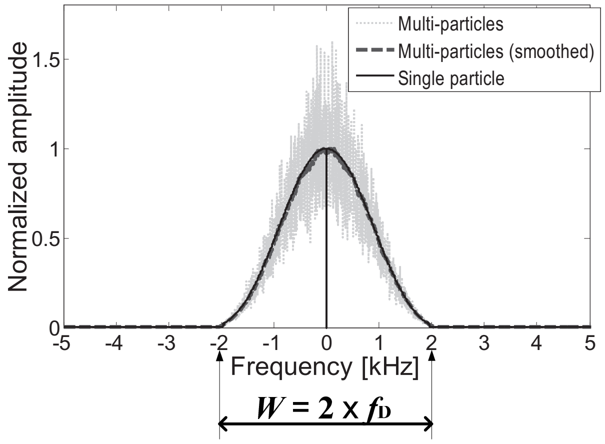

Fig. 3 Comparison of amplitude spectra for a single particle, multiple particles after averaging in frequency domain by 10 runs and smoothed profile of multiple particles.

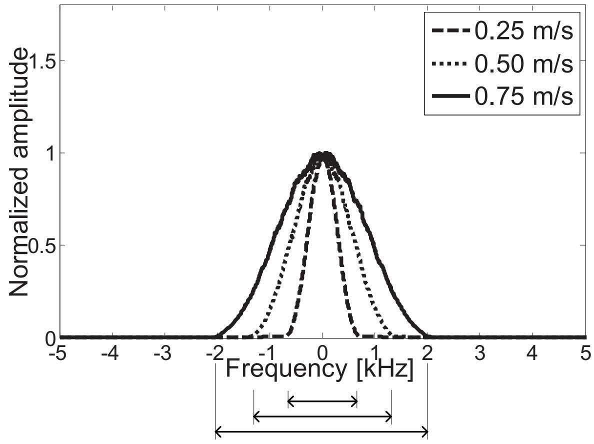

Fig. 4 Amplitude spectra after averaging by 10 and smoothing for multi-particle flows with different velocities 0.25, 0.50 and 0.75 m/s. Bandwidth varies depending on the velocity.

following;
c: 1500 m/s, f_0: 2 MHz, zp: 75 mm, $2a/\lambda$: 1, v: 0.75 m/s. The top of Fig. 2 shows the signal in case a single particle is passing by and the bottom shows that in case multiple particles are continuously flowing along the line with the constant velocity but in random timing of those appearance. Note that here in case of multiple particles, the signal is assumed to be a superposition of the waves scattered by each particles and no multiple scattering effect is considered. **Fig. 3** shows the amplitude spectra of the signals introduced in Fig.2. We observe that those spectra have the finite bandwidth. The spectrum of the multiple particles looks more noisy, however, if it's smoothed with the moving averaging, the profile overlaps with the one of the single paricle. Then, it is found that the bandwidth, particularly the width between zero drops, agrees to the amount of Dopper shift, which would be occurring due to the velocity of moving scatterers. The Dopper shift f_D is given by

$$f_D = f_0 \cdot \left(\frac{c+v}{c-v} - 1 \right). \quad (5)$$

For the case of the simulation described above, the Doppler shift f_D is 2001 Hz. This may be explained as following. When a scatterer is passing across perpendicular to the transducer axis, if the ultrasonic field does not consist of a perfect plane wave, thus contains angled wave components, e.g. due to radiation, Doppler shift occurs on those wave components and the acquired spectrum includes the superposition of all components of the signal to come up with the bandwidth. Among different wave angles, the wave component which is parallel to the scatterer velocity is supposed to generate the largest Doppler shift, in whichever directions, and determine the width between zero drops.

Fig. 4 shows the result of calculations for the different velocity of the multi-particle flows. It is remarkable that the spectra bandwidth vary propotionally to the flow velocity.

3. Conclusions

We run the numerical simulations of the ultrasonic wave scattered by particle(s) and received at the transducer when particle(s) flow perpendicular to the axis of the circular planer transducer which is creating an ultrasonic beam. It was observed that the spectrum bandwidth of the signal was consistent between the cases of a single particle and multiple particles. Besides those bandwidth agreed to the Dopper shift occurring due to components of the velocity of the scatterer, thus the bandwidth varies depending on the velocity. This study implies that the method is feasible for the transverse velocity measurement of a continuous particle flow.

References

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