Velocity Vector Profile Measurement using Multiple Ultrasound Transducers

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Unit of Vector-UVP system, which is an advanced UVP system to measure three directional velocity components on a line by using multiple transducers, was developed. Obtaining information of acoustic field is very important for optimizing Vector-UVP system. We attempted to study it experimentally but found that it is time consuming to measure acoustic field by scanning a hydrophone. Moreover, the measurement result could involve some problems like space resolution and a problem of echo from any surrounding experimental apparatuses. To obtain more accurate data effectively and estimate the influence of existence of a wall, acoustic field under the developed system was calculated by solving two-dimensional wave equation and then the measurement volume and measurement area were estimated to optimize the system. The system applied to measure two directional velocity components of Kármann vortices in a wake of a cylinder as an example of unsteady flow. From the measurement data, vortices were observed and vorticity distribution of cylinder wake was calculated by using Taylor's frozen hypothesis.

Keywords: UVP, Velocity vector measurement, Spatio-temporal velocity profile, Unsteady flow

1 INTRODUCTION

Ultrasonic Velocity Profiler (UVP) has been applied to experimental study of fluid dynamics and fluid engineering. The objective of this study is to develop an advanced UVP system named Vector-UVP that enables us to obtain three directional velocity components of the fluid flow on a line.

The velocity vector of fluid flow is expressed by functions for three velocity components of three directions of space and time. Therefore, in the experimental study for fluid dynamics, it is a goal to obtain such information. Recently, such ideal measurement may be realized by drastic progress of Particle Image Velocimetry (PIV). But PIV cannot be applied to the opaque fluids and an opaque apparatus. On the other hand, Ultrasonic Velocity Profiler (UVP) is a very effective tool for velocity profile measurement of opaque fluids. But UVP gives only one directional velocity component on a measurement line and it is less informative in comparison with velocity vector field given by PIV.

The purpose of this study is to overcome this disadvantage of the conventional UVP by expanding the dimension of velocity vector. We call this velocimetry Vector-UVP.

An idea and concept of Vector-UVP has been reported by Lemmin. [1-4], which is apparently not suitable for fluid dynamic study since measurement volume is too large. So we advance its concept to be applied to the experiment of fluid dynamics as shown in Fig.1.

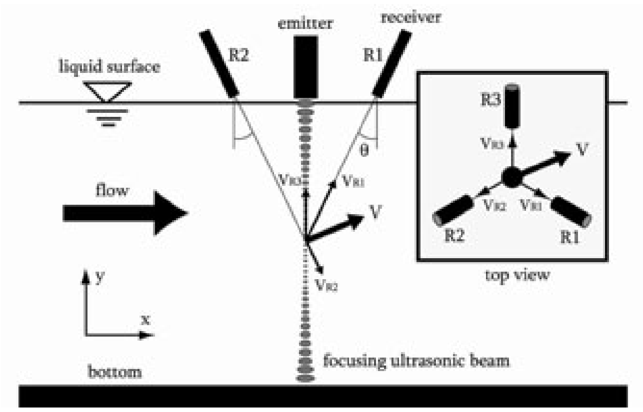

Fig. 1 Schematic illustration of concept of Vector-UVP; multiple ultrasonic receivers are surrounding ultrasonic emitter to take multi-directional information of the velocity vector of the fluid flow

It consists of a central emitter, symmetrically surrounded by three receivers, R1 to R3. An ultrasonic pulse is emitted into fluid from the emitter, and surrounding receivers receive the echo reflected from tracer particles. By analyzing these received echo waves, three directional velocity components can be obtained in the same manner as in the conventional UVP for each receivers and three-dimensional velocity vector can be formed. Since these receivers have a certain spatial range of receivable area, it can receive the echo from each point on the ultrasonic beam in this range. Therefore, this system can obtain the profile of the three-dimensional velocity vector on the ultrasonic beam. In order to reduce spatial uncertainties of the measurement position, a focusing TDX (F-TDX) that is able to decrease the diameter of ultrasonic beam by using acoustic lens was employed as an emitter in Vector-UVP.

In 4th ISUD, Ohbayashi *et al*. presented their achievement of Vector-UVP measurement of flow in the rotating cylinder as an example of steady flow. [6] So in this study, as an example of unsteady flow, two directional velocity components of Kármann vortices in a wake of a cylinder were measured. And as a preparation for optimum design of its experimental apparatus, we calculated sound field made by ultrasonic transducer by solving wave equation and estimated the measurement volume and measurable area.

2 SOUND FIELD MEASUREMENT

For optimizing the V-UVP system, sound field is one of the most important characteristics. Measurement of sound field generated by 8 MHz F-TDX was performed by using a needle hydrophone. (Toray engineering, NH8028, active diameter 0.5 mm) The experimental setup is shown in Fig. 2. The received signal was observed using a spectrum analyzer to record a sound pressure. The measured field spans from 0.5 to 32.0 mm to x-direction and –5.0 to 5.0 mm to y-direction. The interval of each grid was set to *dx* = 0.5 mm and *dy* = 0.5 mm. The medium was water.

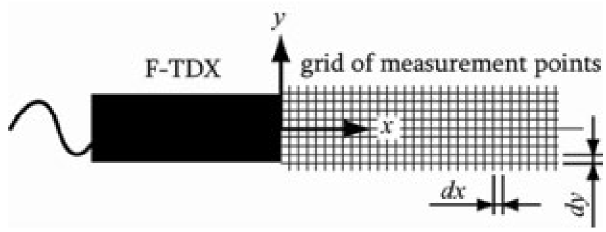

Fig. 2 Experimental setup for measurement of sound pressure made by F-TDX

The measurement result of the sound field and the maximum sound pressure on the centerline of the transducer is shown in Fig. 3. Focusing of ultrasonic beam is clearly shown. The beam diameter is defined as the FWHM of radial intensity distribution of ultrasound beam. The narrowest point of beam diameter is considered as focal point. Therefore, focal point is x = 25mm, which is almost same as the nominal value given by TDX manufacturer. It should be noted, first, that the space resolution is not high enough. Because the active diameter of needle hydrophone is almost three times as large as wave length of ultrasound. Second, the measurement value includes the influence of echo from surrounding walls.

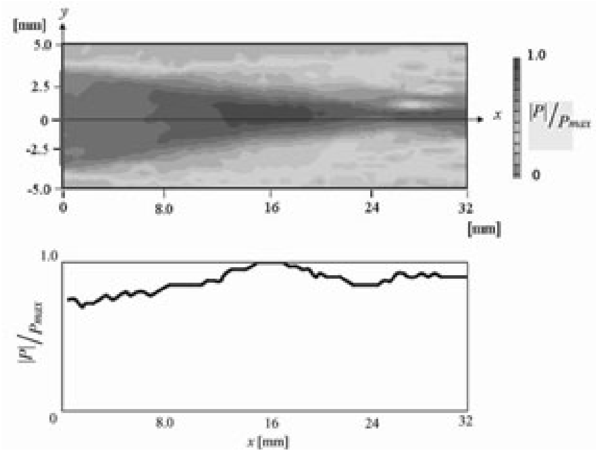

Fig. 3 Experimental results of sound field generated by 8 MHz F-TDX and the maximum sound pressure on the centerline

3 SOUND FIELD CALCULATION

To know sound field effectively without the problem of space resolution and influence of echo from surrounding apparatuses, the sound field was calculated from the following two-dimensional wave equation.

$$\frac{\partial^2 P(x,y,t)}{\partial t^2} = c(x,y)^2 \left\{ \frac{\partial^2 P(x,y,t)}{\partial x^2} + \frac{\partial^2 P(x,y,t)}{\partial y^2} \right\}$$

In practice, TDX generates ultrasound by oscillation of circular piezoelectric element. In this calculation, sound field made by ultrasonic transducer was substituted with superposition of ultrasound made by point sound source. In this calculation, acoustic lens whose curvature radius was 30 mm was attached to the top of TDX in the same way as actual F-TDX. Sound speed of acoustic lens is 2630 m/s. Intervals of spatial step and time step were chosen as 1/10 of ultrasonic wavelength and 1/50 of the period of oscillation of ultrasound. A medium was water whose sound speed is 1480 m/s at 20 °C. 8 MHz F-TDX which has 7 mm effective diameter is employed as an emitter in Vector-UVP. Calculation result of instant sound field and maximum sound pressure on the centerline of the transducer for 8 MHz F-TDX is shown in Fig. 4. By acoustic lens attached to the top of TDX, focal point of this F-TDX becomes 25.7 mm from transducer. Beyond this point, sound pressure distribution becomes smooth. The nominal focal point is 24.96 mm. That is to say, difference between value of this calculation and nominal value is 0.7 mm that is less than spatial resolution of UVP. So this calculated results can be accepted as accurate enough to estimate the sound field.

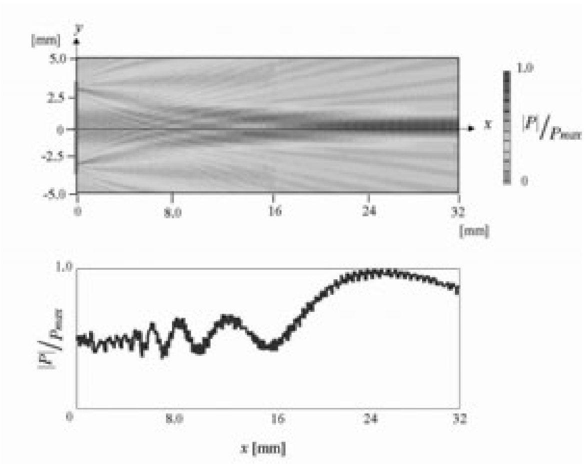

Fig. 4 Sound field generated by 8 MHz F-TDX and maximum sound pressure on the centerline

In many cases, TDX is set outside the wall. The inclusion of a wall will alter ultrasonic beam characteristics. The influence of an inclusion between TDX and working fluid on sound field was investigated by this calculation. As preparation for measurement of Kármann vortices in a wake of a cylinder, the sound field made by 8 MHz F-TDX set on the other side of acrylic wall was calculated. The thickness of acrylic wall was 0.2 mm and sound speed is 2700 m/s. The working fluid was silicone oil whose sound speed is 995 m/s at 20°C. The calculation result is shown in Fig. 5.

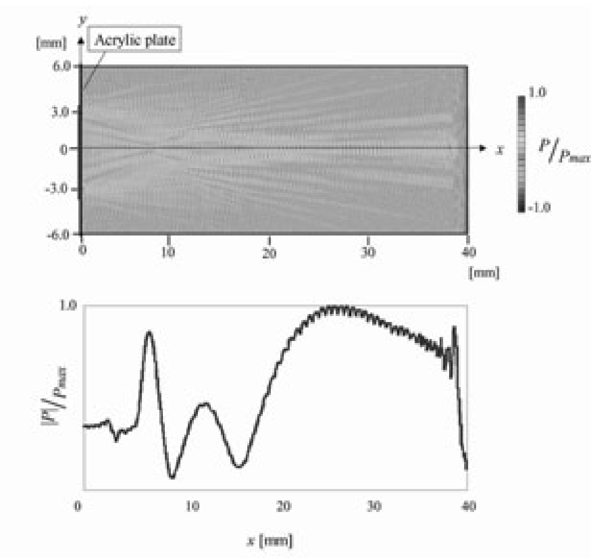

Fig. 5 Sound field generated by 8 MHz F-TDX set upped on the other side of acrylic wall and maximum sound pressure on the centerline

By the reflection on surface of acrylic wall, on the whole, sound pressure is lower than the case without the wall. In a range of 15 mm from 0 mm, the maximum sound pressure on the centerline has different characteristic from the case without the wall. This difference would be made by the influence of multiple reflection echo. But over 15 mm, the maximum sound pressure characteristic is similar to the case without the wall. From this calculation result, the focal point is considered as x = 26.7 mm.

In the other condition, for example, the thickness of wall is 3 mm, and the distance between the top of TDX and the wall isn't 0 mm, the flow field was calculated. From these results, as far as possible, the inclusion should be thin. And TDX should be set upped as the top of TDX directly contact with the inclusion to reduce the influence of inclusion.

4 MEASUREMENT OF KÁRMANN VORTICES IN A WAKE OF A YLINDER

4.1 Experimental setup

Measurement of two directional velocity components of Kármann vortices in the wake of a cylinder was performed as an example of unsteady flow measurement. The cylinder with diameter d = 10 mm is mounted in a channel, which has 160 mm in width and 40 mm in height, at 1700 mm downstream from the inlet of the channel. Working fluid is silicone oil. Ultrasonic transducers, an emitter and a receiver, are mounted on the top of the channel behind the acrylic plate of 0.2 mm in thickness (Fig. 6). Setting of the transducers is optimized based on the results of the numerical simulation for the ultrasonic beam described in the last section: An intersection of the axes of the transducers was chosen to be at the focal point of the emitter, 26.7 mm from the front of the emitter, which is determined by the numerical simulation. The receiver is fixed inclining with 25 degree. An distance of the measurement line from the cylinder, l_x, is chosen as 2.75d or 3.75d.

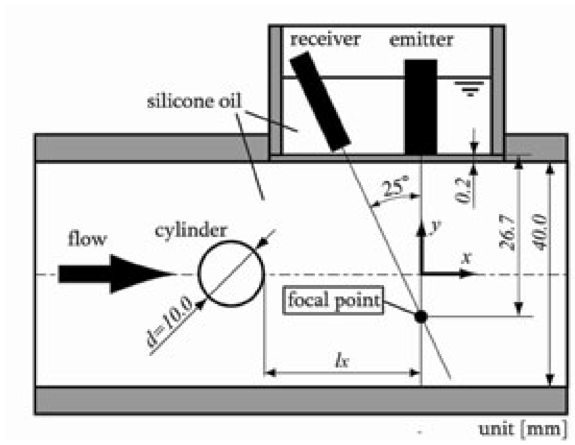

Fig. 6 Experimental setup to measure Kármann vortices in a wake of a cylinder

In this experiment, Reynolds number is defined by following formula.

$$Re = \frac{u_{\mathrm{m}} d}{\nu},$$

where u_{m} is a mean stream velocity in the channel, and ν is kinematic viscosity of silicone oil. The measurement was performed for 4 measurement conditions given in Table 1.

Table 1 Experimental conditions, where l_x expresses a distance of the measurement line from the cylinder

Re	l_x/d	
	2.75	3.75
150	(A)	(B)
250	(C)	(D)

4.2 Results and discussions

As one of the results of the measurement, temporal variation of the velocity vector profile obtained for the measurement condition specified (B) in Table 1 is shown in Fig. 7, where the sampling period is 30 msec and the profiles are arranged inversely to measurement time (from right to left). In the area enclosed with a black line in Fig. 7, two large vortices can be observed. Since the channel does not have enough height in comparison with the diameter of the cylinder, vortex shedding seems symmetric to the center of the channel unlike Karmann vortex street. But the shedding is periodic and the measured velocity vector profiles express it well.

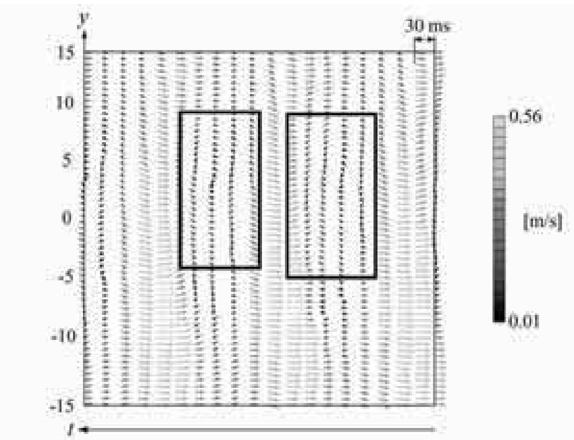

Fig. 7 Two-dimensional velocity vector map of cylinder wake (Re = 150, l_x /d = 3.75)

Velocity vector distribution of the cylinder wake $\mathbf{v}(x,y)$ is determined from the temporal variation of the velocity vector profiles with applying Taylor's frozen hypothesis, where the spatial value x is determined by following equation,

$$x = u_{\mathrm{m}}\, t\ .$$

Vorticity distribution $\omega(x,y)$ (= $\partial v/\partial x$ - $\partial u/\partial y$) is computed from the velocity vector distribution (Fig. 8). We can see an alternating vortex shedding from the top and the bottom of the cylinder even though we cannot confirm that in the temporal variation of the velocity vector profile (Fig, 7). It may be caused by less temporal resolution of the profile (30 msec in temporal resolution corresponds to 4.5 mm in spatial resolution. This value is comparable with the size of the vortex.).

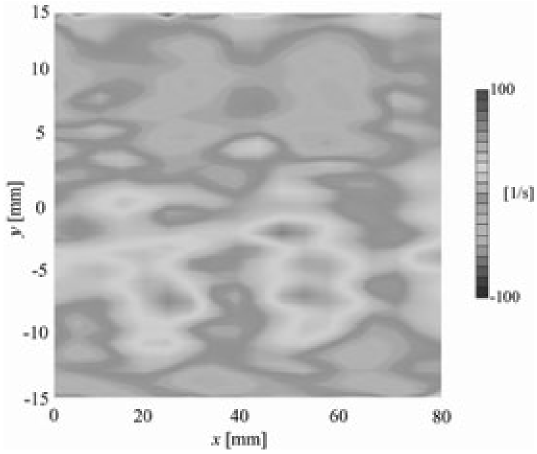

Fig. 8 Vorticity distribution of cylinder wake determined from temporal variation of velocity vector profile (Re = 150, l_x /d = 3.75)

5 CONCLUSIONS

We established the measurement technique for velocity vector profile using ultrasound named Vector-UVP. To design and optimize the system of Vector-UVP, we estimated the measurement volume and measurable range by calculating sound field made by ultrasonic transducer by solving two-dimensional wave equation.

Optimized Vector-UVP system was applied to measure two directional velocity vector profile of unsteady flow, vortex shedding in the wake of a cylinder. The vortex shedding was well reproduced in the vorticity distribution by applying Taylor hypothesis to the temporal variation of velocity vector profile obtained by Vector-UVP.

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