Ultrasonic Velocity Profiling method

Yasushi Takeda[(1)], Prof. Emeritus and Yuji Tasaka[(2)], Asc. Prof.

[(1)]Hokkaido University (yft@eng.hokudai.ac.jp)
[(2)]Hokkaido University, Laboratory for Flow Control, Hokkaido University, N13-W8, Sapporo 060-8628, Japan (tasaka@eng.hokudai.ac.jp)

Introduction

A usage of ultrasonic wave for measuring fluid flow is relatively old. Readers can be reminded that it is used, in clinical application, to measure blood flow along with the so-called echography of visualization of internal structure of human body. Just recently, it has been applied to general fluid mechanical study, namely, EFD = Experimental Fluid Dynamics. By measuring the traveling time of ultrasonic pulse in flowing media, flow metering has been developed and it is now an important device in many kinds of industrial processes.

As you may learn in the book, fluid flow is characterized by a field function. Namely, velocity is represented by a function of space and time; $\mathbf{V}(\mathbf{x},t)$, where $\mathbf{V}$ and $\mathbf{x}$ are vector and represented also in discrete form as $V_i(x_i,t)$. It has been impossible to obtain the information on the flow field in this form, until the UVP method is developed. Assuming a time average is made available, the function can be simplified as $V_i(x_i)$ – spatial distribution. For a case of single velocity component such as x direction only, it is called velocity profile; $u(x)$.

The velocity profile is the same as velocity distribution and it is the most relevant quantity and important information in studying physical fluid flow as well as in designing fluid machinery or civil engineering structure where fluid flow is involved. Therefore, fluid dynamists have been using flow visualization techniques together with photographing the flow quite extensively in order to know "How it flows". The UVP method has very much eased this type of observation on fluid flow in quantitative manner.

Since UVP method can obtain the flow velocity profile instantaneously, it is possible to obtain profiles continually with relatively short sampling period, which can form a time dependent velocity profile. This gives us spatiotemporal information on the velocity field. As mentioned above, the velocity field is represented by a spatiotemporal velocity function and it is a solution of basic governing equations. This has changed a basic style of experimental flow investigation.

Since ultrasonic wave can propagate in non-transparent material, the UVP method can be applied to any opaque fluids such as liquid metals, chemical reagents, pharmaceutical or cosmetic liquids, foods and drinks etc. These opaque liquids have often magnetic characteristics and play important roles in physics study as well as industrial processes.

Various algorithms have been developed for a diversity of flow configurations, and it will be further applied from a micro-scale flow channels such as microfluidics to environmental or civil engineering flows such as rivers, channels and lakes.

Measurement principle

The principle to obtain the spatiotemporal velocity information is based on ultrasonic echography and Doppler effect. Figure 1(a) shows a typical configuration of UVP measurement for a pipe flow: An ultrasonic transducer is mounted on the pipe wall and emitted pulsed ultrasonic wave propagates to the fluid inside the pipe: Impurities and contaminations in the fluid (seeding particles for laboratory use) reflect the wave and the transducer receives the echo (Fig. 1(b)).

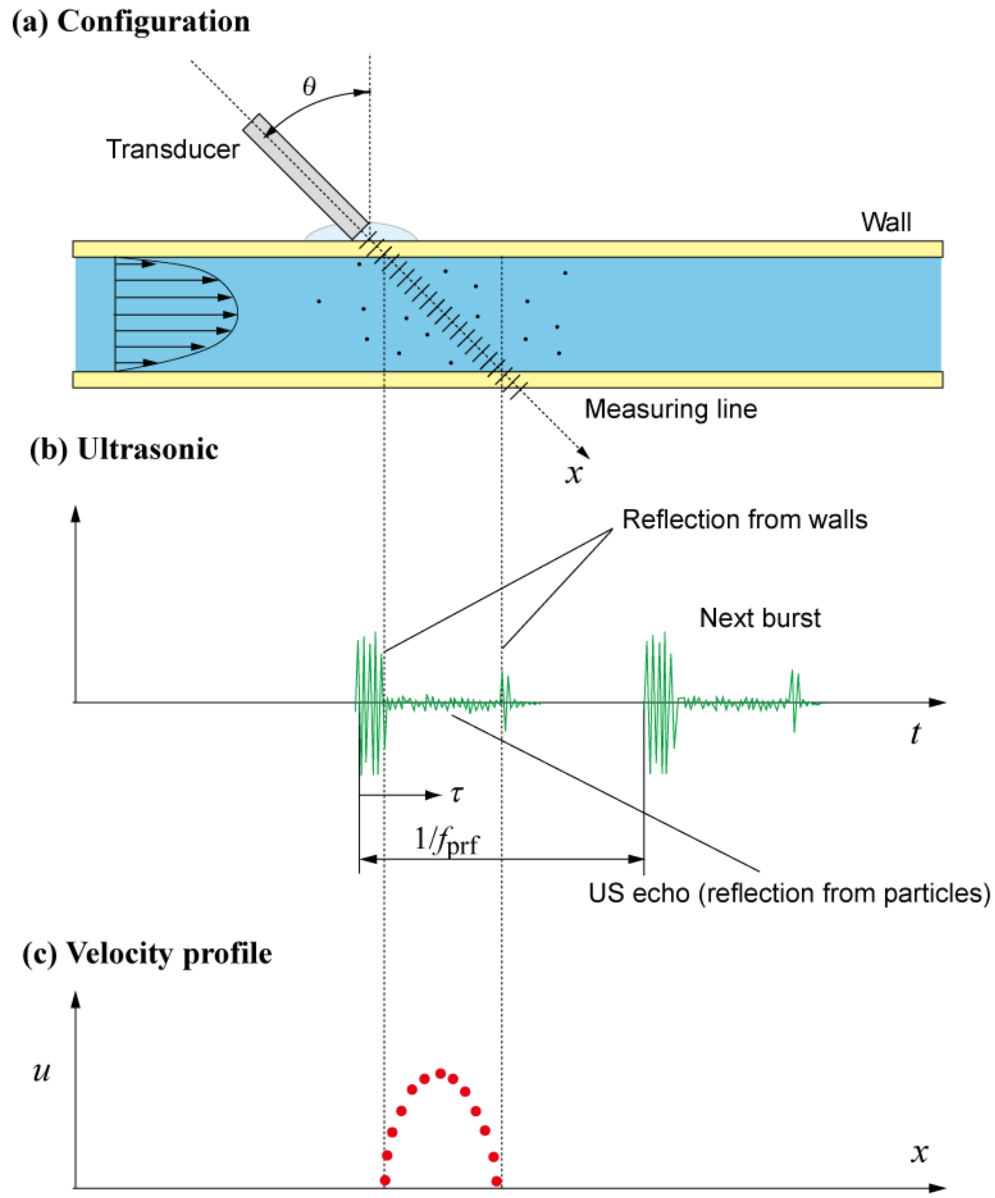

Figure 1: Schematic diagram of UVP measurement; (a) standard configuration for pipe flow measurement, (b) ultrasonic echo and (c) image of obtained velocity profile

The distance from the transducer to the scattering particles, x, is determined by time of flight of the ultrasonic wave, τ, as

$$x = \frac{c\tau}{2} \qquad (1)$$

where c is the speed of sound in the fluid. By assuming that the flow velocity at this position equals the moving velocity of the corresponding particle, the formula of Doppler effect gives the velocity as

$$u = \frac{cf_D}{2f_0} \qquad (2)$$

where f_D and f_0 are Doppler frequency contained in ultrasonic echo from the particles and the main frequency of pulsed ultrasonic wave. Nyquist limit in the sampling theory imposes a limitation on the both maximum measurable velocity range, U_{max}, and the maximum measureable length, X_{max}. These should satisfy the relation,

$$U_{\max} X_{\max} \le \frac{c^2}{8 f_0}. \tag{3}$$

The relation means using higher frequencies for f_0 takes tighter limitation. The higher frequencies, however, can achieve finer measurement volume than lower frequencies. Some algorithms have been proposed to obtain the Doppler frequency and the measurement accuracy and the time resolution of measurement depend on the algorithm. A commonly used Pulse-Doppler method requires multiple transmission of ultrasonic wave, and thus an "instantaneous" velocity profile is usually given as the results of 16 to 64 transmissions (Fig. 1(b) and (c)). Advantage of this method is for being insulated from the influence of noise due to unexpected reflections of ultrasonic wave. Correlation-based method can achieve instantaneous velocity profile measurement by at least two pulse-transmissions. But it is more influenced by the noise than the pulse-Doppler method. Finally it should be noted that the velocity component obtained by the measurement is the component parallel to the measurement direction, x. A correction is required to obtain e.g. main flow velocity in Figure 1(a) using the transducer setting angle, θ, assuming that the direction of flow vector is known.

Confirmation test – Rotating cylinder

A rotating cylinder system shown in Figure 2 is suitable for evaluation of the measurement precision and for the demonstration of spatiotemporal velocity measurement.

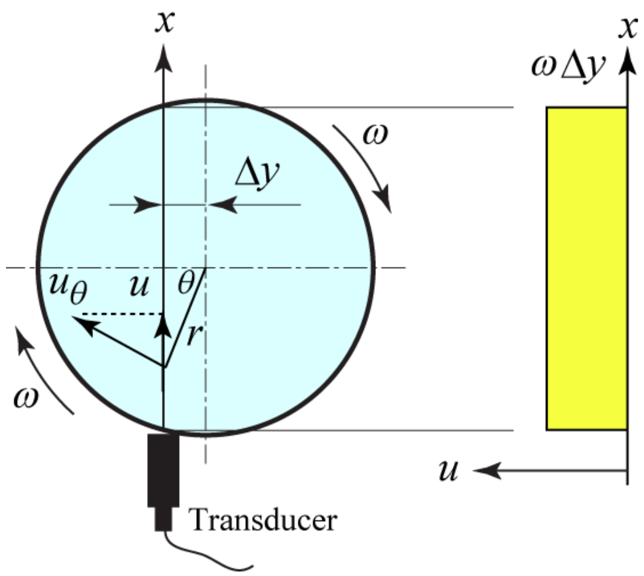

Figure 2: Configuration of UVP measurement of flows in a rotating cylinder (left) and ideal velocity profile along the measurement line (right)

A fluid encapsulated in the cylinder is driven by a cylinder rotation, and the flow velocity in the azimuthal direction gradually increases from the cylinder wall to the center because of viscous momentum diffusion from the cylinder wall. Finally the flow reaches rigid body rotation in which the flow has the unique angular velocity inside the cylinder. In the measurement configuration where the UVP measures a velocity profile parallel to the center line of the cylinder with distance Δy, we obtain a constant velocity profile with $u = \omega\Delta y$ as shown in Figure 2 (that value is given by combination of relations, the azimuthal velocity in the rigid body rotation $u_\theta = r\omega$, $\Delta y = r\cos\theta$, and $u = u_\theta \cos\theta$). Again during the development of the flow to the rigid body rotation after start-up, instantaneous velocity profile in the radial direction has exponential shape, namely the flow takes the same velocity of rotation speed of the cylinder on the wall because of the no-slip condition and gradually decreases toward the cylinder center. We can observe such development of the flow field in UVP measurement. Movie 1 "Motions of a rotating cylinder…" shows motions of the cylinder and corresponding instantaneous velocity profiles that are simultaneously obtained with the movie of cylinder motion. The cylinder is rotated with constant speed from stationary state, then the rotation direction is suddenly changed. Movie 2 "Development of flow field…" also shows the development of the flow field and there is a spatiotemporal representation of UVP data as color contours.

Examples

1. Wavy motion of Taylor vortices

Taylor-Couette flow, a flow between co-axial, rotating double cylinders (Fig. 3), shows variety of flow pattern.

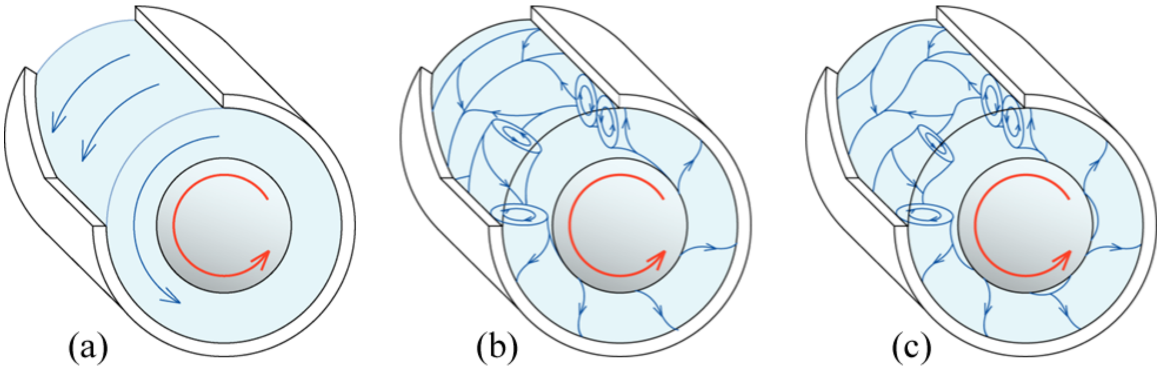

Figure 3: Schematic illustration for flow modes of Taylor-Couette flow with stationary outer cylinder and rotating inner cylinder; (a) circular Couette flow, (b) Taylor vortex flow and (c) wavy vortex flow

The flow transition from laminar to turbulent flow proceeds step by step. For the condition with stationary outer cylinder and rotating inner cylinder, as the primary instability, Taylor vortices which are toroidal vortices shown in Figure 3(b) bifurcates from the circular Couette flow (Fig. 3(a)). Then with increasing the rotation speed (to be exact, increasing Reynolds number or Taylor number of the system), azimuthal waves appear on the Taylor vortices as the second bifurcation (Taylor vortex flow, Fig. 3(c)). That is a time dependent flow and axial oscillation of the vortices propagates in the azimuthal direction with a certain traveling speed. Velocity profiles parallel to the rotation axis measured by UVP represents the waves as Movie 3 "Wavy motion of Taylor Vortices". A color contour of spatiotemporal velocity field on the movie expresses the both of Taylor vortices and its wavy motion.

2. Oscillating pipe flow

Oscillating pipe flow is a simplified model of blood flows, peristaltic flows, and any other pipe flows with flow rate fluctuations. Figure 4 shows overview of an experimental setup for investigating oscillating pipe flow.

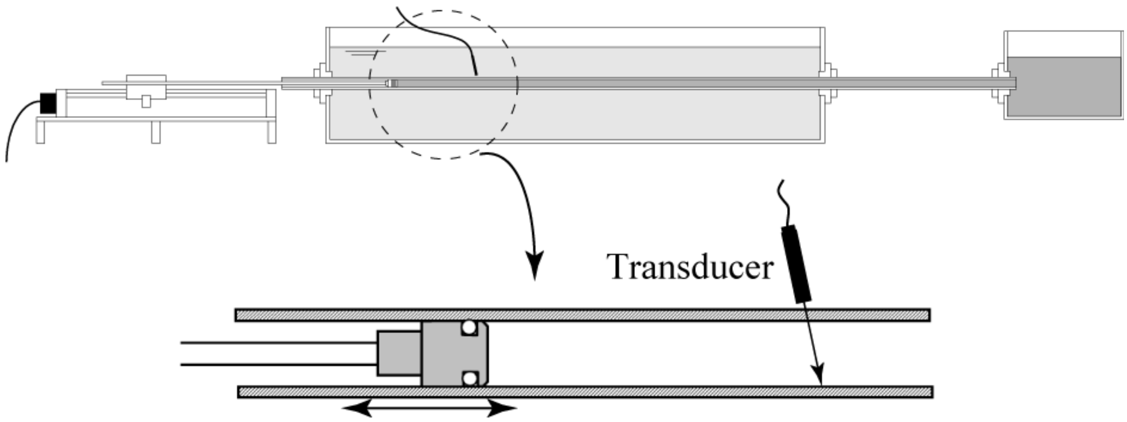

Figure 4: Overview of experimental setup for oscillation pipe flow measurement and enlarged view of measurement section

Here the oscillation is generated by periodic piston motions at the end of the pipe. By pushing and pulling the fluid, the flow near the piston behaves like potential flows. On the other hand the flows far enough from the piston have non-uniform velocity profile on the cross-section of the pipe, because of viscous shear stress and phase delay of momentum transfer in the radial direction. In the profile, depending on the phase of piston motion, velocity at intermediate radial position exceeds that at the center of the pipe (called annular effect). Because of this effect there are double shear layers in the cross section of the pipe and these play important roles on the flow transition. A time series of velocity profiles measured by UVP represent the annular effect explicitly (Movie 4, "Oscillating pipe flow").