Ultrasonic Doppler Method for velocity profile measurement in Fluid Dynamics and Fluid Engineering

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1. Introduction

An Ultrasound Doppler Velocity Profile method (UVP method) has been developed for fluid mechanical measurements in physics and engineering. The principle of the method is straightforward; echography and Doppler effect. This method was originally developed in medical engineering to measure blood flow. However, due to various constraints arising from its direct application to the human body, the measurement method never realized its full potential. We subsequently extended this method to non-medical flow measurements and developed specific application systems. Although the initial motivation was to find a new flow measurement method for liquid metal flows, the method itself was found to be quite useful to flow measurements in general and additionally through years of use has gradually become accepted as a tool to study the physics and engineering of fluid flow. In the sections to follow we will describe the measurement method and review the applications to date.

The working principle of the method is described in detail in Takeda (1995). It uses pulsed ultrasonic Doppler effect together with the echography relationship. An ultrasound pulse is emitted from a transducer into liquid, and the same transducer receives the echoes, which originate from tiny particles suspended in the fluid. The position information is given by the time duration between the pulse emission and the instant of echo reception, thus recording the position from where the echo is reflected. The velocity information is derived from the instantaneous Doppler shift frequency at that instant. The velocity profile is formed by processing the echo signal such that the instantaneous frequency is estimated at each instant. The system to realize such signal processing requires intricate analogue and digital electronics but most of the principal elements and algorithms can be found in Atkinson & Woodcook (1982). The system parameters such as basic frequency, maximum velocity, maximum measuring length and so on can be designed such that for many applications in ordinary fluids measurement requirements and conditions are fulfilled. The typical parameter values available at present can also be found by Met-Flow (1998).

In contrast to other measurement methods, this technique has the following three major advantages:

(1) It obtains a spatio-temporal information about the flow field.

(2) It is applicable to opaque liquids.

(3) It is a line measurement and thus a flow mapping is practicable.

Each of these advantages will be further explained below. We should emphasize that this measurement method is not a pointwise measurement but a linewise measurement. Thus a velocity profile consisting of a multiple number of data points, say 128, is realized and not incrementally scanned from the first through the last data point in the field. This is quite important contrast to the conventional methods, which calls upon the user to re-think the way the data is interpreted. Moreover the means by which data sets are manipulated and analyzed are inherently different. Thus the advantageous features are :

(1) Spatio-temporal information : The velocity field described in an Eulerian frame is a function of both space and time. In conventional measurement techniques, except for PIV (particle image velocimetry) and other image recording schemes, we can obtain the velocity field at one instant or velocity values at one spatial point as a time series. Due to the inherent constraints of such velocimetry, there has been a clear need to develop a measurement technique by which one can obtain velocity fields as a function of time. The UVP, though obtaining data along its beam line, can give such information. A spatio-temporal velocity information is important in physics study such as flow instability, where the spatio-temporal nature of the flow field is essential.

(2) Until recently it was practically impossible to make velocity measurement of opaque fluids. Flow visualization techniques by optical means are obviously impossible and other measurements such as pressure or torque measurements do not give spatially local information. In addition many of these fluids show non-Newtonian behavior and are highly viscous so that immersing any velocity sensing probe disturbs the flow field. By employing the UVP method and non-invasively, it is possible to measure flow field in opaque, non-Newtonian viscous liquids as if it were an ordinary liquid. It is potentially possible to explore areas in rheology, process related flow engineering and liquid metal systems.

(3) In order to validate computational codes, it is desirable to experimentally measure the same velocity field as that calculated. Usually from numerical codes, velocity fields are generated in vector form, from which various related flow quantities such as flow rate are computed. A subset of these results are often compared with experiments in order to validate the codes. This is, however, merely an implicit and insufficient validation procedure since the integration often smears out fine structure existing in the flow. With the UVP used, for the purpose of flow mapping the obtained flow fields can be directly compared with numerical results. The comparison is possible not only concerning the flow pattern but also quantitatively. The speed as well as other physical quantities which are derived from the velocity field, such as stream function or vorticity, can be compared.

In the following sections, investigations employing the UVP method are described from the perspective of the above described features. Some of these works are included in the present issue of the journal. In addition, as the development was largely conducted at PSI, it includes many of reports of myself. The reports which deal with the development and the use are not included.

2. Spatio-temporal velocity field

In the first example of the application of UVP method, we reported an investigation on flow in a gap between two concentric cylinders, the so-called Taylor-Couette system (Takeda et al. 1990). The axial velocity component was obtained as a function of axial position and time, $V_z(z,t)$, in order to investigate the transient behavior of Taylor vortices formation upon a sudden start of the inner cylinder. They observed an evolution of the wave-length of the Taylor vortices and found that the Taylor vortices is really formed in a gap due to a centrifugal instability and not generated by the end wall. He further extended his investigation of this system to azimuthal modulating waves (Takeda et al. 1993) and weakly turbulent flow (Takeda et al. 1994).

The spatio-temporal behavior of flow in the wake of cylinder (Peschard et al. 1996) and also the multiple wake behind a row of cylinders (Le Gal et al. 1996) (both are for parallel plates configuration) have been investigated at Marseille (IRPHE). In the single wake experiment, they identified several fundamental spatial modes from the spatio-temporal velocity distribution. Comparison with numerical calculation verified this experimental result. In the multiple wake experiment, they obtained a transverse velocity distribution and analyzed using a bi-orthogonal decomposition to investigate the collective behavior of such wakes.

A similar investigation has been undertaken by Gifu University where researchers studied flow in the wake behind a torus ring aligned perpendicular and/or oblique to the flow direction (Inoue et al. 1996). Upon scrutinizing the temporal nature by analyzing the power spectrum the data revealed counterrotating vortex rings that are alternately shed from the torus. The structure for the oblique arrangement was characterized by a transverse change in the power spectrum.

Flow on a rotating disc has also been investigated by researchers at Marseille (Schouveiler et al. 1996). When the Reynolds number for this system is defined in terms of the radial position, a range of phenomena for Reynolds numbers ranging from zero to a large number but finite in number can appear simultaneously, and under these circumstances the spatio-temporal observation of the flow field is essential. They found a system of circular and spiral waves, which interact non-linearly, and drive the transition to turbulence. They also determined the flow regimes of various complex wave modes.

In more industrially relevant configuration, flow in a Czochralski (Cz) crystal puller has been investigated (Tokuhiro & Takeda, 1993, Azuma et al. 1997). In a Cz crystal puller the flow, especially near the seed crystal, is critical for producing a silicon crystal of large diameter and with low impurity content. The flow shows quite a complex flow behavior due to not only rotational boundary condition of the seed crystal but as natural convection driven by the heating for melting silicon within the crucible and solidification at crystal. Tokuhiro and Takeda (1993) investigated the transient and spatio-temporal nature of a flow in a simulated Cz-model induced by simple rotation of the seed crystal and determined the critical Reynolds number for breaking of the axisymmetric flow. Azuma et al. (1997) extended this work to a system with natural convection heating of silicon oil. By changing the Reynolds number at a fixed Raleigh number, they observed a steady, oscillatory quasi-periodic flow and turbulence. The associated flow transition was studied by 2D Fourier spectral analysis and a correlation function from which one concluded that the transition occurs via spatio-temporal intermittency.

3. Flow measurement in opaque liquids

The initial motivation of the author to develop a method was to study liquid metal flow. The first test medium was mercury (Takeda 1990). The ultrasonic transducer was immersed directly into mercury and the flow in a T-branch of a pipe was measured to confirm the method. Flow measurement in mercury has recently been extended to study flow in the accelerator target geometry (Takeda & Kikura 1998). The container is made of stainless steel and the transducer is placed externally to the container wall. This is possible thanks to a transmission property of ultrasonic beam for a combination of mercury and stainless steel. They made a flow mapping of the mercury flow.

A group at the Swiss Federal Institute of Technology in Zurich is working on the application to flow of food materials, Uriev et al. (1998). The food materials are usually opaque and non-Newtonian so that to date there was no good way to investigate flow behavior in pipes or other containers. Uriev and co-workers have succeeded in measuring velocity profile of chocolate flow from which a flow rate was estimated. They evaluate such velocity profiles together with pressure difference to obtain various parameters such as shear rate and viscosity, both of which can be used as parameters in process control.

Sawada et al. (1996) have been investigating flow of magnetic fluids. The magnetic fluid is composed of tiny magnetic particles of diameter having the range of 5 to 15 nm suspended in water or oil. They are mostly black liquid and no optical method can be used. This kind of liquids has characteristics that its apparent viscosity changes by the external magnetic field and thus its flow behavior is sensitive to it. Although it has potential for various industrial applications, its use was very limited due to its difficulty to study the flow behavior. They studied a sloshing flow. A rectangular container filled with a magnetic liquid (free surface) is set on a oscillating bench. A transducer is set outside the container and moves together. A permanent magnet is used to apply a magnetic field. They studied an effect of the intensity of magnetic field on flow by time-averaged velocity distributions and power spectrum. A spatial distribution of peak intensities in power spectra for resonant frequency and its higher harmonics agrees well with theoretical prediction. They also found the harmonic components are suppressed by the magnetic field.

Finally in measurement of sodium flow in fast reactor development an effort has been made to measure Na flow in a pipe. The Japanese institute for FBR research and development, PNC, has developed a high temperature transducer which can be used up to 350°C and applied to a flow in a circular pipe [17]. Because of the high temperature and equally reactive environment, the set-up of transducer is constrained and less flexible than in ordinary fluid applications such that multiple reflections from surrounding walls appear to distort the recorded profiles. With careful analysis of each profile, a time-averaged velocity distribution was obtained which shows reasonable agreement with results from numerical calculations.

4. Flow mapping

In fact, a flow mapping is quite often an integral task in the industrial design of cooling channels and shrouds. The complex flow regions and paths in thermal hydraulics in nuclear reactor is also one of the areas of continuing interest.

Several types of flow have been mapped; these being in a square cavity attached to a parallel channel (Takeda et al. 1991) and a circular jet emanating into a tank of the same liquid (Takeda et al. 1995).

An extensive study was made by Wachter et al. (1996) for a flow in a stirrer of waste water tank. The measured field is 40x40x50 cm^3 with a rotating stirrer located centrally at the bottom. Using a traversing mechanism for a single transducer, they measured velocity profiles at 8x8x9 positions; that is a total of 576 velocity profiles. Data analysis was subsequently made such that two dimensional (x,y) velocity vector fields were computed at 9 different heights. This data set is displayed using various formats such as vector fields, relative velocity fields, turbulent velocity fields, and local energy dissipation contours. The results show that full flow mapping enables us to evaluate the flow phenomena using various physical quantities derived from the vector velocity field; that is, quantities such as the stream function distribution and vorticity distribution. A similar study has been made for water flow in a parallel channel flow (Kikura & Takeda 1998).

A group at PSI is also investigating flow of mercury in a stainless steel container (Takeda & Kikura 1998). The investigation is on flow pattern in a hemispherical end region of a double coaxial tube type target container for a spallation neutron source. The axisymmetric 2D flow is being studied in terms of a flow map and in comparison to results from numerical computation. Additionally, it is partly for geometrical optimization of the target design parameters and moreover to validate the computer code, especially as applied to liquid metal flow.

In the field of hydraulics, DeCesare & Boillat (1997) at Ecole Polytechnique Federale de Lausanne have used flow mapping in order to investigate flow with sedimentation. They investigated flow using a model flume and also behind a dam (Beyer-Portner et al. 1998). A flow map was obtained at various times after starting the flow, especially at along the bottom region near the flow bed. These results were compared with numerical computations.

5 Other applications

The UVP method is being used in various other configurations where, mostly, the size of the fluid body of interest is relatively large, typically larger than 1 m. Such large dimension are often encountered in nuclear engineering, civil engineering (Deininger et al. 1996), chemical engineering, environmental sciences such as in oceanic and geophysical flows, where even a time-averaged velocity profile is often difficult to obtain.

Thermal striping, a phenomenon which appears in the fast breeder thermal hydraulics is an issue concerning thermal fatigue of components due to poor thermal mixing of coolant. The phenomenon to date has been investigated mainly using temperature information, but Tokuhiro (1997) are studying its hydrodynamic features in a water based experiment. A hot-cold-hot, three jet configuration simulates flow out of the core with UVP, PIV and temperature recording the spatio-temporal nature of the thermal-hydraulics.

In the area of experimental gas-liquid flows the UVP method can be applied to a moving interface such as bubbles and free surfaces. Aritomi et al. (1996) have been investigating a water-air bubbly two phase flow. At present the application is limited to a bubbly flow with low void fraction, since the ultrasonic beam is totally reflected or deflected by large bubbles in certain flow regimes and at large void fraction multiple scattering amongst the bubbles introduces error into the position information such that the profile is deformed. The purpose of Aritomi's investigation is to apply the method to obtain a void fraction by analyzing the shape of each velocity profile, detecting the position of the bubble (which appears as a sharp change of the velocity on the velocity profile) and noting the rate of such appearance. In order to validate UVP measurements a comparison with visual observation recorded as a video movie has been conducted and showed a good agreement.

Another group at EPFL, Rolland (1994, 1997) has developed their own system using acoustic waves and applied this method to open channel turbulent flows (Lhermitte & Lemmin 1994). They obtained mean vertical water velocity distributions and several turbulent characteristics.

Finally, Nakamura et al. (1996) made simultaneous measurements of velocity profile and interfacial profile in a horizontal duct containing free surface wavy flow. The position of the free surface appears on the velocity profile as a sudden and discontinuous change of the velocity values. A time change of the water level was compared with results from a level detector probe and showed good agreement. The velocity profile in the liquid also showed agreement with results taken by Particle Tracking Velocimetry.

6 ISUD and USDJ Symposium

The First International Symposium on Ultrasonic Doppler method for fluid mechanics and fluid engineering (1. ISUD) was held September 1996 at PSI (Takeda 1996). The main objective of the symposium was to introduce the applications to various flow configurations and to promote this method for a wider variety of flow investigations. The emphasis of the meeting was made on the physical understanding of the data obtained by this method so that plenary talks were given on the physics to be made based on the experimental spatio-temporal data as well as on the mathematical methods to display and analyze such data. Approximately 60 participants gathered, discussed their own applications and exchanged information and experience.

In 1997 a Seminar on flow measurements using Ultrasonic Doppler method (USDJ 97) was held in Yokohama, Japan (Sawada et al. 1998). At the seminar a dozen or so papers oriented toward the industrial applications were presented.

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