Extraction of fluid and flow information from spatio-temporal UVP data obtained in rotating configurations

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In this keynote lecture I introduce some attempts to extract information of flow fields and fluid characteristics utilizing post processing and rotating configurations as an advanced style of UVP-utilized experimental fluid dynamics. The major topics picked up here are (1) flow field estimation of rotating fluids accompanied by free surface deformation that prevents access of optical measurements; (2) effective viscosity measurement of suspensions using ultrasonic spinning rheometry. In the latter topic phase delay on propagation of oscillating flows in a cylindrical container obtained from spatio-temporal velocity distribution by UVP is utilized to estimate effective Newtonian viscosity. Further I introduce some useful tools to reduce noise that is seriously required for advanced post processing on UVP data, and special arrangement of ultrasonic transducers for effective flow mapping.

Keywords: Flow field, effective viscosity, rotating flows, rotating system, noise reduction

1 INTRODUCTION

In the history of experimental fluid dynamics (EFD), the spatio-temporal velocity profile measurement achieved by UVP was sensational and we have been able to obtain energy spectral density, spatial distribution of turbulence intensity, and 2D Fourier spectra of velocity fluctuations to understand complex fluid phenomena. Flow mapping by arrangements of multiple ultrasonic transducers is also useful tool to estimate flow field in some hard measurement situations, for example, opaque fluid flows and environmental flows. Nowadays, however, advancement of PIV together with development of high quality video cameras has made the spatio-temporal velocity profile measurement to common methodology in EFD. In this meaning the UVP has finished its initial role in EFD. Instead the UVP is used to obtain secondary information, for example distribution of void fraction in bubbly flows [1], rheological properties of fluids [2] and etc. In this keynote lecture, I would like to introduce extractions of fluid and flow information from spatio-temporal UVP data (not only velocity data) as one of the methodologies on UVP applications in the next generation. The keyword of the methodology is rotating configurations and some typical examples about this are provided.

2 SUMMARY OF RESULTS

2.1 Flow field estimation

Rotating flows in a cylinder are one of the common configurations in the fluid mechanics and we can easily estimate the corresponding flow field. But giving one additional factor to the configuration changes the flow field dramatically, for example, counter rotations at the top and the bottom (von Karman's swirling flow), accompanying deformable free surface at the top. In the latter case our research group recently found complex phenomena named 'surface switching'. That has irregular vertical oscillations of the free surface with symmetry breaking and recovering of the free surface shape [3]. Estimation of the corresponding flow field is difficult because of high speed rotation of the flow around 800 rpm and existence of largely deformed free surface: these refuse applications of PIV. Applying UVP with giving some assumptions, however, achieves flow field estimation. Applying Taylor's hypothesis of frozen turbulence on the time variations of radial velocity profile, we can obtain radial-azimuthal flow field as

$$u_r(r,\theta_0,t) \approx u_r(r,\theta_0 - Ut, t_0)\,, \qquad (1)$$

where U is velocity of traveling flow structure and is estimated from period of velocity fluctuations. Assuming two dimensional incompressible flows, equation of continuity,

$$\frac{\partial u_\theta}{\partial \theta} + \frac{\partial}{\partial r}(r u_r) = 0\,, \qquad (2)$$

provides the estimation of azimuthal velocity component u_θ as

$$\begin{aligned} u_\theta(r,\theta) &= u_\theta(r,0) - \int_0^\theta \frac{\partial}{\partial r}\left[r u_r(r,\theta')\right] d\theta' \\ &= u_\theta(r,0) - A(r,\theta) \end{aligned}\,. \qquad (3)$$

Total value of u_θ cannot be obtained without additional information but spatial fluctuation component of u_θ is obtained as

$$\tilde{u}_\theta(r,\theta) = \langle A(r,\theta)\rangle_\theta - A(r,\theta)\,. \qquad (4)$$

For the purpose to estimate the flow field caused by surface switching, even fluctuation component will provide useful information. According to the assumption of 2D flow field, calculating stream function from the obtained 2D vector field as

$$\psi(\boldsymbol{x}) = \int_{\boldsymbol{x}_0}^{\boldsymbol{x}} (u_r r d\theta - u_\theta dr) + \psi(\boldsymbol{x}_0), \qquad (5)$$

gives good representation of vortices. Figure 1 shows the results of flow field estimation in the surface switching, where the white object represents free surface position on the measurement line determined by spatio-temporal informatin of UVP, ultrasonic echo and velocity [4]. The stream function represent quadrupole vortices. This procedure to obtaine the flow field acompanies numerical derivations of the UVP data and requires noize reduction to prevent enhancement of the spiky noise superimposed on the spatio-temporal velocity profiles.

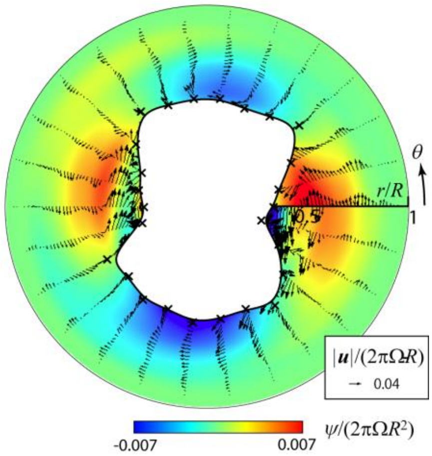

Figure 1: Velocity vector field, stream function and free surface position estimated by UVP in a rotating flow accompanied by free surface deformation

2.2 Estimation of fluid properties

Some attempts to derive rheological properties of fluids from velocity profiles obtained by UVP have been performed [1,5,6]. These studies utilized additional information, for example the pressure drop in pipe flows [1] and the axial torque of a rotating cylinder [5] to solve the equation for momentum conservation. Fitting analytical solutions of the equations obtained with applying constitutive equations on the spatio-temporal velocity profiles allows reducing influences of measurement noise. We also developed UVP-based rheometry termed 'ultrasonic spinning rheometry' by a cylinder in oscillating rotation. Off-axis setting of the measurement line of UVP and assumption of axisymmetric, one-directional flow provide conversion equation from original obtained velocity u_ξ to the azimuthal velocity component as $u_\theta = u_\xi r\Delta y$ [7], where r and Δy are radial position and the off-axis displacement. Figure 2 shows comparison of the spatio-temporal velocity field induced by cylinder oscillation between (a) analytical solution and (c) UVP data. These show good agreement, and the assumption may be satisfied in the present configuration.

As shown in the figure the information of the oscillation of cylinder wall propagate into the inner part of the fluid layer and the phase delay of the oscillation between each radial position depends on viscosity of fluid. Investigating the phase delay, therefore, provides local kinematic viscosity of the test fluid. The derivation of the phase delay is achieved Fourier transform of the spatio-temporal velocity profile and this operation can reduce influences of the measurement noise. We applied this technique to investigate the effective viscosity of both particle and bubble suspensions. In the case of particle suspensions, fraction of the effective viscosity μ^* is defined as

$$\eta = \frac{\mu^*}{\mu} = \frac{\left[\rho(1-\alpha)+\rho_p\alpha\right]\nu_p}{\rho\nu}, \qquad (6)$$

and obtained from fraction of kinematic viscosity, ν_p/ν, where α, ρ, ρ_p are the volume fraction of particles, density of the fluid and particles. Figure 3 shows the results of ultrasonic spinning rheometry on particle suspensions and it seems to agree with the semi-empirical equation of the effective viscosity.

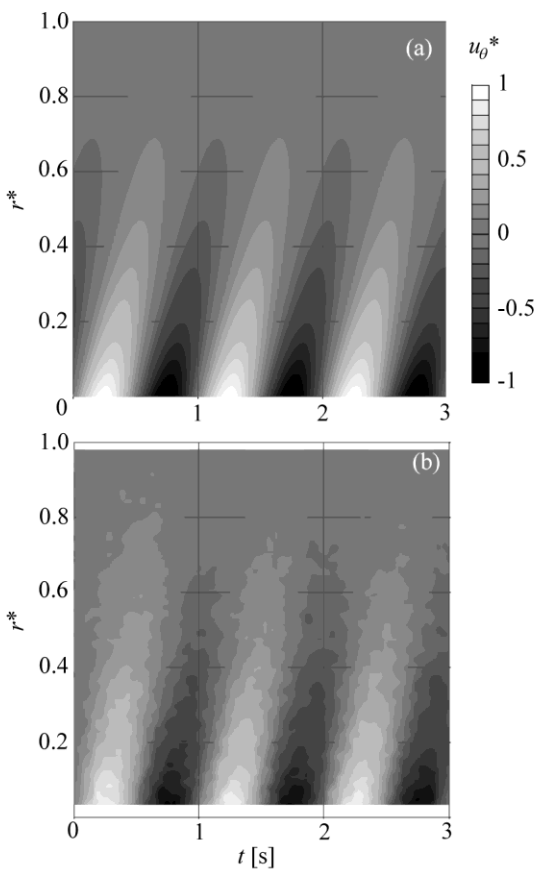

Figure 2: Spatio-temporal velocity field of flows driven by oscillating cylinder wall: (a) analytical solution and (b) a result of UVP measurement

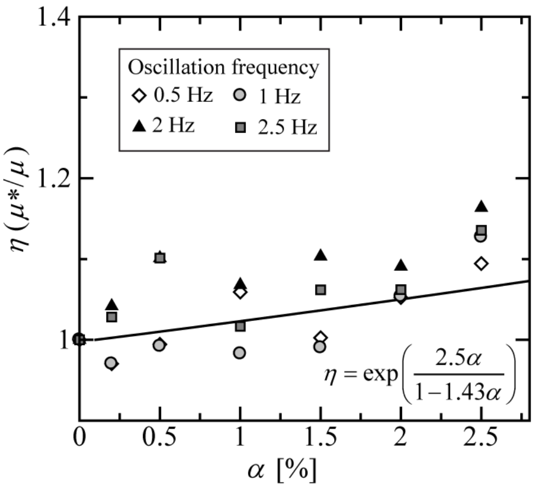

Figure 3: Variation of effective viscosity of particle suspensions with volume fraction

2.3 Useful tools

In extractions of fluid and flow information as explained above, how to reduce the measurement error in the post processing is important. Spiky errors typically observed in UVP data induce crucial problem in the process of numerical derivations that magnify the error. Fitting with analytical solutions derived with constitutive equation, giving noise reduction filter such as median filter, smoothing filter, etc., have been achieved depending on the situation. But there is possibility that the selection of the constitutive equation and the filters determine the result. Using power series expansion provides relatively objective noise reduction. In the knowledge of data analysis, particularly Chebyshev series expansion,

$$f(x) = \sum_{n=0}^{N} a_n T_n(x)$$
$$a_n = \frac{2}{\pi}\int_0^{\pi} f(\cos\theta)\cos n\theta d\theta \qquad (7)$$
$$T_n(x) = \cos(n\theta),\ x = \cos\theta$$

provides suitable representation of the original fluctuations. The expansion allows analytical derivation of derivatives of velocity profile as

$$f'(x) = \sum_{n=0}^{N} a_n T_n'(x)$$
$$T_n'(x) = \frac{n}{\sqrt{1-x^2}}\sin(n\cos^{-1}x) \qquad (8)$$

Figure 4 shows an example of Chebyshev series expansion, where the number of terms is N = 25. In the figure the both analytical derivative on the Chebyshev series expansion and simple numerical derivative of time averaged UVP data are displayed for the comparison. The former provides much smoother derivative than the latter.

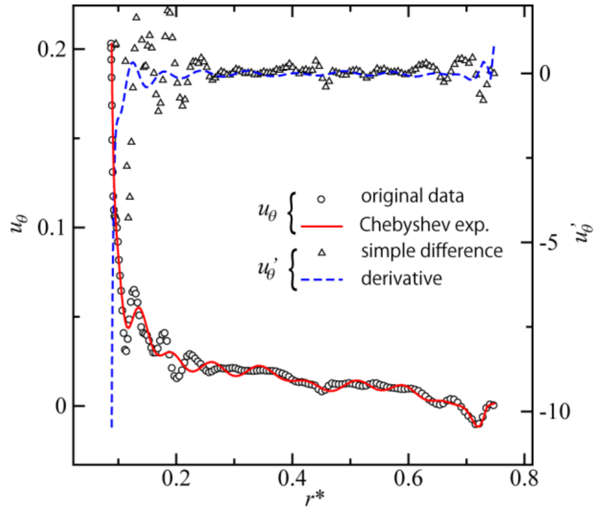

Figure 4: Example of Chebyshev series expansion of a time averaged velocity profile and its derivative

For the flow mapping by UVP, arrangement of multiple ultrasonic transducers is usually required [8]. Traversing the transducers also achieves the mean flow observation, but it requires big effort and spending time. To reduce the cost to obtain a rough estimation of large scale flow fields, we propose rotating multi-transducer system as shown in Fig. 5, where the multiple transducers are fixed with certain distance from the centerline of the system. The system is rotated with a fixed azimuthal step, $\Delta\theta$. Then crossing points of measurement lines are created. This idea is from post processing of PIV for flows in a cylindrical container [9]. For the horizontal (θ = 0) measurement line produced by TDX-1 that has l_1 in the displacement from the center line, the crossing points produced by TDX-2 with l_2 in the displacement have to satisfy

$$l_1 = \tan\theta x + l_2(\sin\theta\tan\theta + \cos\theta).$$

Solving this equation about the horizontal position x, the location of crossing points (x, y) is given as

$$x = \frac{l_1}{\tan\theta} - l_2\left(\sin\theta + \frac{\cos\theta}{\tan\theta}\right),\ y = l_1. \qquad (9)$$

For $l_2 > 0$, in actual use $l_1/l_2 > 4$ is required. Even though the condition is satisfied, we cannot avoid that the crossing points concentrate around the TDXs. So $l_2 < 0$ is recommended from the above estimation. According to this discussion, the total number of the crossing point is given by

$$N = \left(\frac{90}{\Delta\theta} - 1\right) \times \frac{360}{\Delta\theta} \times N_{T1} \times N_{T2}, \quad (10)$$

where N_{t1} and N_{t2} indicate the number of transducer setting in the top and bottom halves of the system. N increases with decreasing $\Delta\theta$, but it also causes concentration of the crossing points near the system, and is not suitable to estimate the flow field. Figure 6 shows the example of crossing points for the case of four transducers; l_1 = 65 mm and 130 mm, l_2 = -65 mm and 130 mm; $\Delta\theta = 15°$. The total number of crossing points is $N = 480$.

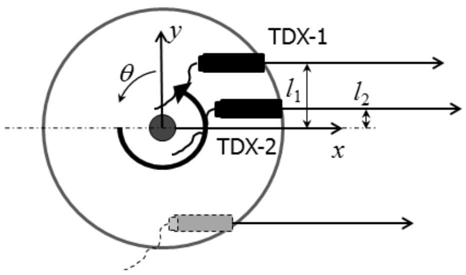

Figure 5: Schema of rotating multi-transducer system for flow field measurements

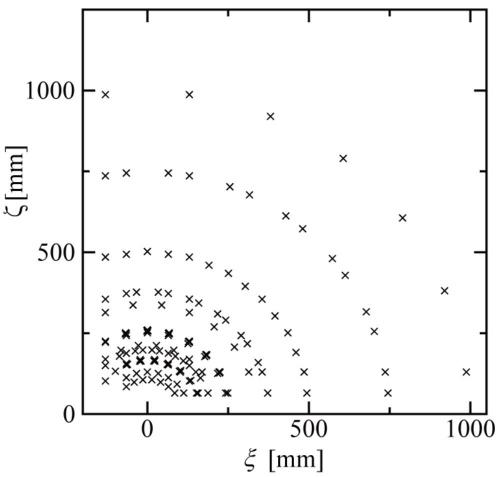

Figure 6: Expected crossing points of ultrasonic measurement lines of rotating multi-transducers

3 CONCLUDING REMARKS

I summarized two examples for extraction of flow field and fluid information adopting rotating systems. As these results the UVP has further possibility to promote EFD with considering configurations of ultrasonic transducers and post processing techniques. In the lecture, I will explain the details of these two topics and some additional trials performed in Laboratory for Flow Control, Hokkaido University.

REFERENCES

[1] Murai Y, *et al*.: Development of Ultrasonic Void Fraction Profiler, Meas. Sci. & Technol. 30 (2009) 114003.

[2] Wiklund J, Standing M: Application of in-line ultrasonic Doppler-based UVP-PD rheometry method to concentrated model and industrial suspensions, Flow Meas. Inst. 19 (2008), 171-179.

[3] Tasaka Y and Iima M: Flow transition in the surface switching of rotating fluid, J. Fluid Mech. 636 (2009) 475-484.

[4] Murai Y, *et al*: Ultrasonic detection of moving interfaces in gas-liquid two-phase flow, Flow Meas. Inst. 21 (2010), 356-366.

[5] Derakhshandeh B, *et al*: Thixotropy, yielding and ultrasonic Doppler velocimetry in pulp fibre suspensions, Rheol. Acrta 51 (2012) 201-214.

[6] Gallot T, *et al*.: Ultrafast ultrasonic imaging coupled to rheometry: Principle and illustration, Rev. Sci. Inst. 84 (2013) 045107.

[7] Shiratori T, *et al*.: Development of ultrasonic visualizer for capturing characteristics of viscoelastic fluids, J. Vis. 16 (2013) 275-286.

[8] Takeda Y and Kikura H: Flow mapping of the mercury flow, Exp. Fluids 32 (2002) 161-169.

[9] Murai Y, *et al*.: Off-axis PTV for 3-D visualization of rotating columnar flows, Exp. Thermal Fluid Sci. 51 (2013), 342-453.