Spatio-temporal measurement of flow field using ultrasonic Doppler method and its application to flow structure analysis

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Ultrasonic Doppler method, a novel measurement method of fluid flow, enables us to obtain flow field data in the form of spatio-temporal dimension. This method is introduced and its capability for investigation of fluid flow structure is presented using the results applied to a Taylor-Couette Flow configuration.

1. Introduction

As is well acknowledged, physical variables to describe fluid motion are functions of space and time. Therefore, experimentalists in fluid mechanics have been seeking measuring methods to obtain spatio-temporal information about the flow field. Recently ultrasonic Doppler method (UDM) for velocity profiling has been developed. It utilizes pulsed echography of ultrasound together with detection of instantaneous Doppler shift frequency. This enables us an instantaneous single dimension line measurement of velocity distributions, and to analyze spatio-temporal structure of the flow fields.

As a consequence of such a development of novel measuring technique, a new analytical tool has been needed for a flow study. We use a Singular System Analysis (SSA) to characterize a spatio-temporal flow field data. This technique for data analysis is one of the various orthogonal decomposition methods such as POD, and BOD to decompose the flow field into a set of orthogonal eigenfunctions. A resulted eigenvalue spectrum can be used to investigate energy flow among the flow modes.

In this paper, we introduce this new measuring method is introduced and present what we can do in experimental fluid mechanics in terms of spatio-temporal flow structure. The example flow field is Taylor-Couette Flow.

2. Ultrasonic Doppler Method

The principle is to use an echography of ultrasound. The ultrasonic pulse is emitted from a transducer and reflected by particles suspended in fluids and received with the same transducer. For deriving instantaneous velocity profile, position information is given by a time lapse between pulse emission and reception of the echo. The velocity information can be obtained from an instantaneous frequency of the echo at each time instant.

By analyzing the echo signal such that instantaneous frequencies at various instant after the emission are computed, the instantaneous velocity profile can be obtained. For the most of the system constructed so far, velocity values at 128 positions with separation of equal distance are obtained with a time resolution of around 132 ms. The measuring volume of each data points has a disc shape of radius 2 mm and thickness 3/4 mm.

The device can be designed for required flow configurations and fields, and those numbers given here are typical for laboratory experiments. Beam characteristics are also strongly dependent on the basic frequency of ultrasound and the dimension of a transducer to be used.

3. Taylor Couette Flow application - Data obtained

UDM obtains the field data in the form of spatio-temporal dimension and usually displayed in color density plot as Fig.1. The velocity component obtained is a projection of the true velocity vector on the measurement line ($V(z)$ for the present example), but as it is instantaneous for all the data points, it has a spatio-temporal nature in itself. As shown in this example, this nature is clearly depicted and this kind of representation helps greatly to catch the flow nature instinctively. Especially, flow instability reveals as the change of spatial structure of the flow fields at the initial stage, and thereafter spatio-temporal structure changes. In this sense, UDM data is advantageous even though it is 1C1D in spatial coordinate.

Fig. 1  Color density plot of a Taylor Couette Flow after a sudden start. Coordinate is time and abscissa is position

4. Power and Energy spectrum (Fig.2)

It is an obvious approach to compute a power spectrum by taking Fourier transform on time. This generates space-dependent power spectra, whereby spatial dependence of any distinctive temporal modes can be investigated.

More important of this method is a capability of obtaining Energy Spectral Density directly by taking Fourier transform of the data in space. By point-wise measurements, it was impractical to collect a large data set to obtain such quantity, so
that it was usual to convert the power spectrum to energy spectrum adopting the Taylor’s frozen hypothesis. It was the first time to have obtained the energy spectral density as a function of wave number (spatial) without using the Taylor’s hypothesis. Further important is that the energy spectral density so obtained is time-dependent.

5. Orthogonal decomposition

A spatio-temporal nature of the data obtained by this method is fully used when the data set is analyzed by any kind of orthogonal decomposition techniques. Two-dimensional Fourier analysis (2D-FFT) and Proper Orthogonal Decomposition (POD) are typical in the flow analysis.

Since TCF has a very good spatial periodicity, 2D-FFT is very effective to analyze the flow field (Fig.3). On the ($k,f$) 2D-spectrum, the stationary Taylor Vortex Flow (TVF) shows a strong peak on the spectrum at $f=0$, Wavy Vortex Flow (WVF) corresponds to isolated peaks at ($k_1,f_1$). The spectrum shows various harmonic peaks at ($nk_1,mf_1$). A different mode appears as isolated peaks at the different $k$ or $f$ so that it could be easily distinguished from others.

It is however not the case for other configurations since spatial periodicity cannot be expected and their spectrum is more or less continuous. It might be stated that this way of analysis corresponds to realizing a conditional sampling in experimentation in a very objective manner.

In order to extract a characteristic structure of the flow field, a Proper Orthogonal Decomposition (POD) technique is used. Its applications were however very rare and only two-dimensional data obtained by hot wire array measurements is reported. Holmes gave theoretical work extensively. We applied this technique to the spatio-temporal data set (Fig.4). It could extract spatial and spatio-temporal structures such as TVF and WVF in a similar way to those obtained by 2D-FFT. Still higher order modes were also obtained. The spatial eigenvectors for a first few modes are highly periodic and appear to be similar to FFT results, while the higher order modes exhibit no periodicity. Problem we found there is that profiles of eigenvectors are not exactly the same from data set to another and comparison among them might not be very precise. It was however useful to obtain energy spectrum (or energy spectral density) of the flow field.

6. Concluding remarks

Ultrasonic Doppler Method enables us to obtain spatio-temporal information of velocity field of fluid flow, which might open a new scope of horizon in the experimental fluid mechanics. For analyzing such form of experimental data to make physics, orthogonal decomposition techniques are useful; especially to investigate flow structures which strongly involves spatio-temporal nature such as flow transition to turbulence.

References

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