Some remarks to correlation measurements in has flow

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Correlation measurements are well known for velocity measurements of solid bodies. But this measurement principle is not appropriate to the measurement of mean flow velocities of fluids .This will be shown by means of system theory. Fluids have completely other properties and characteristics than solids. Turbulent fluids show a velocity dependent flow profile and the probability density of single velocity components is a skewed function. The peak of the cross correlation function represents the travelling time of the most frequent components between two ultrasonic barriers in the fluid but not the mean flow velocity. The system must be calibrated in any case. Small artificially generated vortices travelling with mean flow velocity can solve the problem. Furthermore, the combination of vortex and correlation measurement results in a self monitoring system.

1. Introduction

Still now in literature, publications, industrial research laboratories as well as in some national metrological institutes the preconceived idea prevails that the mean flow velocity of fluids can be directly determined by cross correlation measurements [1, 2]. The pattern of turbulent structures in the fluid is realised optically, by ultrasound, lasers or other sensors dependent on the kind of fluid. In the case of question two ultrasonic barriers detect the complex modulated signals which are cross correlated. In this case conclusions are drawn from velocity measurements of solid bodies as vehicles, steel in rolling mills, driving belts and others by cross correlation functions. The method has bee proved good and bases upon the fact that the cross correlation function represents the autocorrelation function shifted by the travelling time of a pattern between two measuring points. This knowledge is transferred to liquids or gasses with completely other properties and characteristics than solids. Fluids show a velocity dependent profile and the single velocity components in the streaming fluid are not symmetrically distributed. This results in deviations of up to 10% between the real mean flow velocity and the measured travelling time by cross correlation functions.

2. Experimental Setup

All measurements were performed in a test arrangement with a pipe diameter of 100 mm. The length of the pipe from the inflow to the test chamber with ultrasonic sensors was 5m to ensure a fully developed flow profile. A turbine gas meter was used as reference with a deviation within 1% of the mean flow, fig. 1. . The ultrasonic transducers were usually operated with a carrier frequency of 220 kHz. For best results they had a distance of 60 to 100 mm. The test fluid was air at 1 bar static pressure.

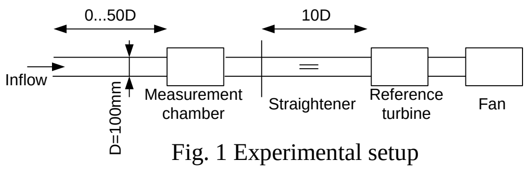

Fig. 1 Experimental setup

3. Physical Explanation

The ultrasonic signals were complex modulated by stochastically distributed turbulent structures in the fluid [3]. The transit time of these structures between the two ultrasonic barriers is usually determined by the maximum of the cross correlation function. But this maximum does not represent the real transit time.

Two explanations shall be presented. The first one proceeds from the idea that the complex demodulated sensor signals are composed by single-signal velocity components with different travelling times [4]. The cross correlation function of both sensor signals corresponds to the sum of all cross correlation functions of the single-signal components. All components generate their own maximum superposing each other. The travelling time is to be determined by the highest maximum. So the travelling time of all other components do not influence the result. That means that the cross correlation function of the sum of signals results in the sum of single cross correlation functions of all signal components. Hence follows that without considering dissipation the most frequent velocity components will be detected corresponding to the modal value of the density distribution function, fig.2.

Correlation functions presuppose ergodic processes. A stochastic process is called ergodic if its ensemble averages equal appropriate time averages [5]. As the modal value of the cross correlation function is a mean value within the meaning of statistics the theorem of ergodicity is fulfilled. These reflections are in accordance with the analysis of systems theory.

The second explanation is given by Schneider [6, 7]. It has its origin in systems theory. Without going into details of fluid mechanics it could be shown that the impulse response of the system can be determined by the application of the theorem of ergodicity to the convection process which is superposed by the diffusion process. The probability density distribution shows a high skewness depending on the flow profile and velocity. This probability density function corresponds to the impulse response h(t) of the system. The cross correlation function $\Phi_{12}(t)$ of the two modulated sensor signals is given by the convolution of the autocorrelation function $\Phi_{11}(t)$ of the first signal with the skewed impulse response h(t), fig. 3. So the maximum represents the most frequent velocity components but not the mean velocity. The impulse response depends on a series of flow parameters as velocity profile, turbulence characteristics, properties of coherent structures, geometric parameters of pipe and sensors. It can be determined from the flow profile applying the theorem of ergodicity and the transformation laws for probability functions [1]. Additionally, mainly the diffusion process of the fluid between the two ultrasonic barriers must be taken into account [6].

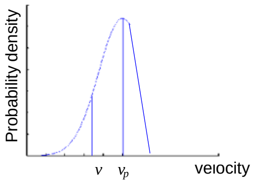

Fig. 2 Modal value v_p and mean value $\bar{v}$ of velocity components

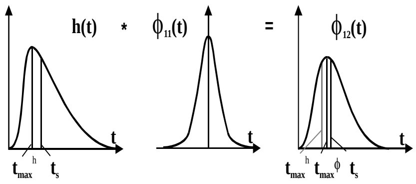

Fig. 3 The unsymmetrical impulse response h(t) influences the position of the maximum of the cross correlation function $\Phi_{12}(t)$ [6].

The only way to get a symmetrical probability density of velocity components is to use artificially generated vortices by a small bluff body. The combination of vortex and correlation measurements results in a self-monitoring system [8]. The vortices dominate all other stochastic structures and result in a nearly sinusoidal modulation of the ultrasonic waves. In this case the density probability function is not skewed but symmetric resulting in a symmetric cross-correlation function. The maximum of this function represents the transit time of the vortex patterns. In other words, the vortices are travelling with the mean flow velocity which is directly measured by the cross-correlation function. A comparison of measurement results is shown in fig. 5.

4. Measurement Results

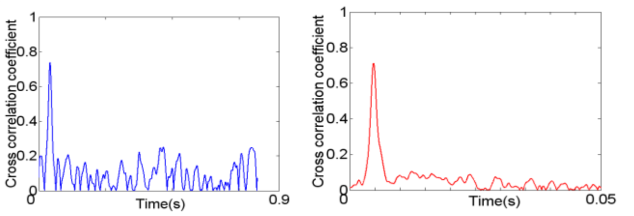

Fig. 4 Cross correlation functions at v = 2 m/s (left) and v = 20 m/s (right)

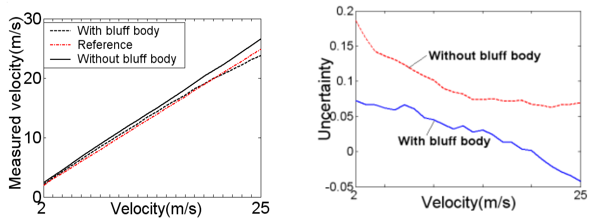

Fig. 5 Comparison of measurement results and uncertainties with and without bluff body

Measurements have been made in a range from v = 2 m/s up to v =20 m/s. Fig. 4 shows the cross correlation functions. The direct evaluation of the maxima of the cross correlation functions results in relatively big uncertainties. The uncertainty of measurement depends essentially on the kind of signal processing. Best results could be obtained by software based Hilbert Transform of the complex modulated signals [9]. For small velocities the uncertainty was about 10%, decreasing to a minimum of 3% in the range of v = 10 m/s and increasing to 8 % at v = 20 m/s. Applying bluff bodies with a symmetrical probability density distribution of the vortices results in clearly less uncertainty. A comparison is shown in fig.5.

5. Conclusions

The evaluation of the peak of cross correlation functions of ultrasonic signals for the determination of the mean flow velocity of fluids results in deviations. By means of system theory it could be shown that the peak represents the velocity of the most frequent velocity components. On account of the velocity dependent profile of the flow the impulse response of the system is a skewed probability function. A calibration of the system is necessary. Applying artificially generated vortices the impulse response gets symmetrical. It is advantageous to combine vortex and correlation measurements for a self monitoring system.

6. REFERENCES

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