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Self-monitoring ultrasonic gas flow meter

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Abstract. Ultrasound is predestined for gas flow velocity measurements on account of its high sensitivity to all kinds of natural and artificial turbulences in the fluid. Vortex measurements behind a bluff body as well as cross-correlation methods have been proved good. Cross-correlation measurements of natural structures determine the most frequent velocity components in the fluid. Therefore, the measured flow velocity deviates from the real mean flow velocity because of a skewed probability density distribution of the velocity components. Vortex measurements base on the principle that the frequency of the vortices generated in the wake of a bluff body is proportional to the mean flow velocity. The measurement of the periodic vortices with cross-correlation functions leads to the direct determination of the real mean flow velocity. The combination of both measuring methods results in a self-monitoring system.

1. Introduction

Modern measuring methods of gas flow velocity use ultrasound on account of its high sensitivity to all kinds of turbulences in the fluid. Usually the principle of transit time measurement of ultrasonic impulses is applied. Cross-correlation measurements, however, are working with two continuous ultrasonic waves in a well defined distance. The ultrasonic signals are complex modulated by natural stochastically distributed structures or artificial vortices in the streaming fluid. The transit time of structures between two ultrasonic barriers depends on the determination of the maximum of the cross-correlation function.

Vortex measurements take advantage of the fact that the frequency of vortices generated by a bluff body is directly proportional to the mean flow velocity. Usually pressure sensors are applied to detect the vortex frequency presupposing big bluff bodies resulting in big pressure losses [1]. The high sensitivity of ultrasonic waves admits a drastic reduction of the bluff body size resulting in pressure losses to be neglected.

The ultrasonic wave is complex modulated by the structures in the streaming fluid. Amplitude modulation is caused by diffraction, reflection and damping due to density changes in the fluid. Phase modulation is mainly caused by the mechanical drift of the ultrasonic wave by the fluid and by radial velocity components of turbulent structures or vortices superposing the ultrasound wave de- and accelerating the signal.

The modulation degree is low and in the case of modulating natural structures the bandwidth is small. The sidebands of the signal in the frequency domain containing the information of modulation are in a range of about 3 kHz. They are narrow to the carrier frequency of 220 kHz of the ultrasonic signal. The main task of signal processing is the demodulation of the modulated signal. The carrier frequency can be suppressed by digital undersampling. Phase and amplitude of the complex signal can

be determined by hardware or software based Hilbert Transform. The procedures can be applied to vortex measurements as well as to cross-correlation methods. Detailed descriptions are given in [2].

2. Measurement of vortices

Vortices in a streaming fluid are generated by a bluff body. The vortices are separated from both sides on the back of the bluff body that is flowed around. The frequency of separated vortices on one side is proportional to the mean flow velocity, which is described by

$$v = f \frac{d}{S} \quad (1)$$

where d is the diameter of bluff body in the dimension of m and S is the dimensionless Strouhal number. S can be taken as constant over the interesting velocity range. The principle is shown in figure 1.

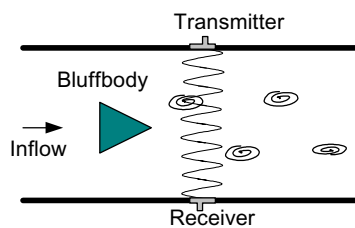


Figure 1. Karman vortex street behind a bluff body

In industrial flow meters the vortex frequency is mostly measured with pressure sensors. But the low sensitivity of pressure sensors requires strong vortices generated by large bluff bodies [1]. The high sensitivity of ultrasound permits the detection of very small vortices generated by small bluff bodies [3,4]. Usually triangular bluff bodies are applied facing the flat side to the inflow. But this instruction is not valid for measurements with ultrasonic waves. This kind of arrangement causes secondary vortices in the wake of the bluff body preventing a simple signal processing. Lots of experiments have shown that it is better to turn the bluff body around by 180 degrees with the tip of the bluff body facing the inflow. No secondary vortices or other disturbing effects could be observed [5]. Additionally the sensitivity of the vortex meter increases more than twice. The sensitivity is given by

$$E = \frac{df}{dv} \quad \text{Hz/(m/s)} \quad (2)$$

referring to the number of vortices per meter and representing the periodic length of vortices. The sensitivity as function of the bluff body size is shown in figure 2 [4].

The length of the bluff body was twice as long as the height d . The mean characteristic can be determined by curve fitting as $E = 223 d^{-0.89}$. This very simple relation permits the determination of the vortex meter characteristic as function of the dimension of the bluff body.

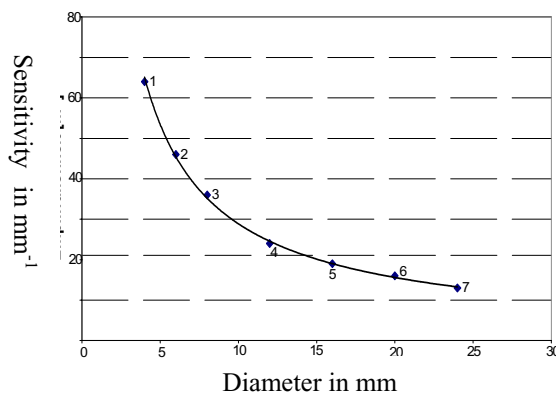


Figure 2. Sensitivity of triangular bluff body facing the tip to the inflow versus bluff body diameter

Measurements have been made in a test equipment shown in figure 3. The pipe had a diameter of 100 mm. To get a fully developed profile the distance from inflow to the test chamber was 5 m. Measurements have been made in gas flow (air) in a velocity range from $v = 2\text{ m/s}$ to 25 m/s , corresponding to Reynolds numbers 13 000 to 163 000.

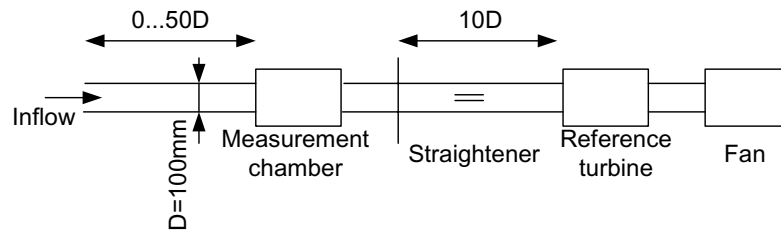


Figure 3. Test equipment

Considering equations (1) and (2) the Strouhal number can be expressed as $S = 0.223 d^{0.11}$ as function of the bluff body diameter d in mm. An example of the characteristic of vortex flow meter is given in figure 4. The tip of the bluff body of 4mm height was facing to the inflow. The sensitivity is $E = 65\text{ Hz/(m/s)}$ and the Strouhal number is $S = 0.26$.

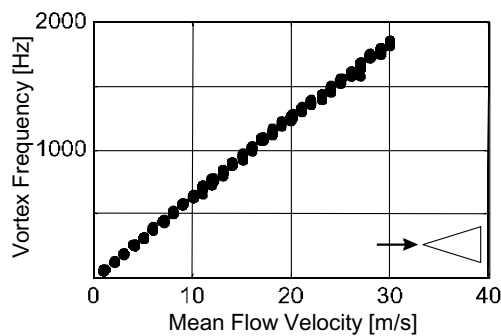


Figure 4. Characteristic of vortex flow meter

Cross-correlation measurements

Cross-correlation functions (ccf) for the determination of flow velocity are well known but not often realized on account of difficult signal processing and the necessity of calibration. The calibration factor depends on the flow profile and with that on the flow velocity.

Flow velocity measurements by ccf base on the determination of travelling time of patterns between two ultrasonic barriers, figure 5. The maximum of ccf is a measure of highest similarity of the two modulated ultrasonic signals and indicates the travelling time of the modulating patterns. The ccf represents the autocorrelation function (acf) shifted by the travelling time.

Mathematically the ccf $\Phi_{12}(t)$ results from the convolution of the acf $\Phi_{11}(t)$ with the impulse response $h(t)$, figure 6. The structures in the fluid are transported with different velocities corresponding to the flow velocity profile and dependent on the position in the pipe [6]. The impulse response is influenced by this transportation process. A second effect is the diffusion process of structures in the fluid between the two barriers. A detailed exact description is given in [6, 7].

The transportation process is related to the probability density function (pdf) of the flow velocity. Experiments with particle image velocimetry (piv) have shown that the velocity components in a turbulent streaming fluid correspond with a skewed probability density distribution, figure 7 [8].

The peak of this distribution (modal value) represents the most frequent value of the velocity components. It determines the impulse response and therefore the peak in the skewed cross-correlation function. It is obvious that this modal value does not correspond to the mean flow velocity. The ratio of both represents the calibration factor.

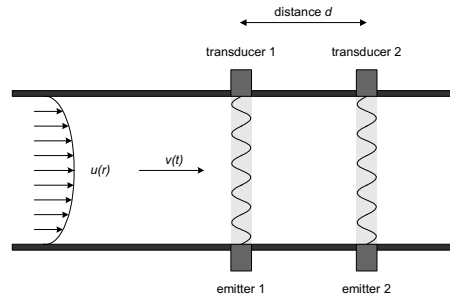


Figure 5. Principle of cross-correlation measurement

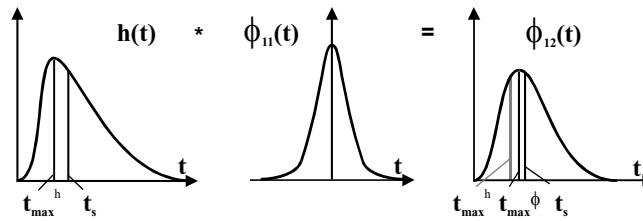


Figure 6. Influence of the asymmetry of impulse response on the peak of the cross-correlation function

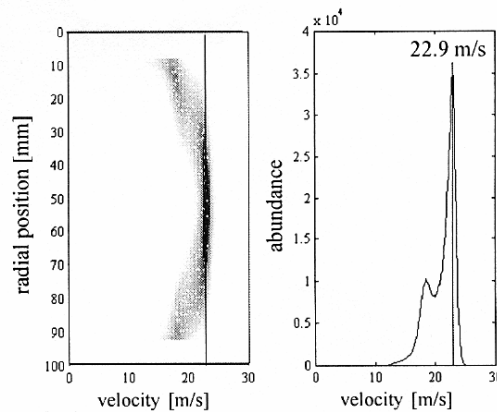


Figure 7. Flow profile (left) and frequency density distribution of flow velocity components

3. Self-monitoring system

In the self-monitoring system vortices are generated by a bluff body passing two ultrasonic waves. After demodulation of the signals the mean flow velocity is determined by the cross-correlation function, figure 8. In this case the periodic vortices are much stronger than other natural stochastic turbulences in the fluid. They dominate the cross-correlation function. While in natural turbulent flow the most frequent velocity components determine the peak of the ccf, as mentioned, and with that the measured flow velocity the periodic vortices are travelling with the real mean flow velocity. No corrections are needed. The travelling time can be detected directly from the cross-correlation function. A comparison of measurements with and without bluff body is shown in figure 9 [9]. The corresponding uncertainty is illustrated in figure 10. The measured uncertainty with the bluff body is obviously smaller than that without bluff body i.e. with natural turbulences.

The system is self-monitoring. If one of the sensors goes wrong vortex measurements still run but correlation measurements do not work. If any defects of the bluff body as result of abrasion, inclination or others occur cross-correlation measurements work well. The two measuring methods are

independent of and separated from each other. The principle results in increased reliability.

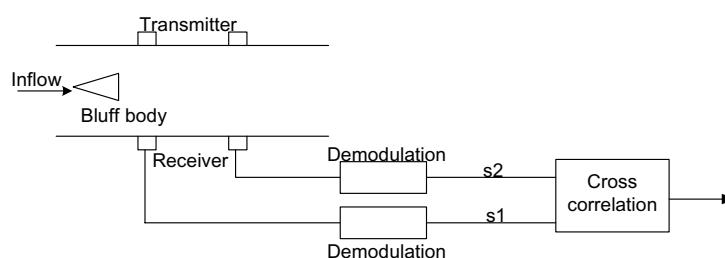


Figure 8. Self-monitoring system of vortex and cross-correlation Measurement

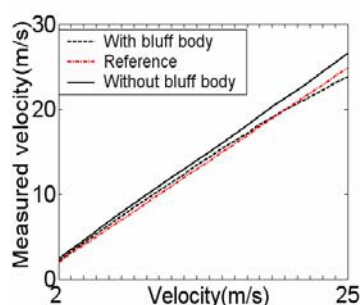


Figure 9. Measured flow velocity versus real flow velocity

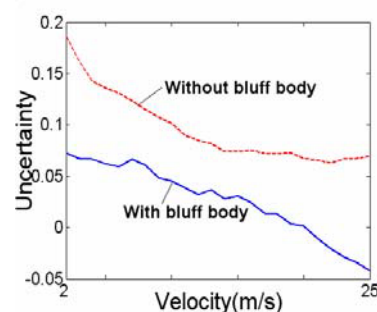


Figure 10. Measurement uncertainty with and without bluff body

4. Conclusion

The high sensitivity of ultrasound is best suited for the measurement of all kinds of natural and artificial turbulences in a streaming fluid. Small bluff bodies with pressure losses to be neglected result in high vortex frequencies which are directly proportional to the mean flow velocity. Cross-correlation functions determine the flow velocity of the most frequent velocity components in the turbulent fluid and require calibration. The correlation measurement of artificial vortices, however, results in a direct determination of the mean flow velocity. The combination of both vortex and cross-correlation measurement results in a self-monitoring system.

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