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IMPROVING VORTEX FLOW METERING USING ULTRASOUND

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ABSTRACT
Commercial vortex flowmeters use the well-known effect of Karman vortex street. The frequency of vortices generated in the wake of a bluff body is proportional to the average flow velocity. Usually it is detected by pressure sensors which are not very sensitive. Therefore bluff bodies of big sizes are required. An alternative method to detect the vortices in the streaming fluid is to use a high sensitive ultrasonic wave which is complex modulated. The demodulation can be executed by digital signal processing. Small sizes of bluff bodies can be realized. The bluff body size and the carrier frequency must be harmonized.

INTRODUCTION

Commercial vortex flowmeters are based on the physical effect that the frequency of vortices f behind a bluff body is proportional to the average velocity $\bar{u}$ of the flow

$$\bar{u} = f \cdot \frac{d}{S} \quad ,$$

where d is the diameter of bluff body and S is the Strouhal number.

The frequency of vortices usually is measured with pressure sensors which are installed in the pipe wall or in the bluff body. On account of the low sensitivity of pressure sensors, bluff bodies of large dimensions of about 24 – 26 per cent of the pipe diameter are necessary for generating well defined vortex structures and pressure signals [1, 2]. They result in high pressure losses of the flow.

An alternative method is presented by an ultrasonic barrier behind the bluff body perpendicular to the pipe axis and to the bluff body, figure 1. This technique is much more sensitive to inhomogeneous structures in the fluid than pressure sensors. The vortices modulate the ultrasonic signal complex in amplitude and in phase.

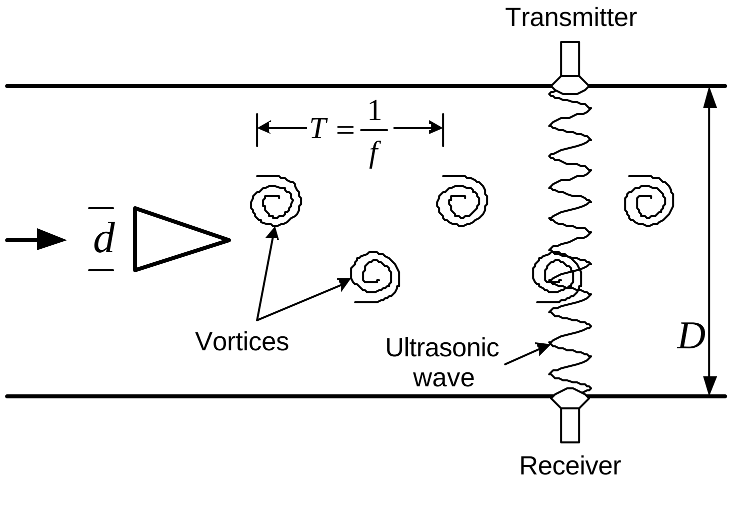

Figure 1: Principle of vortex shedding metering with ultrasonic wave

For simple signal processing it is necessary to get a well defined modulation of the signal. For this purpose special requirements of the geometry and size of the bluff body must be fulfilled.

The causality of the modulation is the interaction of properties of the streaming fluid and its vortices with the ultrasonic wave. Physically speaking vortices passing the ultrasonic wave lead to a modification of viscosity and result in amplitude modulation. Variations of pressure and density are damping the ultrasonic signal and modulate the amplitude, too. Phase modulation, however, is mainly caused by the mechanical drift of the ultrasonic wave by the fluid and by radial velocity components of vortices superposing the ultrasound velocity.

All these physical effects result in a complex modulation of the ultrasonic signal. The modulation frequency depends on the flow velocity and the size of bluff body. It is in the range up to 3 kHz and the side bands are very close to the carrier frequency. The separation of the side bands for further signal processing can be realized by digital undersampling [3].

Another physical effect to be considered is the influence of the carrier frequency of the ultrasonic signal. Modulation effects can only occur if the wavelength of the ultrasonic wave is smaller than that of the vortex street or other structures in the fluid.

Usually the vortex frequency f is defined by the one-sided separation of vortices which can be measured by pressure sensors in the pipe wall. In the case of ultrasonic measurements the wave is modulated by separating vortices on both sides of the bluff body. This effect doubles the sensitivity of the system because the modulation frequency is twice as high as the vortex frequency.

<u>SIGNAL PROCESSING</u>

Digital signal processing of complex modulated signals answers the purpose to separate the carrier frequency from the side bands by undersampling with an integer divisor [4, 5]. On the other hand the side bands containing the information about the modulation must fulfil the Nyquist theorem of the sampling frequency. In the present case the carrier frequency was in the range of 80 kHz to 220 kHz, with modulation frequencies of a few Hz up to 3 kHz. A sampling frequency of 20 kHz has been proved good.

The separation of amplitude modulated and phase modulated signal parts can be described by

$$a(t) = \sqrt{\left[\mathrm{Re}\{a(t)\}\right]^2 + \left[\mathrm{Im}\{a(t)\}\right]^2} \tag{1}$$

for the amplitude and for the phase by

$$j\,(t) = arc\ \tan \frac{\mathrm{Im}\{a(t)\}}{\mathrm{Re}\{a(t)\}} \quad . \tag{2}$$

As modulated oscillation is an analytical signal the real and imaginary parts are connected with the Hilbert transform. In digital signal processing the Hilbert transform can be easily realized by sampling two points of the signal shifted by 90 degrees [6]. As the $arc\ \tan$ function $j\,(t)$ is only valid in the range of $\pm p/2$ phase shifting outside this range can be reconstructed by special algorithms [7].

EXPERIMENTAL DEVICE

Experiments have been done with a set up shown in figure 2. The pipe diameter is D = 100 mm. The measuring cell is 50 D downstream of the flow inlet for a stationary fully developed flow profile. The test fluid used is air at 1 bar static pressure. The flow velocity is controlled in a range of 1 m/s to 30 m/s. A turbine gas meter is used as reference with an uncertainty within 1 % of the average flow. A lot of various shapes of bluff bodies have been tested. Only the main interested sizes and shapes will be presented in the following chapters.

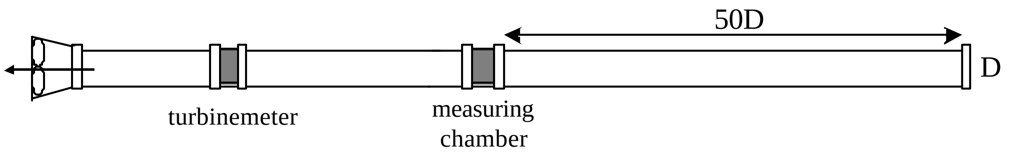

Figure 2: Experimental device

TRIANGULAR BLUFF BODY

As mentioned in literature a bluff body diameter of 24 % of the pipe diameter is recommended [1, 2]. In this connection it is assumed that the vortex frequency is measured by pressure sensors which are insensitive to low pressure changes in comparison to ultrasonic waves. Usually the flat side of the bluff body faces the inflow as shown in figure 3 (left). The simulation of the pressure plot shows that a vortex at the lower side has been fully separated but has brought a smaller secondary vortex in its wake [8].

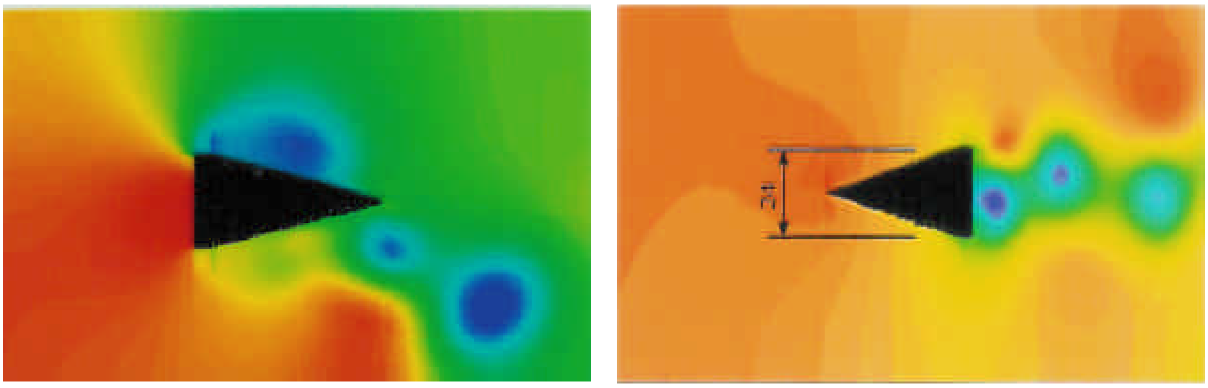

Figure 3: Simulated pressure field of a vortex street of triangular bluff body
left: flat side right: tip of the bluff body facing to the inflow

This secondary vortex will not be detected by pressure sensors but it modulates the ultrasonic wave leading to a second frequency of double value in the frequency domain. It prevents a simple signal processing.

The same shape and size of bluff body turned around by 180 degrees leads to very different results with large benefit for the ultrasonic measurement method. Figure 3 (right) shows the pressure plot of the triangular bluff body facing the tip to the inflow. Vortices separate on the backside without developing any secondary vortices. This arrangement leads to good sinusoidally modulation in the time domain and a single spectrum line resulting in simple signal processing.

The sensitivity of a triangular bluff body with a height of 24 percent of the diameter in an arrangement corresponding to figure 3 (left) is 6,7 Hz per m/s according to 6,7 primary vortices per meter. The Strouhal number is $S = 0{,}16$. The sensitivity of the same bluff body in an arrangement corresponding to figure 3 (right) is 14 Hz per m/s and a Strouhal number of $S = 0{,}34$.

On account of the high sensitivity of ultrasound it is self-evident to reduce the size of the bluff body systematically. Best results could be obtained with a bluff body 4 mm high and 8 mm long. This is a considerable reduction to 4 % of the pipe diameter resulting in drastically decreasing pressure losses. The sensitivity in the arrangement according to figure 3 (left) is 25 Hz per m/s with a Strouhal number of $S = 0{,}1$. The arrangement according to figure 3 (right) leads to much higher sensitivity of 60 Hz per m/s with a Strouhal number of $S = 0{,}24$.

Results with best sinusoidal modulation of the ultrasonic wave were obtained with a threaded control rod M 4. Naturally, this bluff body is unsuitable for practical industrial application on account of soiling of the thread. But it is well suited for basic investigations with well defined vortices, no disturbing effects and a distinct frequency spectrum. The characteristics are very stable. The sensitivity increases to 60 Hz per m/s with a Strouhal number of $S = 0{,}24$. The smallest size with good results was obtained by a threaded control rod M 3 with a sensitivity of 80 Hz per m/s and a Strouhal number $S = 0{,}26$.

In the following table 1 the results are summarized:

Bluff body		Stream	Sensitivity	Strouhal	Pressure losses
Shape	Size	to	in Hz per m/s	number	in Pa at u = 30 m/s
Delta	24 x 48	Flat side	6,7	0,16	109
Delta	24 x 48	Tip	14	0,34	87
Delta	4 x 8	Flat side	25	0,1	42
Delta	4 x 8	Tip	60	0,24	20
Threaded control rod	M 20		12,8	0,26	75
	M 4		60	0,24	18
	M 3		80	0,24	15

Table 1: Characteristic data of different bluff body sizes and arrangements

An important parameter for vortex measurements is the carrier frequency of the ultrasonic wave. The ultrasonic wave can only be modulated by structures greater than the wave length of ultrasound. Experiments have been made with carrier frequencies of 80, 160 and 220 kHz with corresponding wavelengths of 4,25 , 2,13 and 1,55 mm.

The periodicity of the vortices depends on the size of the bluff body. The smaller the bluff body size the smaller is the periodicity of vortices. In the present case the size is a threaded control rod M4 causing a periodicity of vortices of 16,7 mm. In addition to the vortices, natural turbulences modulate the signal resulting in noise.

Figure 4 shows an example of the influence and interaction of carrier frequency and bluff body size at a flow velocity of $u = 25\ m/s$. At low carrier frequency of 80 kHz noise is much more in evidence than at higher frequencies.

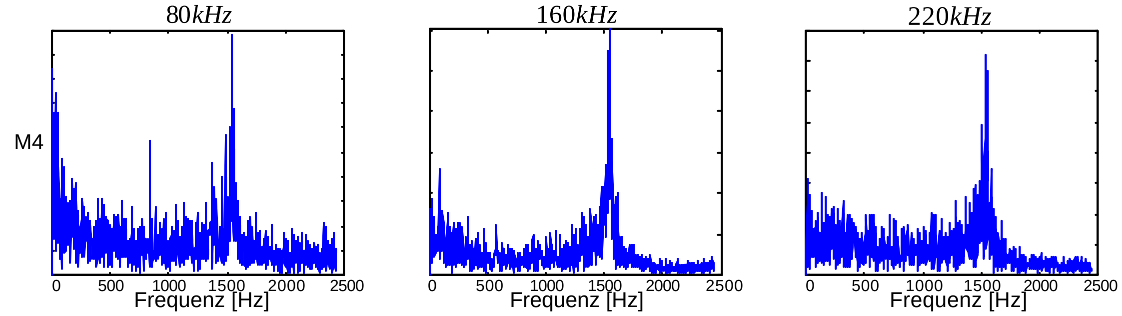

Figure 4: Spectrum of phase demodulated signal of M 4 bluff body for different carrier frequencies at flow velocity $u = 25\ m/s$

In comparison to a small bluff body size a big size of M 20 is shown in figure 5. The sensitivity is 12,8 Hz per m/s with $S = 0{,}256$. The permissible range of phase modulation is exceeded by the interaction of the very big vortices with the small wave length of the 220 kHz carrier frequency. Only noise of smaller structures can be observed. The phase angle of the lower carrier frequency of 80 kHz is much less affected by the big vortices and a distinct peak in the spectrum indicates the vortex frequency.

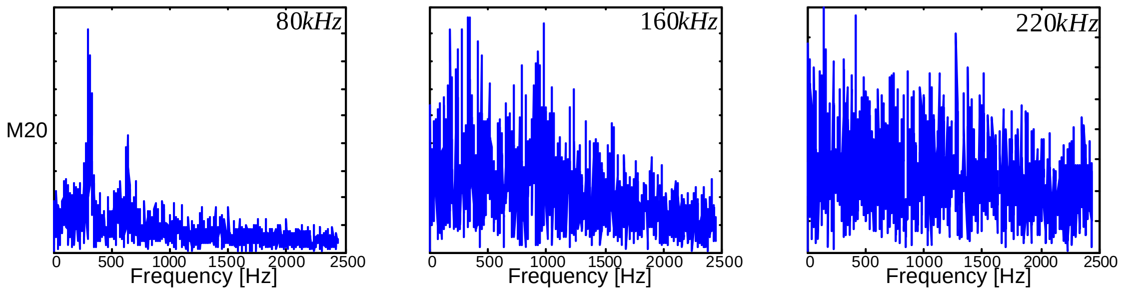

Figure 5: Spectrum of phase demodulated signal of M 20 bluff body for different carrier frequencies at flow velocity $\bar{u} = 25\ m/s$

The phase modulation by big and low frequent vortices caused by big bluff body sizes leads to high modulation degrees of higher carrier frequencies exceeding the range of the *arc tan*-function. This effect is smaller for lower carrier frequencies with longer wave length. That means that carrier frequency and bluff body size must be adapted. High carrier frequencies are well suited for bluff bodies of small sizes whereas bluff bodies of big sizes require low carrier frequencies.

CONCLUSION

A vortex metering method using ultrasound has been introduced. Commercial vortex meters detect the vortex frequency with pressure sensors. They need big bluff body sizes for the generation of big vortices causing high pressure differences. Ultrasonic waves are very sensitive to all kinds of modulating structures. Therefore small vortices lead to phase modulations which are clearly defined resulting in distinct peaks in the spectrum which can be easily detected by simple signal processing. Shape and size of the bluff body determine the sensitivity of the system. The carrier frequency of the ultrasonic wave and the bluff body size must be harmonized. On account of small sizes of bluff body pressure losses can be reduced drastically.

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