INFLUENCE OF TURBULENCE ON ULTRASONIC FLOW MEASUREMENTS

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ABSTRACT

The Ultrasonic transit time method is well established to measure the volumetric flow rates of liquids and gases. In most applications the measured flows are turbulent. The ultrasonic measurement technique has advanced to a level of accuracy where the turbulence of the measured media is the main source of fluctuations in the measured flow value. Experiments on flowmeters with different diameters were performed to characterise the statistical properties of the turbulence induced fluctuations. The results have practical implications on the repeatability of volume metering by ultrasonic methods.

INTRODUCTION

Ultrasonic flow meters operating on the transit time principle are popular metering devices for a broad range of media ranging from natural gas to oil and, of cause, water. In water metering and control applications ultrasonic meters posses several advantages as low pressure loss, low maintenance and a cost advantage, especially for large pipe diameters. So called Clamp-On devices also operate non-intrusively, which makes them often the only available solution to a metering problem.

For any flow meter the accuracy, range, repeatability etc. of the device are important parameters to determine if the meter is appropriate for a given application.

This contribution focuses only on the repeatability of flow measurements with ultrasonic transit time meters. Theoretical considerations show how turbulence affects the meter reading, i.e., how the statistical properties of the turbulent flow determines the statistical properties of the fluctuations of the meter reading. The measurements we performed on different size ultrasonic flow meters support our view that turbulence is in fact the mayor source of fluctuations in the measurement signal. Especially electronic noise can be neglected in comparison to turbulence induced noise.

Because there is always a trade off between response time and repeatability our findings have implications for applications where a high repeatability and a fast response time is needed, for example in leak detection applications.

1 ULTRASONIC FLOW MEASUREMENT

To understand the influence of turbulence on ultrasonic flow measurement we first review the basic principle of the transit time method: The velocity of sound propagation in a flowing medium is increased by the flow velocity if the sound travels in the flow direction. Consequently, the transit time of an ultrasonic pulse is decreased when traveling with and increased when traveling against the flow, respectively.

Figure 1 A) shows a meter operating on the transit time principle. In such a device the difference in transit times Δt of ultrasonic pulses with and against the flow is measured. Pulses travel on a sound path that is tilted by an angle α through the medium with sound velocity c. According to [1] the transit time difference is given by the flow velocity component along the sound path averaged over its length. For the typical case that the sound traverses the medium much faster than the time scale of changes in the flow field one obtains:

$$V(t) \equiv \Delta t \frac{c^2 k}{2L} = \frac{k}{L}\int_0^L v(x,t)dx \qquad (1),$$

with $k = \sin(\alpha)^{-1}$.

The path averaged flow velocity can be envisaged as a snap shot of the flow field along the path. Assuming a certain flow profile the area averaged velocity, and from this the volumetric flow rate, are calculated from the path velocity. Alternatively, the total flow velocity can be approximated without assumptions on the flow profile by measuring the velocity over several paths.

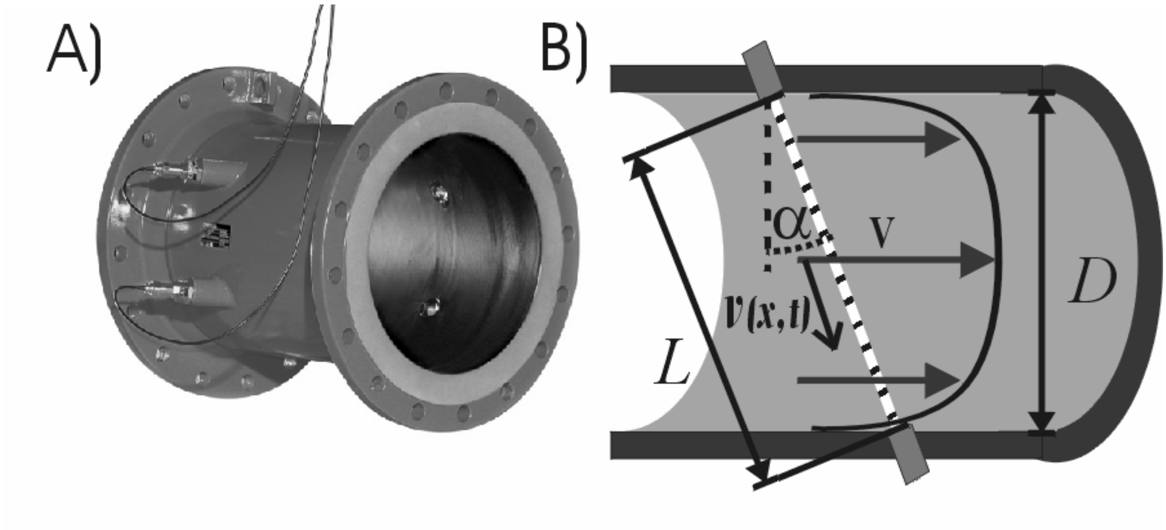

Figure 1 – (A) Ultrasonic flow meter with two parallel paths. (B) Schematic view of a sound path and flow profile.

In most applications the flow will be turbulent so that the flow field is never stationary. Even under constant flow conditions random fluctuations are superimposed on the well known flow profiles for turbulent pipe flow. According to (1) these fluctuations directly lead to fluctuations in the measured flow rates and more over, the statistics of the turbulent fluctuations determines the statistics of the fluctuations in the meter reading.

2 MEASUREMENT OF TURBULENT FLOWS

The fluctuations of the measured flow velocity with respect to the time averaged velocity $\overline{V}$ are given by:

$$\delta V(t) = \frac{k}{L}\int_0^L \delta v(x,t)dx \qquad (2).$$

In the following sections we will try to deduce the statistical properties of the measured fluctuations from the statistical properties of turbulent pipe flow and present corresponding measurements.

2.1 Fluctuation amplitude

The mean square amplitude of the fluctuations deduced from (2) is given by $\overline{\delta V^2} = \left(\frac{k}{L}\right)^2 \int_0^L\int_0^L \overline{\delta v(x)\delta v(x')}dxdx'$. The data for the spatial correlation function of the turbulent fluctuations along the ultrasonic path which is involved in the calculation of the amplitude has not been measured directly so far. It is, however, well known that the spatial correlation does not vanish, because the turbulent flow field consist of vortices of different length scales. The experimental results on the correlation of turbulent fluctuations in [2] are sufficient to estimate the order of magnitude of the correlation. In [2] a typical amplitude $\overline{\delta v^2(x)} \approx 10^{-3}\overline{V}^2$ of the turbulent velocity fluctuations was reported and we thus estimate:

$$\overline{\delta V^2} \approx 10^{-3}\overline{V}^2 \text{ and } \Delta V = \sqrt{\overline{\delta V^2}} \approx 0.03\overline{V} \qquad (3).$$

The exact value of the pre-factor in (3) depends of cause on the ultrasonic path geometry, i.e., the angle α. Similar findings of numerical simulations have been reported in [3].

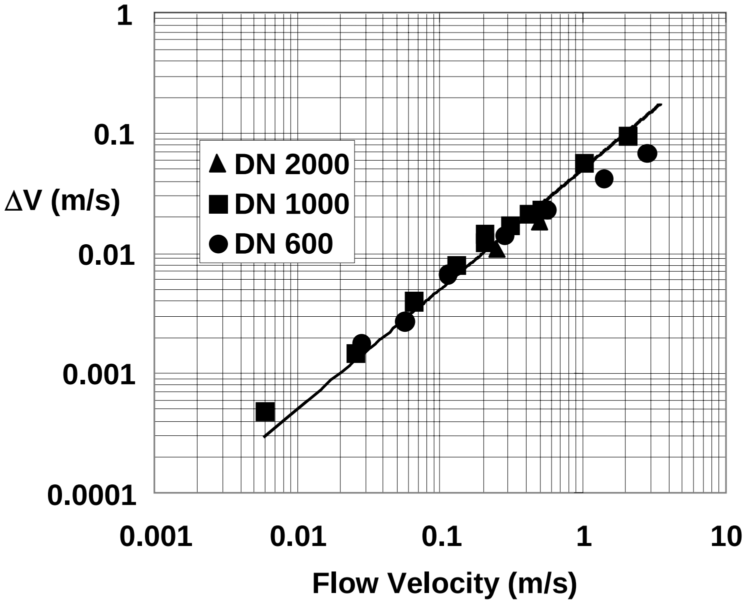

Figure 2 – Standard deviation *ΔV* of the flow velocity measurements as function of the flow velocity for different nominal pipe diameters DN in mm.

Measurements to confirm the above predictions were performed with Inline ultrasonic meters of the type shown in figure 1 (A) where α = 37° and diameters 350, 600, 1000 and 2000 mm. The flow velocity reading (1) of the meter was sampled with a frequency of 5 Hz under different constant flow conditions in a calibration rig with 6 m of straight inlet after a flow conditioner. The standard deviation of the velocity fluctuations is plotted against the flow velocity in Figure 2 and shows the predicted scaling and size. Especially at very low flow velocity the scaling is still valid which shows that the fluctuations of the meter reading are in fact determined by the fluctuations of the turbulent flow. Other sources of noise in the meter reading, like electronic noise, can be neglected.

2.2 Fluctuation time scale

Because fluctuations of the meter reading are usually damped by averaging over a certain time interval the time scale of the fluctuations is important. The number of statistical independent measurements in the averaging time interval is determined by the temporal correlation of the fluctuations. Only averaging over statistically independent measurements leads to a reduction of the fluctuation amplitude.

In fact one expects the measured velocity fluctuations to be correlated with time [2]. This correlation is caused by vortices in the turbulent flow that decay only slowly in a frame moving with the average flow. In the ultrasonic flowmeter the vortices are transported past the measurement sound beam by the average flow velocity and their spatial correlation leads to temporal correlation of the measured velocity values.

To confirm this we calculated the temporal auto-correlation function $C(t)=\frac{1}{T\overline{\delta V^2}}\int_0^T \delta V(t')\delta V(t'-t)dt'$ from the measured data sets. We defined the correlation time τ, i.e., the time after which successive velocity measurement become statistically independent by $C(\tau)=0.5$. Figure 3 shows the measured correlation times. The correlation time increases with decreasing velocity and increasing pipe diameter and scales approximately as $\tau \propto D/\overline{V}$.

At high velocities the correlation time is bounded by the sampling frequency of the flow measurements (5 Hz). It is important to note that as long as the correlation time of the flow is larger than the sampling time an increase in the sampling frequency of the meter does not yield additional information on the flow.

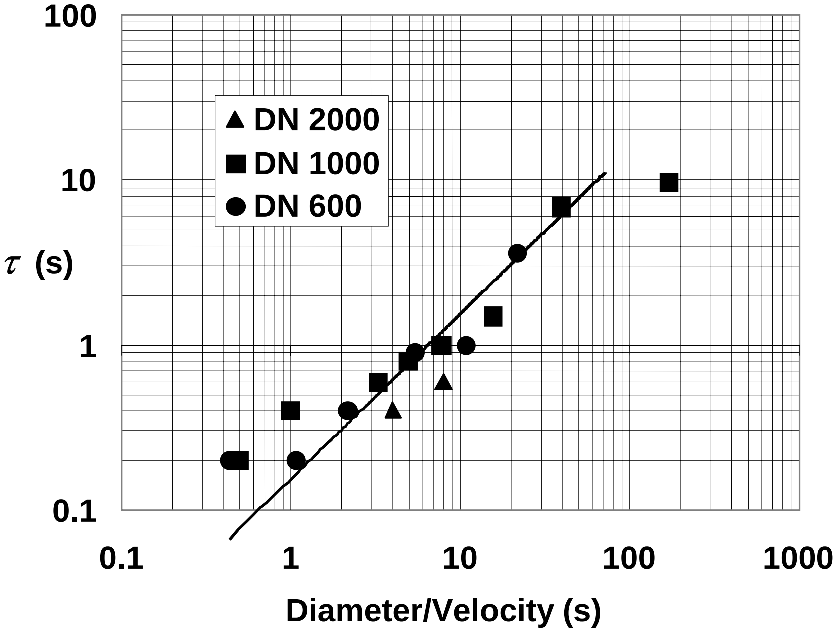

Figure 3 – Scaling of the correlation time of velocity fluctuations with meter diameter divided by flow velocity.

4 DISCUSSION

The above scaling relations lead to an estimate of the repeatability of a volume measurement with an ultrasonic flow meter. It is important to note that the fluctuations in the measured volume are only caused by the turbulent fluctuation in the flow and not by electronic noise of the meter electronics.

Assume we meter the flow with average flow velocity $\overline{V}$ during the time T and the measured volume will be $Vol \propto \overline{V}D^2T$. During this time $T/\tau \propto Vol/D^3$ measurements are statistically independent, assuming $T > \tau$. Because of (3) the mean square of the measured volume fluctuations scales like $\overline{\delta Vol^2} \propto Vol \cdot D^3$, or $\overline{\delta Vol^2} \approx 10^{-3} Vol \cdot D^3$, approximately. The relative statistical error of the measured volume caused by the turbulent fluctuations is given by:

$$\Delta Vol/Vol = \sqrt{\overline{\delta Vol^2}}/Vol \approx 3\%\sqrt{D^3/Vol} \qquad (4).$$

Again the exact value of the pre-factor in (4) depends on the sound path geometry. Data for the relative standard deviation of repeated volume measurements for meters of different size and under different constant flow conditions are shown in figure 4, confirming the scaling relation (4).

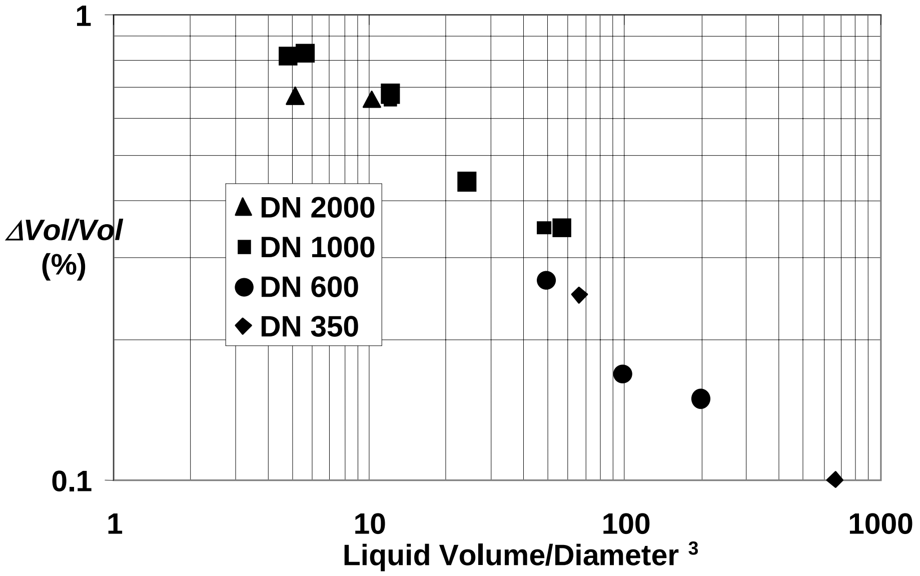

Figure 4 - Relative standard deviation of measured volumes. The standard deviation scales with the square root of volume divided by the cube of the pipe size.

To conclude, it was demonstrated that the dominant source of fluctuations in flow reading for an ultrasonic flow meter are the turbulent fluctuations of the flow. This leads to fluctuations of the measured volumes. For a typical meter configuration the standard deviation when repeatedly metering the 'meter volume' D^3 is about 3% of the volume. For larger volumes, which are of more practical relevance, the standard deviation decreases with the square root of the volume divided by the cube of the meter size.

NOMENCLATURE

α	angle of sound path	(deg)
c	sound velocity of liquid	(m/s)
$C(t)$	correlation function	
D	pipe diameter	(mm)
DN	nominal pipe diameter	(mm)
L	length of ultrasonic path	(mm)
τ	correlation time	(s)
$v(x,t)$	flow field component along sound path	
$V(t)$	velocity along sound path	(m/s)
$\bar{V}$	average velocity	(m/s)
$\delta V(t)$	fluctuation of velocity	(m/s)
ΔV	standard deviation of velocity	
Vol	measured volume	
ΔVol	standard deviation of volume	

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