Study on Transducer Protrusion Effect of Ultrasonic Flowmeter Using Wind Tunnel and LDV

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Abstract

Transducer protrusion into the flow is one of the most important uncertainty sources of ultrasonic transit-time flowmeters. It introduces a symmetric error by locally distorting the velocity profile along the acoustic path, and incomplete sampling of velocity along the path that arises from the transducer not being flush mounted in conduits or channels. Transducer protrusion effect depends on the protrusion ratio and the shape of the transducer mount. It should be estimated and corrected for flowmeters without being calibrated using flow standard facility. A stretchable model transducer made of plexi-glass is mounted on a flat plate in wind tunnel. Local velocity distributions are observed along possible acoustic paths using Laser Doppler Velocimetry (LDV) technology. Three different positions of transducer protrusion are tested to analyse mechanism of protrusion effect and its correction method. Assuming that the transducer protrusion only distorts path velocity profile in a certain distance and velocity profile beyond this distortion distance stays the same, protrusion effect for different path lengths can be estimated using a three-zone (two distorted velocity zones at both ends and one undistorted zone in the middle) distance-weighted averaging method. Based on this quantitative analysis of the protrusion effect, better measurement performance should be obtained for flowmeters with similar transducer design. Although the experiment is done in a wind tunnel, it is also applicable to water flowmeters after a scale conversion under Reynolds law of similarity.

Key words: flowrate, ultrasonic transit-time, transducer Protrusion, wind tunnel, LDV

1 Introduction

The ultrasonic flowmeter is popularly used, especially for flow rate measurement in conduits and channels with large cross section. The ultrasonic flowmeter has many advantages e.g. no pressure loss, high accuracy and the possibility to be installed on existing conduits and channels. This type of flowmeter is based on the principle that the ultrasonic pulse transit times along acoustic paths are altered by the fluid velocity. An ultrasonic pulse sent upstream travels at a slower speed than an ultrasonic pulse sent downstream. Thus, acoustic paths cannot be perpendicular to the flow direction, and transducers are mounted with their surface at a degree with respect to the inner surface of conduits or open channels.

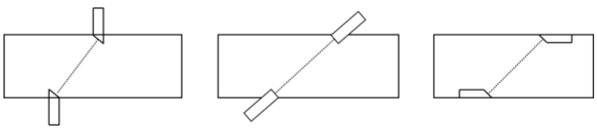
It has been found that transducer mounting introduces a systematic error and shall be considered in an uncertainty analysis. Voser et al. (1996) numerically simulated flow in hydraulic smooth and rough conduits with the flow rate measured by an 8-path ultrasonic flowmeter, and found that the measurement error due to transducer protrusion must be taken into account. Transducer protrusion or recession locally distorts velocity profile along the acoustic paths, and causes incomplete sampling of velocity along the paths. The uncertainty depends on the Reynolds number and the shape of the transducer mount (projecting or recessed). The effect of local velocity profile distortion and that of incomplete sampling tend to be in opposite directions, with the former underestimates while the latter overestimates flow rate, but do not typically cancel completely. According to the results of Voser (1996), the transducer protrusion error was smaller than ±0.5% for diameters larger than 2 m and velocities greater than 0.1 m/s, and the findings were experimentally confirmed by Lowell et al. (1998). The systematic error for any installation is highly dependent on the transducer design and may vary from the above values. When the ratio of the protrusion of the transducer to the path length exceeds 0.25%, then validated CFD analysis or hydraulic laboratory testing of the transducer must be performed. Correction factors and the associated uncertainty, including the shape and design of the transducer, shall be documented. Zheng et al. (2011) and Zhang et al. (2012) used respectively the CFD method and physical experimentation to investigate the effect of different transducer mountings on ultrasonic flow rate measurement.

To improve the accuracy of ultrasonic flow measurement, taking into account the effect of transducer protrusion, it is desirable to know the flow details in the vicinity of the transducers. Using numerical simulations, visualizations and Laser Doppler Velocimetry (LDV), Loland et al. (1998) investigated the 2D vortex structure inside a transducer cavity. Raisutis (2006) described a methodology for measurement and experimentally obtained results of local flow velocity components using invasive flow sensors (thermoanemometers) in the transit time ultrasonic flowmeter recesses. It was found that the symmetry of flow profile along ultrasonic paths were destroyed by the recesses and an additional measurement error might occur if calculating the total flowrate not taking into account the local character of the profile distortions.

The objective of this research was an experimental investigation of the flow velocity profiles along the acoustic paths and in turn their impact on flow rate measurement using the ultrasonic flowmeter. For this purpose a stretchable model transducer made of plexi-glass was mounted on a flat plate in a wind tunnel. Local velocity profiles in the vicinity of the transducer were observed along possible acoustic paths using Laser Doppler Velocimetry (LDV), and from the observation the effect of transducer protrusion was analyzed. Although the experiment was carried out in a wind tunnel, the findings can be also applied to water flow rate measurement after a scale conversion.

2 Transducer protrusion effect

As illustrated in Fig. 1 the mount of transducers can be perpendicularly or inclined inserted into the walls of conduits or channels, or pasted on the inner wall surface. Either way, the surface of transducers must be at a degree with respect to the inner surface of conduits or channels.



(a) Perpendicularly inserted (b) Inclined inserted (c) Pasted

Fig. 1 Installation of ultrasonic flowmeter probe

As stated in the previous subsection, no matter how transducers are mounted, their surface must be at a certain angle with respect to the inner surface of conduits or channels. Thus the transducers are either projecting to or recessed from the flow. It has been widely acknowledged that transducer protrusion or recession locally distorts velocity profile along the acoustic paths, and causes incomplete sampling of velocity along the paths. This introduces a systematic error and shall be considered in an uncertainty analysis.

As in Fig. 2, the length between the opposite walls along the acoustic path is denoted as L, and the distance between the surface of the transducer and the correspondent wall t. When the transducer is projecting t is positive, while t is negative when the transducer is recessed. Assuming that the transducer only distorts velocity profile in a certain distance along the path and velocity profile out of this distortion distance stays the same, the distortion distance of the transducer at the upstream and downstream end is respectively denoted as b_1 and b_2. The acoustic path was divided into three zones, two distorted velocity zones at both ends and one undistorted zone in the middle. In the undistorted zone the velocity is unchanged while in the two distorted velocity zones flow velocity is not as same as that without the transducer. In this study we would investigate the disturbed flow filed around upstream and downstream transducers and analyze transducer protrusion effect by weighted average method.

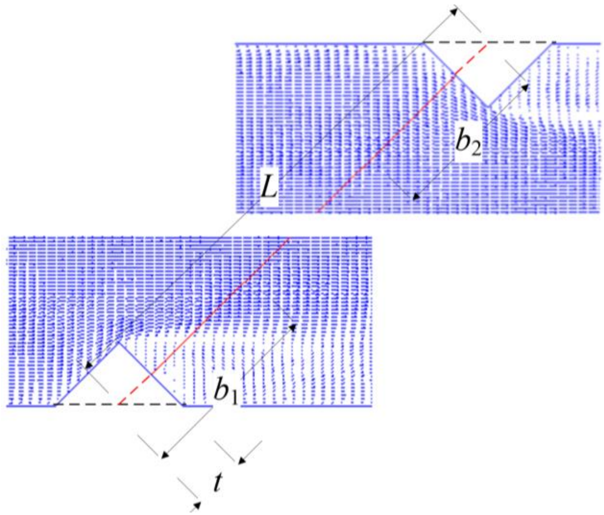


Fig. 2 Sketch of disturbed flow filed around upstream / downstream transducers used to analyze protrusion effect

3 Experimental setup

3.1 Wind tunnel and LDV

The NIM wind tunnel showed in Fig. 3 is designed and used to calibrate anemometers like Pitot tubes, hot wires, etc. The axial fan at the downstream drives air flow from the test section through the diffuser. The upstream flow conditioning section starts from a honeycomb where there are 4 layers of nets regulating flow and shattering swirls produced in the upstream, and then a contraction nozzle with Vischinski shape curve of a 9:1 contraction ratio. The total length of the tunnel, including the flow conditioning section, test section, diffusor, and axial fan, is 6.8 m. It can provide a stable jet flow with the velocity in the range of (0.2~30) m/s after the 200 mm diameter nozzle. The jet flow is very stable and the profile of the axial velocity is very flat. The standard deviation of the axial velocity measured by LDV is only 0.35% in the range of (-70 mm, 70 mm) away from the nozzle outlet.

DanTec LDV showed in Fig.4 (a) is used as the working standard for anemometer calibration. LDV is a widely accepted tool for fluid dynamic investigations in gases and liquids with particular advantages of non-intrusive measurement, high spatial and temporal resolution. It is very suitable for applications with reversing flow where physical sensors are difficult or impossible to use. Liquids often contain sufficient natural seeding, whereas gases must be seeded. We used a smoke generator upstream of the honeycomb to seed particles about 10 µm in diameter which would reach the jet flow we investigated. Uncertainty of our LDV is expected to be less than 0.3% (k=2) which can be ensured by the test result using our spinning-disc LDV calibration facility.

3.2 Mounting plate and velocity measurement around probe bar

To investigate the local velocity field in the vicinity of transducers projecting into or recessed from the flow at a variety of distance, and in turn assess the impact on ultrasonic flow rate measurement, a 400 mm long and 200 mm wide plate as depicted in Fig.4 was manufactured. In the center of the plate, there is an inclined circular hole with a diameter of 36 mm. In the hole a cylindrical bar was mounted to mimic the transducer, and the position of the bar is variable, which can mimic the transducer projecting into or recessed from the flow. The plate is 10 mm thick, except for that around the hole it is thickened to help fix the bar and the edges are beveled to reduce the disturbance on the flow field. The plate was vertically fixed in the test section of the wind tunnel, 10 mm downstream from the nozzle. The plate was parallel to the axis of the wind tunnel with the side facing the model transducer at a distance of 50 mm to the wind tunnel axis. The axis of the hole housing the transducer is at the same height with the axis of the wind tunnel. The velocity distribution in the core region, within the radius of 70 mm around the axis, is nearly uniform, and the plate is right inside this region. Through measuring the velocity in the vicinity of the transducer, the disturbance of the transducer on the flow field can be assessed.

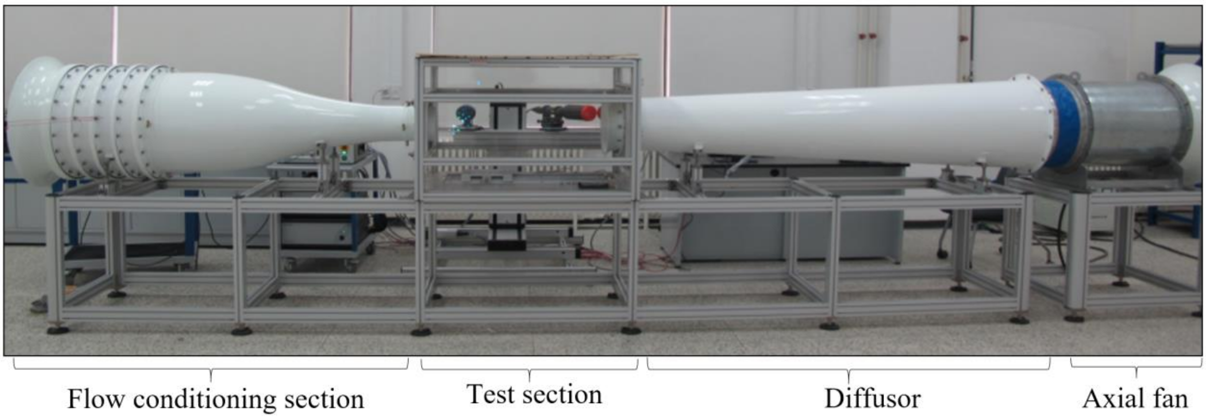
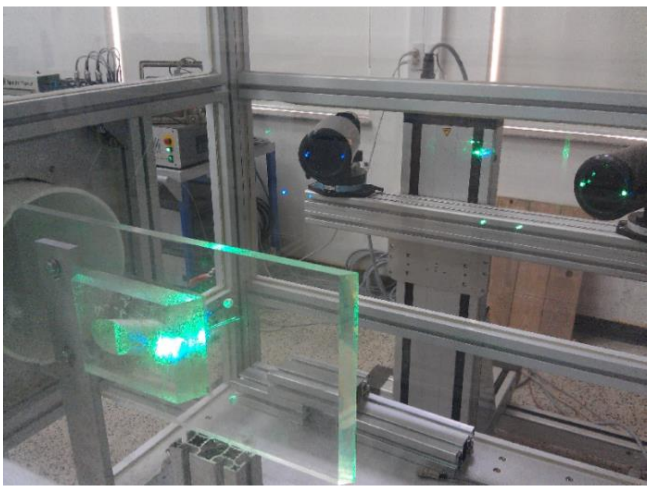
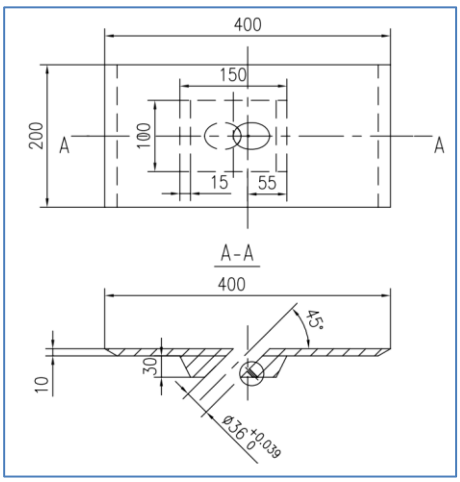


Fig. 3 Photo of NIM wind tunnel



(a) Test layout



(b) Dimensional drawing of mounting plate

Fig.4 LDV and test layout

The experiments were carried out with the velocity in the core region of the jet being 15 m/s. The velocity distribution under our concern is that in the vicinity of the transducer along the acoustic path as in Fig. 5. The diameter of the transducer is not infinitesimal but finite, and the ultrasonic pulse sent from transducers also has a finite size. The vortex generated because of the disturbance of solid walls make the velocity distribution in the cross-section of the ultrasonic wave beam non-uniform. So besides the center point M, we chose 4 additional points L, R, U and D at the surface of the transducer as in Fig. 5(b). Each of the 4 points is 10 mm away from the center. Supposing the five points are where the possible acoustic paths intersect the surface of the transducers, the velocity distribution in the vicinity of the transducer along the five possible acoustic paths were measured using two LDV probes. The velocity far away from the transducer, i.e. in the undistorted zone, was not measured, and supposed undisturbed, and it was considered that the distortion distance b_1 and b_2 were not greater than 75 mm.

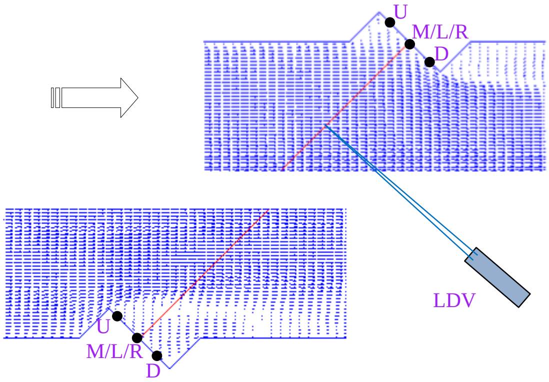
The velocity profiles within the distortion distance along the 5 supposed acoustic paths, as depicted in Fig. 5(a), were measured using LDV in each case. Velocity profiles around both an upstream facing and downstream facing transducer were measured. A transducer facing upstream is called downstream transducer, while a transducer facing downstream called upstream transducer hereinafter. Since an upstream transducer is symmetric to a downstream one, the two kinds of transducers were switched by rotating the plate 180 degrees in the vertical plane. We also measured the flow field with only a plate in the wind tunnel, and it was used as the reference velocity distribution.

4 Results analysis

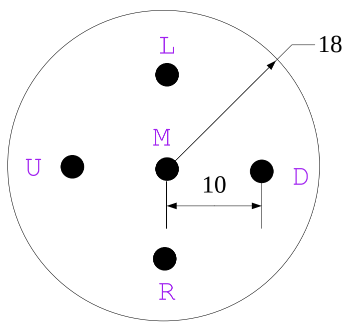
4.1 Velocity distribution along acoustic path

The local flow field was observed and measured in the vicinity of the model transducer, with the velocity in the core region of the wind tunnel being 15 m/s. The intervals between the measuring points were adjusted according to the velocity gradient, and the minimum value is 1 mm. The profiles of the velocity v along the acoustic paths corresponding to the three mounting methods, with respectively projecting, half-projecting, and recessed transducers, were illustrated in Fig. 6. In Fig. 6, v_0 is the undisturbed velocity, and D = 36 mm is the diameter of the mounting hole. In Fig. 6, the horizontal coordinate 0 corresponds to the surface of the transducer. When the transducer was projecting then $t = 0.5D$; when the transducer was half-projecting $t = 0$; and when the transducer was recessed $t = -0.5D$.

From Fig. 6 it can be seen that no matter how the transducer was mounted, the distortion distance was not greater than 2.5D. Within the distortion distance there was difference not only among the velocity profiles of the three mountings, but between of the upstream and downstream transducers. As in Fig. 6 (a), when the transducer is projecting, the velocity profiles along the five acoustic paths around the downstream transducer are nearly the same; while the velocity profiles along the five acoustic paths around the upstream transducer were very different. This was because that there was vortex forming downstream from the transducer. In Fig. 6(b) it can be seen that the velocity profiles around a half-projecting upstream transducer were similar to those around a projecting upstream transducer, while the profiles around a half-projecting downstream transducer were quite different. Fig. 6(c) shows that the difference among profiles around a recessed downstream transducer was more significant than that around a half-projecting one; the velocity profiles around a recessed upstream transducer were still similar to the other two kinds of upstream transducers. The difference of velocity profiles among different kind of mountings indicated that the measure acoustic path average velocity should be corrected according to the correspondent mounting.

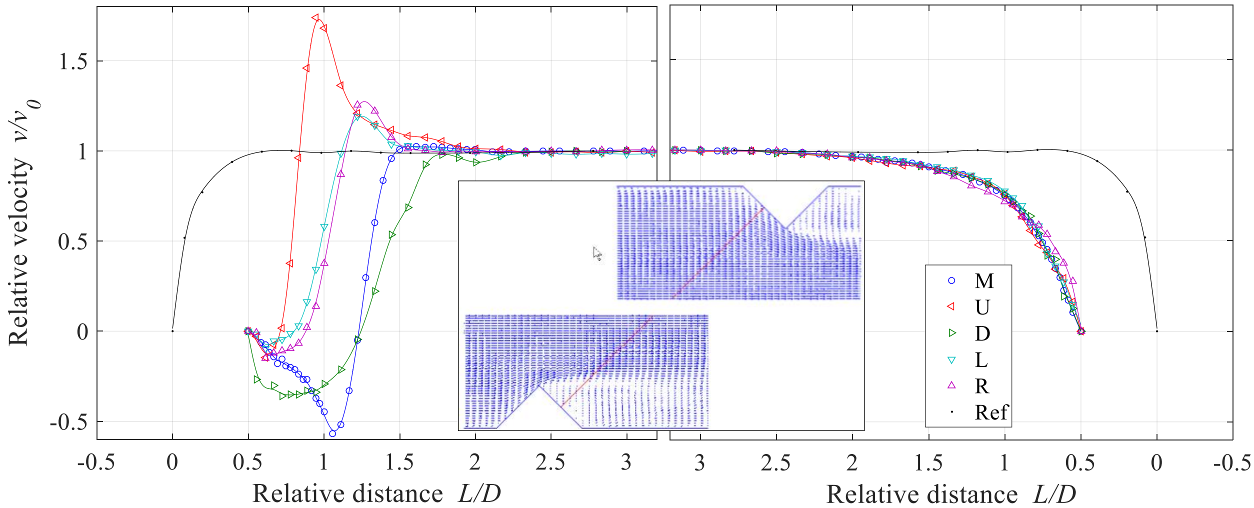


(a) Top view

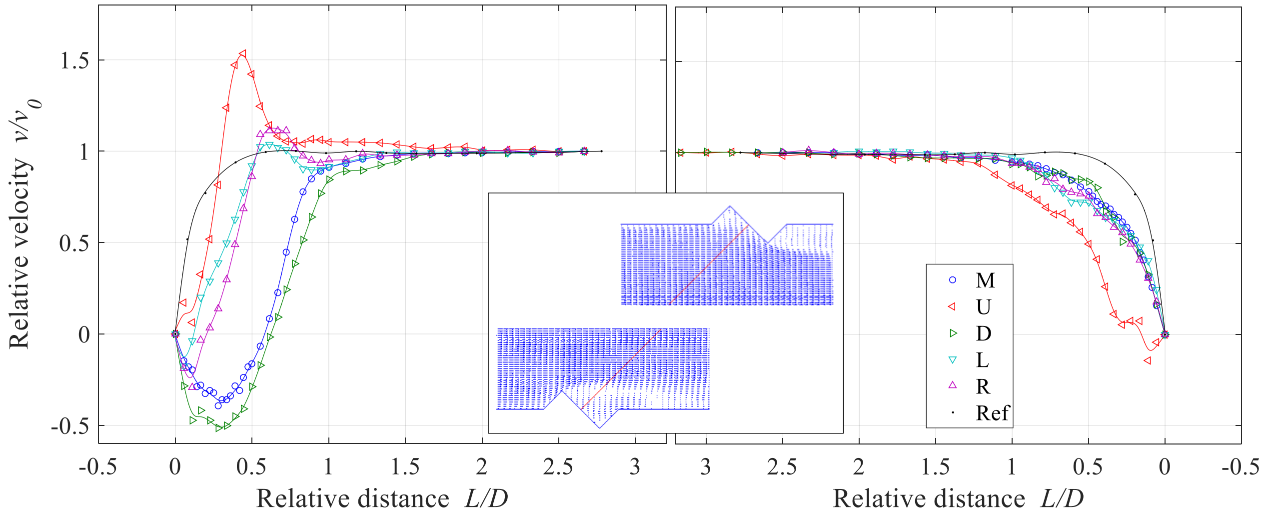


(b) End-face points

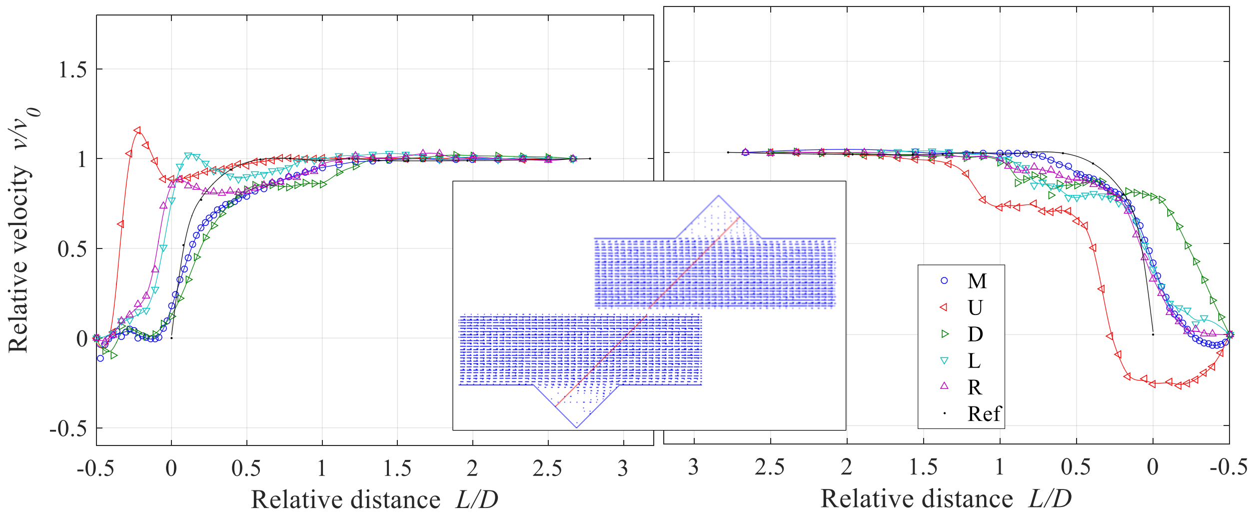
Fig. 5 configuration of velocity-tested path



(a) Protrusion position



(b) Middle position



(c) Recessed position

Fig.6 Velocity distribution along acoustic path

4.2 Effect on flowrate calculation

Through the comparison of the velocity profiles along the acoustic path with and without the disturbance of the transducers, the errors brought about by this disturbance can be analyzed. As stated above supposing the length between the opposite walls along the acoustic path is L, and the distance between the surface of the transducer and the correspondent wall is t. Then t = 0.5D, 0, and -0.5D respectively for projecting, half-projecting and recessed transducers. From the results in the previous subsection the distortion distance of the upstream and downstream transducer, b_1 and b_2, can be assumed that b_1=b_2=2.5D. Based on this, the averaged velocities of the three zones, two distorted velocity zones at both ends and one undistorted zone in the middle, were calculated and listed in Table 1.

Table 1 Relative velocity in distorted velocity zones

start point of path	protrusion position		middle position		recessed position	
	down	up	down	up	down	up
M	0.803	0.497	0.872	0.630	0.797	0.746
U	0.798	0.972	0.737	0.988	0.564	0.935
D	0.802	0.410	0.867	0.556	0.840	0.732
L	0.815	0.775	0.868	0850	0.782	0.852
R	0.808	0.751	0.858	0.831	0.771	0.829
reference	0.943					

* ’down’ means local average velocity near downstream probe, and ‘up’ means upstream side probe.

When the transducer is projecting t is positive, while t is negative when the transducer is recessed. Assuming that the transducer only distorts velocity profile in a certain distance along the path and velocity profile out of this distortion distance stays the same, the distortion distance of the transducer at the upstream and downstream end is respectively denoted as b_1 and b_2. The acoustic path was divided into three zones, and in the undistorted zone the velocity is unchanged while in the two distorted velocity zones flow velocity is not as same as that without the transducer.

From the velocity of each zone, a length-weighted average velocity of each acoustic path was calculated for all the cases including the reference case.

$$V_m = \frac{V_1 b_1 + V_2 b_2 + V\left(L - b_1 - b_2\right)}{L} \quad (1)$$

$$V_m^{'} = \frac{V_1'\left(b_1 - t\right) + V_2'\left(b_2 - t\right) + V\left(L - b_1 - b_2\right)}{L - 2t} \quad (2)$$

Thus we arrived at the error of transducer disturbance for different length of acoustic paths,

$$E = \frac{V_m^{'} - V_m}{V_m} \times 100\% \quad (3)$$

as illustrated in Table 2. When calculating $V_m^{'}$, the acoustic path with the fastest ultrasonic speed was chosen, that is maximum value of local average velocities around both downstream and upstream probe should be used when ultrasonic wave travels downstream and minimum value of local velocities should be used when wave travels upstream.

The results in Table 2 show that the error brought about by the transducers is always negative, no matter the transducers are projecting, half-projecting or recessed. And the impact of the transducers positively correlates with the protrusion ratio. It is noteworthy that only results with v_0 =15 m/s were presented in this paper. In fact, according to our research, the variation of v_0 has an insignificant effect on the magnitude of the error。

Table 2 Error for different length acoustic paths

Channel width (mm)		1000	3000	5000	10000
path length (mm)		1414	4243	7071	14142
reference	V_m	0.9928	0.9976	0.9986	0.9993
protrusion position	R_p	2.55%	0.85%	0.51%	0.25%
	$V_m^{'}$	0.9738	0.9914	0.9949	0.9974
	E	-1.92%	-0.62%	-0.37%	-0.18%
middle position	R_p	0	0	0	0
	$V_m^{'}$	0.973	0.991	0.9946	0.9973
	E	-1.99%	-0.66%	-0.40%	-0.20%
recessed position	R_p	-2.55%	-0.85%	-0.51%	-0.25%
	$V_m^{'}$	0.9654	0.9883	0.9929	0.9965
	E	-2.75%	-0.93%	-0.56%	-0.28%

* R_p=2t/L is the path length reduced ratio.

5 Conclusion

The mounting of transducers has an effect on the local velocity distribution in the vicinity of the transducers and changes the velocity sampling length i.e. the acoustic path length. Thus it is a major factor of the accuracy of a ultrasonic flowmeter. The effect of transducer mounting increases with path length reduced ratio. It is important to assess this effect and accordingly carry out correction, especially for the flowmeters that cannot be in situ calibrated.

Local velocity profiles in the vicinity of the transducers were observed along possible acoustic paths using LDV technology in a wind tunnel. And it was found that the effect of the transducers does not exceed the range of 2.5D of the transducer diameter. Through comparison of the length weighted velocity along the acoustic path with and without the disturbance of transducers, the errors brought about by this disturbance were analyzed. The results showed that the transducers always causes an underestimation of the velocity, no matter the transducers are projecting, half-projecting or recessed. And the impact of transducers decreases as the length of acoustic paths increases. But the underestimation of the velocity still has a value of 0.2%~0.3% even if the reduced ratio decreases to 0.25%.

Utilizing the theory of similarity, the findings can be applied to air flows with a different acoustic path length, and also to water flows. From which, the impact of transducers on flow rate measurement in both open channels and close conduits can be assessed.

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