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Ultrasonic Transit-time Flowmeters for Pipes: A Short Review

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ABSTRACT

Flow measurement is essential in many process monitoring, instrumentation and control applications in various fields of science and technology. The ultrasonic flowmeters are one of the most popularly used devices for flow measurements. From the inception of first of its kind, enormous advancement has been registered in terms of its wave reflection such as Doppler and transit-time, and mounting to get completely non-invasive and non-intrusive measurements. The ultrasonic flowmeters have been used for various types of flow including sediment laden, viscous and slurry flow in different pipe materials and pipe sizes under fully- and partially-filled conditions. The flowmeters have been developed using both active and passive principles, and have achieved high accuracy using multiple paths. The technological advancements especially in signal processing, electronic circuitry and availability of high precision transducers have given an edge to the researchers and developers of ultrasonic flowmeters. This paper presents a short review of the advancements in various aspects of ultrasonic transit-time flowmeters for pipes.

KEYWORDS

Ultrasonic flowmeters, pipes, transit-time, Doppler, instrumentation and control.

1 INTRODUCTION

The measurement of flow in pipes is important in many applications, including water management, power and energy using diesel and fuel oil, irrigation, food processing, mining and medical interventions. Several flowmeters are commercially available based on various principles such as mechanical flowmeters based upon positive displacement principle which includes popular rotameter and several gear and turbine flowmeters; differential pressure flowmeters based upon Bernoulli's principle which includes popular Pitot-tube, Venturimeter and Orificemeter; magnetic and electromagnetic flowmeters based on Faraday's law of electromagnetic induction and Lorentz principle; ultrasonic flowmeters based on ultrasound wave propagation principle which includes popular Doppler and transit-time flowmeters. While some flowmeters haven't changed much, others have made significant improvements during the last few decades. Out of these flowmeters, the ultrasonic flowmeters are one of the fastest growing flow measurement devices. They have gained enormous popularity in the past 50 years due to their high accuracy, ease of use, fast response, non-invasive and non-intrusive nature, usefulness for single or multi-phase flows in all types of regime (laminar, transitional or turbulent), low power consumption, and low installation, operation and maintenance costs (Lynnworth and Liu, 2006).

Ultrasonic flow meters are based upon two principles: Doppler and transit-time. Doppler ultrasonic flowmeters use sound pulse reflection principle to measure liquid flow rate. Solids or bubbles suspended in the liquid reflect the sound back to the receiving transducer. The flow velocity is calculated assuming that the reflecting particle velocity is representative of the average flow velocity. In transit-time ultrasonic flowmeters, two ultrasonic transducers alternatively emit and receive signals. The signal going with the flow travels the distance faster than the one against the current. This time difference is measured and used for the calculation of the flow velocity and the volume flow rates. Due to recent advancement in signal processing and availability of more powerful transducers, transit-time technology has far surpassed Doppler based technique in measuring clear and dirty flow (Joseph, 2009).

On the basis of fitting, the ultrasonic flowmeters are of two types: *wetted or intrusive type* in which transducers are submerged and *clamp-on or non-intrusive type* in which transducers are clamped on the surface of the pipe and are not in direct contact of water and hence do not affect the flow in any manner. Due to their non-intrusive nature, the clamp-on ultrasonic flowmeters have become very popular. The popularity of ultrasonic transit-time flowmeters can be gauged with the fact that when the Google patent was searched with a keyword “Ultrasonic transit-time Flowmeter”, a total of 644 patents were found which were published between the years 1950 to 2016. Most of these patents were filed by the countries outside India such as USA, Canada, Japan, Denmark and China.

This paper reviews the unique capabilities of transit-time ultrasonic flow measurement technology and explains how recent advances have allowed this technology to be used in various applications. The paper starts with the review of literature on the transit-time ultrasonic flowmeters and its use in various applications. It then discusses the literature based on the comparative study of transit-time ultrasonic flow measurement technique with other techniques, presents the parameters that govern the accuracy of transit-time ultrasonic flowmeters and remarks on the market availability of ultrasonic transit-time flowmeters. The paper ends with a set of concluding remarks.

2 TRANSIT-TIME ULTRASONIC FLOWMETER

Traditional flow metering devices for pipes like orifice or venturi meters obstruct the flow causing a measurable pressure drop thereby affecting the flowrate & its measurement. Consequently, non-intrusive and non-invasive measurement devices are becoming increasingly popular as they do not generate any pressure losses. The clamp-on transit-time ultrasonic flowmeter is one such device which requires no *pipe work* and never comes in contact with the liquid, and therefore causes no contamination or pressure drop in the liquid being measured. Transit-time flowmeters are based on the time difference between upstream and downstream sound propagation intervals. This approach provides good accuracy (±1-2%), and works well for clean flow or flow with minor particles. The applications of these flowmeters include pure water, sea water, wash water, sewage, process liquids, oils, chemicals, and any homogeneous liquids which are capable of ultrasonic wave propagation.

Methodology: The transit-time ultrasonic flowmeter uses at least one pair of transducers with centerlines inclined at an angle to the axis of pipe containing the flow. The transducers on the same acoustic path transmit and receive ultrasound waves mutually and therefore, the path velocity is a function of the difference in the flight time of the sound transiting in the flow direction and in the reverse direction. The flow velocity averaged over the entire cross-section can be computed with the path velocities according to certain integration. The principle is schematically illustrated in Fig. 1. The mathematical equations for a multipath flowmeter can be given as follows:

$$v_i = \frac{L_i}{2\cos\theta}\left(\frac{1}{t_{i\_up}} - \frac{1}{t_{i\_down}}\right) \quad (1)$$

$$v = \sum_{i=1}^{n} \frac{L_i w_i}{2\cos\theta}\left(\frac{1}{t_{i\_up}} - \frac{1}{t_{i\_down}}\right) \quad (2)$$

where, i represents the path number, L_i denotes the distance between the two transducers, θ is the angle between the acoustic path and the pipe axis, t_i_up and t_i_down are the flight times corresponding to upstream and downstream sound propagation situation, respectively, v_i is the axial velocity average along the i^{th} flight path, w_i is the matching weighting coefficient determined by the flowmeter integration.

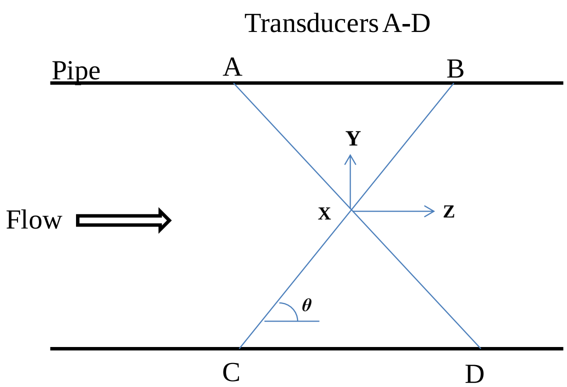

Figure 1: Two pairs of transducers (A–D) are placed in the flowmeter body with the transducer centerlines inclined at an angle to the flow direction

The volume flow rate can be given as follows:

$$Q_v = \pi R^2 \sum_{i=1}^{n} \frac{L_i w_i}{2\cos\theta}\left(\frac{1}{t_{i\_up}} - \frac{1}{t_{i\_down}}\right) \quad (3)$$

where Q_v is the volume flow rate and R is the internal radius of the pipe.

The first clamp-on ultrasonic flowmeter were developed in mid of 20th century and had been demonstrated with water flowing through small plastic pipes (Kritz, 1955a, b). Later in early 1960s, many such flowmeters came into existence for flow measurement in small (100 mm) to large (1 m) diameter pipes (Ito and Yamamoto, 1966). In the early 1970s, the concept of multipath in ultrasonic transit-time flowmeters was introduced (Malone and Whirlow, 1971; McShane, 1974; Sochaczewski et al., 1981). The single-path flowmeters utilize one pair of transducers to form one ultrasonic path to intercept the flow in a pipe and are suitable for small and medium size pipes. For larger diameter pipes with shorter straight pipe runs and where greater accuracy is needed, multi-path transducer installation is a better option. Multi-path flowmeters are relatively more expensive than a single-path flowmeters, and are often implemented in applications where accuracy is of paramount importance. Currently, the clamp-on ultrasonic transit-time flowmeters are the most widely used non-invasive flowmeters (Genthe and Yamamoto, 1974; Yuliang and Luo, 1982; Sanderson and Yeung, 2002; and Mahadeva et al., 2008, 2009). They can measure flow in small (e.g. sub-mm blood vessels; www.transonic.com) and large sections (e.g. up to tens of meters), are applicable for various pipe materials including steel and other metals/nonmetals, and for single- and multi-phase liquids and gases.

3 COMPARISON OF ULTRASONIC TRANSIT-TIME FLOWMETER WITH OTHER TYPE OF FLOWMETERS

Many studies have compared the flow measurements obtained from the clamp-on transit-time ultrasonic flowmeters with other measurements devices such as ultrasonic Doppler flowmeters (e.g., ultrasonic Doppler, Acoustic Doppler Current Profiler (ADCP), and Laser Doppler Anemometer (LDA)), electromagnetic flowmeters, and pressure transducer based current meters. Among these methods, ultrasonic transit-time method appears most promising because it is non-intrusive, accurate, applicable to wide range of flow velocities, cost-effective, easy to calibrate and has high resolution. Its popularity can be gauged by the fact that it is considered one of the fastest growing flow measurement technologies (Trofatter, 2002). Cascetta (1994) compared the measurements obtained from a clamp-on transit-time portable ultrasonic flowmeter with an in-line (or wetted) electromagnetic meter and concluded that the measurements from both the meters are substantially close to each other and the transit-time ultrasonic device seems to be quite adequate for water industry applications. In addition, the clamp-on ultrasonic flowmeters are significantly economical in terms of installation and maintenance costs. Lozano and Mateos (2009) compared transit-time and Doppler ultrasonic flowmeters for measuring discharge in irrigation canal with the propeller current meter and found that both ultrasonic instruments provided measurements that were highly consistent with those obtained from the propeller meter. They also reported that the ultrasonic flowmeter based on transit-time principle operated without interruption during the entire irrigation season.

Lynnworth and Liu (2006) reviewed the progress of ultrasonic flowmeter and suggested the following four technical aspects that are necessary to support the improvements and growth of ultrasonic flowmeters – (i) achieving versatility, ease of use and accuracy with clamp-on; (ii) achieving accuracy despite uncertainty in flow profile; (iii) measuring flow velocity with one or more other parameters like temperature; and (iv) measuring transit time to high precision without cycle skipping, despite turbulence encountered with the flow, against the flow, and at high flow.

4 PARAMETERS AND ACCURACY OF ULTRASONIC TRANSIT-TIME FLOWMETER

Many researchers have identified critical parameters that determine accuracy of ultrasonic transit-time flow measurements and given recommendations for optimizing them. The literature suggests that *mounting of transducers* in flowmeters have a significant bearing on the accuracy of flow measurements. The “V-mode” is usually the recommended installation method because it provides the best trade-off between the travel time values and the signal strength compared to "W-mode" and "Z-mode". In addition, the set-up and alignment of “V-mode” is easier than “Z-mode” as the transducers are on the same side of the pipe. Sanderson and Yeung (2002) compared "W-mode" and “V-mode” installations and reported that the wave travel distance can be calculated easily and more accurately in "V-mode" installations. Rychagov and Tereshchenko (2004) used the multipath flowrate measurements of symmetric and asymmetric flows by using more than one pair of transducers and found more accurate measurements.

Mahadeva et al. (2009) investigated the effect of *separation distance between the transducers* on the flowmeter output signal. They examined the sources of experimental error that might affect the validity of the data obtained for the transducer separation, and then, used the ray-tracing and finite-difference models to examine this relationship theoretically. Han et al. (2014) studied the effect of *transducer’s frequency, incident angle* and *the separation distance* on flow measurements. They presented a guideline for the selection of transducer's frequency based on the analysis of the ultrasonic attenuation characteristics in the liquid, and reported that the accurate estimation of separation distance between the transducers is necessary to guarantee accurate measurements. Liu et al. (2014) suggested that the accuracy of an ultrasonic flowmeter depends on the ratio *of average flow velocity in a pipe and average velocity of an ultrasonic propagation path*. Liu et al., (2015) applied the *tomographic reconstructions* to ultrasonic measurements for improving reliability and accuracy of flow velocity in pipes. However, the potential of tomographic reconstructions has not been fully utilized for pipe flows. Dadashnialehi and Moshiri (2011) proposed a new monitoring method for flow measurements in bubble contained flows. The method is based on optical observation for bubble identification through a combination of image processing and wavelet analysis.

Many researchers suggested that the ultrasonic flowmeters should be tested to various flow disturbances generated by cone couplings, single and double elbows, T-junction and other assembly on the measurements of ultrasonic flowmeters before use (Hakansson and Delsing, 1992; Wada et al., 2012; TUV NEL Ltd, National measurement System). The proper distance of flowmeter from the flow disturbing assembly should be fixed prior to the use of the flowmeter. The transducers should be mounted on the straight part of the pipe assembly and this is addressed using a commonly accepted terminology "straight runs". The straight run is the minimum required upstream and downstream lengths of the pipe where the transducers are to be mounted. The lengths of these straight runs are dependent upon the pipe fittings like bends, valves, tee, expansion pipes, reducers and pumps in the pipe network. The selection of the straight runs is an iterative process and a newly assembled ultrasonic flowmeter should be tested under these pipe fittings and a suitable length of straight runs should be determined accordingly. The values of K_1 and K_2 (Fig. 2) should be obtained from the various trials for different pipe fittings for the nominal diameter of pipe (D).

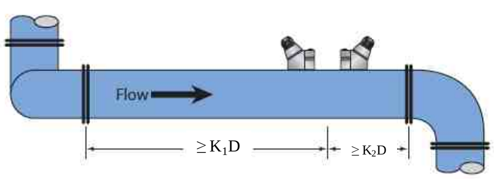

Figure 2: Transducers positioning

5 MARKET OF ULTRASONIC FLOWMETERS

USA, Canada, Japan, China and many European countries are the world leaders in manufacturing the ultrasonic flowmeters. There is no well-known Indian manufacturer for transit-time ultrasonic flowmeters for various applications, and due to this reason the instruments based on this technology are very costly ranging from 2 to 6 lakhs. Moreover, these instruments require site-specific configuration and calibration for optimal results and therefore, the lack of indigenous expertise makes the installation, operation and maintenance of this technology expensive.

6 CONCLUSIONS

The literature highlighted the growing importance of ultrasonic transit-time devices for flow measurements in various applications. It revealed critical parameters that affect the accuracy of ultrasonic transit-time flow measurements, and showed state-of-the-art procedures for optimizing those parameters.

The multipath, quadrature, and tomography continue to offer improvements in accuracy of the flow measurement by ultrasonic flowmeters. The literature also suggested that future improvements in ultrasonic transit-time flow measurements will oscillate in one or more of the following areas - transducers, signal processing, flow conditioning, and tomographically obtaining a flow image and integrating over pixels. Though, the ultrasonic flowmeter technique reached greater heights and continuously improving, the cost of the instrument, especially in India, is very high due to lack of indigenous manufacturers and expertise. It is hoped that future research efforts will focus in these directions to manufacture indigenous clamp-on ultrasonic transit-time flowmeters for pipe and open channel flow.

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