ASME MFC-5.1–2011

(Revision and Partition of ANSI/ASME MFC-5M–1985)

Measurement of Liquid Flow in Closed Conduits Using Transit-Time Ultrasonic Flowmeters

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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Three Park Avenue • New York, NY • 10016 USA

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This Standard will be revised when the Society approves the issuance of a new edition. There will be no addenda issued to this edition.

ASME issues written replies to inquiries concerning interpretations of technical aspects of this document. Periodically certain actions of the ASME MFC Committee may be published as Cases. Cases and interpretations are published on the ASME Web site under the Committee Pages at http://cstools.asme.org as they are issued.

The American Society of Mechanical Engineers
Three Park Avenue, New York, NY 10016-5990

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FOREWORD

The need for a standard describing measurement of liquid measurement of liquid flows by means of transit-time ultrasonic flowmeters has been recognized for many years. The ASME Standards Committee MFC, Measurement of Fluid Flow in Closed Conduits, developed a standard, ANSI/ASME MFC-5M–1985 to address this need. Subsequently, it was decided to revise and partition ANSI/ASME MFC-5M into three standards to assist the readers in understanding the three technologies: transit time, cross-correlation, and scattering (Doppler).

This Standard applies to ultrasonic flowmeters that base their operation on the measurement of transit time of acoustic signals. This Standard concerns the volume flow-rate measurement of a single-phase liquid with steady flow or flow varying only slowly with time in a completely filled closed conduit.

The next standard planned in this series, Measurement of Liquids Using Cross-Correlation Ultrasonic Flowmeters (ASME MFC-5.2M), will apply to ultrasonic flowmeters that base their operation on the cross-correlation of modulated acoustic signals. It will be concerned with the volume flow-rate measurement of a single-phase or multiphase liquid with steady flow or flow varying only slowly with time in a completely filled closed conduit.

The last standard planned for this series, Measurement of Liquids Using Scattering (Doppler) Ultrasonic Flowmeters (ASME MFC-5.3M), will apply to ultrasonic flowmeters that base their operation on the scattering (Doppler) of acoustic signals. It will be concerned with the volume flow-rate measurement of two-phase liquid with steady flow or flow varying only slowly with time in a completely filled closed conduit.

Suggestions for improvement of this Standard are welcome. They should be sent to The American Society of Mechanical Engineers; Attn: Secretary, MFC Standards Committee; Three Park Avenue; New York, NY 10016-5990.

This Standard was approved as an American National Standard on January 28, 2011.

ASME MFC COMMITTEE
Measurement of Fluid Flow in Closed Conduits

(The following is the roster of the Committee at the time of approval of this Standard.)

CORRESPONDENCE WITH THE MFC COMMITTEE

General. ASME Standards are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Standard may interact with the Committee by requesting interpretations, proposing revisions, and attending Committee meetings. Correspondence should be addressed to:

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Three Park Avenue
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Proposing Revisions. Revisions are made periodically to the Standard to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Standard. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

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Subject:	Cite the applicable paragraph number(s) and the topic of the inquiry.
Edition:	Cite the applicable edition of the Standard for which the interpretation is being requested.
Question:	Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. The inquirer may also include any plans or drawings that are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in this format may be rewritten in the appropriate format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

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MEASUREMENT OF LIQUID FLOW IN CLOSED CONDUITS USING TRANSIT-TIME ULTRASONIC FLOWMETERS

1 GENERAL

1.1 Scope

This Standard applies to ultrasonic flowmeters that base their operation on the measurement of transit time of acoustic signals. This Standard concerns the volume flow-rate measurement of a single-phase liquid with steady flow or flow varying only slowly with time in a completely filled closed conduit.

1.2 Purpose

This Standard provides

(a) a description of the operating principles employed by the transit-time ultrasonic flowmeters

(b) a guideline to expected performance characteristics of transit-time ultrasonic flowmeters

(c) a description of calibration, verification, and diagnostic procedures

(d) a description of potential uncertainty sources and their reduction

(e) a common set of terminology, symbols, definitions, and specifications

1.3 Terminology and Symbols

(a) Paragraph 1.3.1 lists definitions from ASME MFC-1M used in this Standard.

(b) Paragraph 1.3.2 lists definitions specific to this Standard.

(c) Table 1-1 lists symbols used in this Standard.

(d) Table 1-2 lists subscripts used in this Standard.

1.3.1 Definitions From ASME MFC-1M

accuracy: closeness of agreement between a measured quantity value and a true quantity value of a measurand.

NOTES:
(1) The concept "measurement accuracy" is not a quantity and is not given a numerical quantity value. A measurement is said to be more accurate when it provides a smaller measurement error.
(2) The term "measurement accuracy" is sometimes understood as closeness of agreement between measured quantity values that are being attributed to the measurand. "Measurement accuracy" should not be mistaken for "measurement precision."

acoustic path: path that the acoustic signals follow as they propagate through the measurement section. There may be one (single path) or more (multipath) acoustic paths in the measurement section. Common transit-time path types are axial, diametrical, and chordal.

axial flow velocity: component of liquid flow velocity, V_{ax}, at a point in the measurement section that is parallel to the measurement section's axis.

calibration: experimental determination of the relationship between the quantity being measured and the device that measures it, usually by comparison with a traceable reference standard; also including the act of adjusting the output of a device to bring it to a desired value, within a specified tolerance, for a particular value of the input.

NOTE: This document is written with calibration defined as the determination of difference from a reference and the adjustment to align within a specified tolerance. This is common U.S. usage. It is understood that in other parts of the world some countries and groups define calibration as only the determination of difference from a reference. A second term used is calibration adjustment, which is to align within a specified tolerance.

cross-flow velocity: component of liquid flow velocity at a point in the measurement section that is perpendicular to the measurement section's axis.

measurement section: section of conduit in which the volumetric flow rate is sensed by the acoustic signals. The measurement section is bounded at both ends by planes perpendicular to the axis of the section and located at the extreme upstream and downstream transducer positions. The measurement section is usually circular in cross section; however, it may be square, rectangular, elliptical, or some other shape.

nonrefractive system: an ultrasonic flowmeter system in which the acoustic path crosses the transducer/process liquid interfaces at a right angle to the boundary surface.

refractive system: an ultrasonic flowmeter in which the acoustic path crosses the conduit boundary/process liquid interfaces at other than a right angle.

transit time, t: time required for an acoustic signal to traverse an acoustic path.

uncertainty: parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used.

NOTES:
(1) Measurement uncertainty is often comprised of many components: Some of these may be evaluated by Type A evaluation

of measurement uncertainty from the statistical distribution of the quantity values from series of measurements and can be characterized by standard deviations. The other components, which may be evaluated by Type B evaluation of measurement uncertainty, can also be characterized by experimental standard deviations derived from probability density functions based on experience or other information.

(2) In general, for a given set of information, it is understood that the measurement uncertainty is associated with a stated quantity value attributed to the measurand. A modification of the value of this measurand may result in a modification of the associated uncertainty.

(3) If the result of a measurement depends on the values of quantities other than the measurand, the uncertainty of the measured values of these quantities contribute to the uncertainty of the result of the measurement.

velocity profile correction factor, S: dimensionless factor based on measured knowledge of the velocity profile used to adjust the meter output.

verification: experimental determination of the relationship between the quantity being measured and the device that measures it, usually by comparison with a traceable reference standard.

1.3.2 Definitions Specific to This Standard

diagnostics: comparison of internal direct and derived measurement values to allow the user to ascertain the condition of the operation of the ultrasonic flowmeter.

mode conversion: when an ultrasonic wave passes at an oblique angle between two materials of variant acoustic impedance, mode conversion can occur. As an example, when a wedge-type transducer is coupled to the outside of a pipe, the longitudinal waves generated by the ultrasonic transducer produce both longitudinal and shear waves in the pipe wall.

ultrasonic transducer: a device designed to convert electrical signals into directed ultrasonic waves and vice versa, usually by inclusion of materials exhibiting the piezoelectric or piezomagnetic effects. When employed for flow measurement, ultrasonic transducers are commonly referred to simply as "transducers." The transducers transmit and receive acoustic energy. They may be factory mounted or field mounted by clamping, threading, or bonding. Transducers may be wetted by the liquid or be nonwetted. Wetted transducers may be flush mounted, recessed, or protruding into the flow stream. Some transducers may be removed while the line is in service, depending on the manufacturer's design.

1.3.3 Symbols Used in This Standard. See Table 1-1.

1.3.4 Subscripts Used in This Standard. See Table 1-2.

2 GENERAL ULTRASONIC FLOWMETER DESCRIPTIONS

The ultrasonic flowmeter can be thought of as comprising a primary and secondary device. The primary device consists of a measurement section, transducers, and acoustic paths. The measurement section may be a whole spool piece, or an existing section of conduit to which transducers are installed in the field.

The secondary device comprises the electronic equipment required to operate the transducers, make the measurements, process the measured data, and display or record the results. The processing section, in addition to estimating the flow rate from the measurement, should be capable of rejecting invalid measurements, noise, etc. The indicated flow rate may be the result of one or more individual flow velocity determinations.

Most meters have outputs available, either as standard features or as optional equipment. Displays may show flow rate, integrated flow volume, and flow direction, and may be analog or digital. Signal outputs usually include one or more of the following: current, voltage, digital, and a pulse rate proportional to flow. These outputs may or may not be electrically isolated. Flowmeters may also include alarms and diagnostic aids.

3 TRANSIT-TIME FLOWMETER DESCRIPTIONS

The ultrasonic transit-time flowmeter is a sampling device that measure discrete path velocities of one or more pairs of transducers. Each pair of transducers is located a known distance, L, apart such that one is upstream of the other (see Fig. 3-1). The upstream and downstream transducers send and receive pulses of ultrasound alternately, referred to as contra-propagating transmission, and the times of arrival are used in the calculation of average axial velocity, $\bar{v}_x$. At any given instant, the difference between the apparent speed of sound in a moving liquid and the speed of sound in that same liquid at rest is directly proportional to the liquid's instantaneous velocity. As a consequence, a measure of the average axial velocity of the liquid along a path can be obtained by transmitting an acoustic pulse along the path in both directions and subsequently measuring the transit-time difference.

The volumetric flow rate of a liquid flowing in a completely filled closed conduit is defined as the average velocity of the liquid over a cross section multiplied by the area of the cross section. Thus, by measuring the average velocity of a liquid along one or more acoustic paths lines (not the area) and combining the measurements with knowledge of the cross-sectional area and the velocity profile over the cross section, it is possible to obtain an estimate of the volumetric flow rate of the liquid in the conduit.

Several techniques can be used to obtain a measure of the average effective speed of propagation of an acoustic pulse in a moving liquid in order to determine the average axial flow velocity along an acoustic path line. Two approaches, time domain and frequency domain, are discussed here.

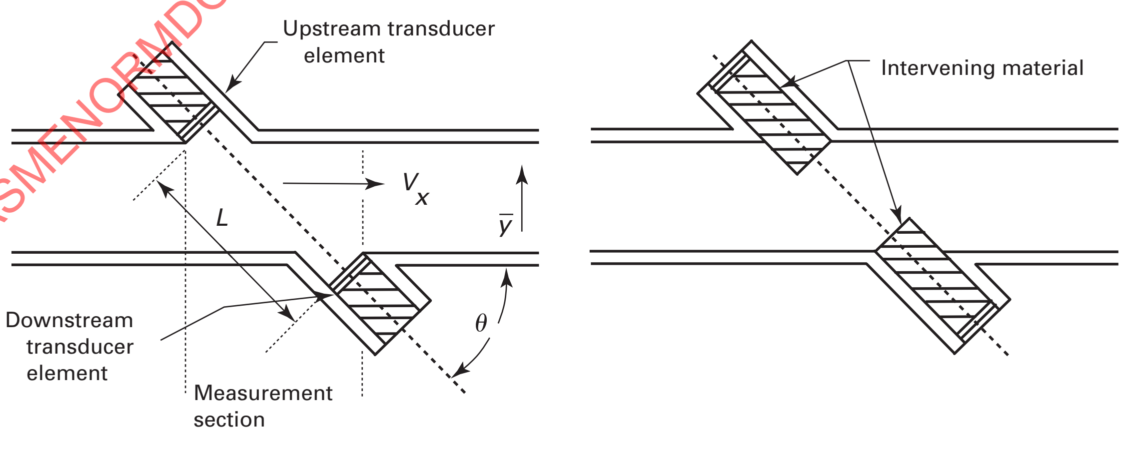
Table 1-1 Symbols

Symbol	Quantity	Dimensions	SI Units
A	Cross-sectional area	L^2	m^2
c	Speed of sound	LT^{-1}	m/s
f	Frequency	T^{-1}	s^{-1}
L	Distance between the upstream and downstream transducers	L	m
n	Number of paths	. . .	. . .
Q	Volume flow rate	L^3T^{-1}	m^3/s
S	Velocity profile correction factor	. . .	. . .
t	Time	T	s
v	Flow velocity	LT^{-1}	m/s
w	Weighting factor for acoustical path	. . .	. . .
η	Unit vector normal to the wave front	. . .	. . .
θ	Angle between the pipe wall and the direction of acoustic propagation	. . .	rad
φ	Angle between the pipe wall normal and the direction of acoustic propagation	. . .	rad

Table 1-2 Subscripts

Subscript Symbol	Description
up	Upstream transmission path
dn	Downstream transmission path
fluid_up	Upstream transmission path through the fluid only
fluid_dn	Downstream transmission path through the fluid only
fluid_up/dn	Abbreviation including both directions, fluid_up and fluid_dn
meas_up/dn	Total signal transmission path from transmit to receive in each direction = fluid_up/dn + t_0 (i.e., $t_{meas\_up/dn} = t_{fluid\_up/dn} + t_0$)
i	Path number
x	Direction corresponding to the pipe axis
y	Direction orthogonal to the pipe axis and in the plane formed by the acoustic path and pipe axis

Fig. 3-1 Wetted Transducer Configurations



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3.1 Time Domain

The basis of this technique is the direct measurement of the transit time of acoustic signals as they propagate between a transmitter and a receiver. The velocity of propagation of the ultrasonic signal is the sum of the speed of sound, c, and the flow velocity in the direction of propagation. Therefore the transit time upstream and downstream can be expressed as

$$t_{\text{fluid\_up/dn}} \approx \int_{l=0}^{L} \frac{1}{c + v_l \times \eta}\, dl$$

where

η = unit normal vector to the wave front
v_1 = flow velocity vector at location, l, on the path, L

NOTE: This covers whether the transmitter is upstream or downstream.

It can be shown that the transit time upstream and downstream, assuming flow velocity in the x direction with zero flow velocity in the y and z directions, and assuming $\bar{v}_x << c$ (≈ replaced with =)

$$t_{\text{fluid\_up}} = \frac{L}{c - \bar{v}_x \cos\theta}$$

$$t_{\text{fluid\_dn}} = \frac{L}{c + \bar{v}_x \cos\theta}$$

$$\frac{1}{t_{\text{fluid\_dn}}} - \frac{1}{t_{\text{fluid\_up}}} = \frac{t_{\text{fluid\_up}} - t_{\text{fluid\_dn}}}{t_{\text{fluid\_up}} t_{\text{fluid\_dn}}} = \frac{2\bar{v}_x \cos\theta}{L} \tag{1}$$

$$\bar{v}_x = \frac{L}{2\cos\theta} \frac{\Delta t}{t_{\text{fluid\_up}} t_{\text{fluid\_dn}}}$$

where

L = distance between the transducers
Δt = difference in transit times
θ = angle of inclination of the acoustic signal with respect to the x direction of the flow

The speed of sound can be calculated as follows:

$$\frac{1}{t_{\text{fluid\_dn}}} + \frac{1}{t_{\text{fluid\_up}}} = \frac{t_{\text{fluid\_up}} + t_{\text{fluid\_dn}}}{t_{\text{fluid\_up}} t_{\text{fluid\_dn}}} = \frac{2c}{L} \tag{2}$$

$$c = \frac{L}{2} \frac{(t_{\text{fluid\_up}} + t_{\text{fluid\_dn}})}{t_{\text{fluid\_up}} t_{\text{fluid\_dn}}}$$

In addition to the time the acoustic signal spends in the fluid, consideration must be given to the total time between the acoustic signal being transmitted and received. Depending on the flowmeter design, the acoustic signal may penetrate the transducer mounting, pipe wall, liner, and fluid. Each of these steps introduces a time delay and refraction of the acoustic path (see para. 3.3).

3.2 Frequency Domain

In a frequency difference measurement approach (often called "sing around"), the reception of an acoustic signal at the receiver is used as a reference for generating a subsequent acoustic signal at the transmitter. Assuming no delays other than the propagation time of the acoustic pulses in the liquid, the frequency at which the pulses are generated or received is proportional to the reciprocal of their transit time. Thus, assuming

$$f_{\text{fluid\_up/dn}} = \frac{1}{t_{\text{fluid\_up/dn}}}$$

then

$$f_{\text{fluid\_up}} = \frac{1}{t_{\text{fluid\_up}}} = \frac{c - \bar{v}_x \cos\theta}{L} \tag{3}$$

$$f_{\text{fluid\_dn}} = \frac{1}{t_{\text{fluid\_dn}}} = \frac{c + \bar{v}_x \cos\theta}{L}$$

$$\bar{v}_x = \frac{L}{2\cos\theta}(f_{\text{fluid\_dn}} - f_{\text{fluid\_up}}) \tag{4}$$

3.3 Time Delay Considerations

In paras. 3.2 and 3.3 it was assumed that the acoustic pulse spends all of the transit time in the fluid and that the direction of propagation is at an angle, θ, to the pipe wall. In a real system, the measured time between the acoustic pulse leaving the transmitter and being received at the receiver includes a time delay, t_o, due to intervening materials, electronics, signal processing, cable lengths, etc. In this case

$$t_{\text{meas\_up/dn}} = t_{\text{fluid\_up/dn}} + t_0$$

and for the frequency domain

$$\frac{1}{f_{\text{meas\_up/dn}}} = \frac{1}{f_{\text{fluid\_up/dn}}} + t_0$$

Equations (1) and (2) then take the form

$$\bar{v}_x = \frac{L}{2\cos\theta} \frac{\Delta t}{(t_{\text{meas\_up}} - t_0)(t_{\text{meas\_dn}} - t_0)} \tag{5}$$

$$c = \frac{L}{2} \frac{(t_{\text{meas\_up}} + t_{\text{meas\_dn}} - 2t_0)}{(t_{\text{meas\_up}} - t_0)(t_{\text{meas\_dn}} - t_0)} \tag{6}$$

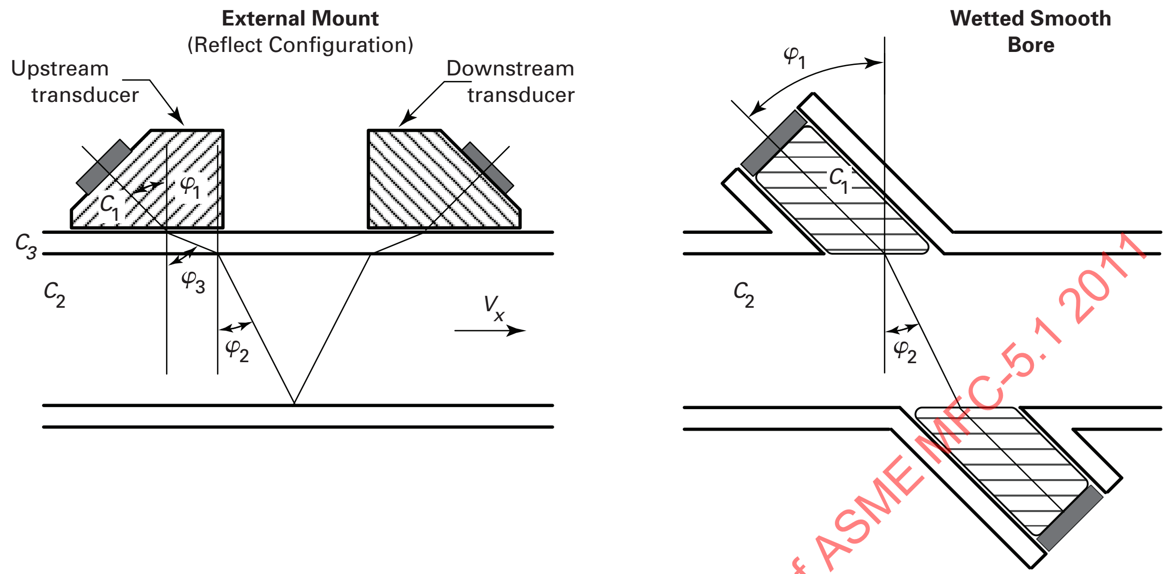
and eq. (4) takes the form

$$\bar{v}_x = \frac{L}{2\cos\theta}\left(\frac{f_{\text{meas\_dn}}}{1 - t_0 f_{\text{meas\_dn}}} - \frac{f_{\text{meas\_up}}}{1 - t_0 f_{\text{meas\_up}}}\right) \tag{7}$$

3.4 Refraction Considerations

Ultrasonic flowmeters that utilize external mount or wetted smooth-bore transducer arrangements (see Fig. 3-1) must compensate for acoustic refraction in order to operate properly and accurately. When a sound wave passes through an interface between two materials at

Fig. 3-2 Protected Configuration With Both an External Mount and a Wetted Smooth Bore



typical oblique angles and the materials have different acoustic impedances, both reflected and refracted waves are produced. In the case of ultrasonic flowmeters, although they represent lost sound wave energy, the reflected waves can be ignored by the user (see para. 4.1.4.2). Sound-wave refraction will take place as the sound passes from the transducer into the pipe wall, from the pipe wall into pipe lining (if present), and from the pipe or pipe lining into the liquid interfaces. This is due to the different velocities of the acoustic waves within these materials.

Snell's Law describes the relationship between the angles and the velocities of the waves. Using the example of the external mount arrangement in Fig. 3-2, Snell's Law equates the ratio of material velocities, c_1, c_2, and c_3, to the ratio of the sines of incident angle, φ_1, to refracted angle, φ_2, and of incident angle, φ_2, to refracted angle, φ_3. Equation (8) describes indices of refraction as the sound waves pass through the various materials.

$$\frac{\sin\varphi_1}{c_1} = \frac{\sin\varphi_3}{c_3} = \frac{\sin\varphi_2}{c_2} \tag{8}$$

where
- c_1 = sound speed in medium 1
- c_2 = sound speed in medium 2
- c_3 = sound speed in medium 3

As a consequence, θ and L in eqs. (5), (6), and (7) become functions of the sound speeds, c_1, c_2, and c_3 and hence in general, of the temperature, pressure, and composition of the process fluid and intervening materials. Through Snell's Law, substituting the angle in the fluid with the angle in the transducer's coupling wedge, the measured flow velocity is not directly dependent on the fluid sound speed. This substitution is taken into account, and is valid for small changes in fluid speed of sound, by rearranging eq. (5), into eq. (9) as follows:

$$\bar{v}_x = \frac{c_1}{\sin\varphi_1}\frac{\Delta t}{(t_{meas\_up} + t_{meas\_dn} - 2t_0)} \tag{9}$$

3.5 Estimating Volumetric Flow

Once the average axial flow velocity along an acoustic path line has been found, the volumetric flow rate can be calculated from the following equation:

$$Q = SA\sum_{i=1}^{n} w_i\bar{v}_{xi} \tag{10}$$

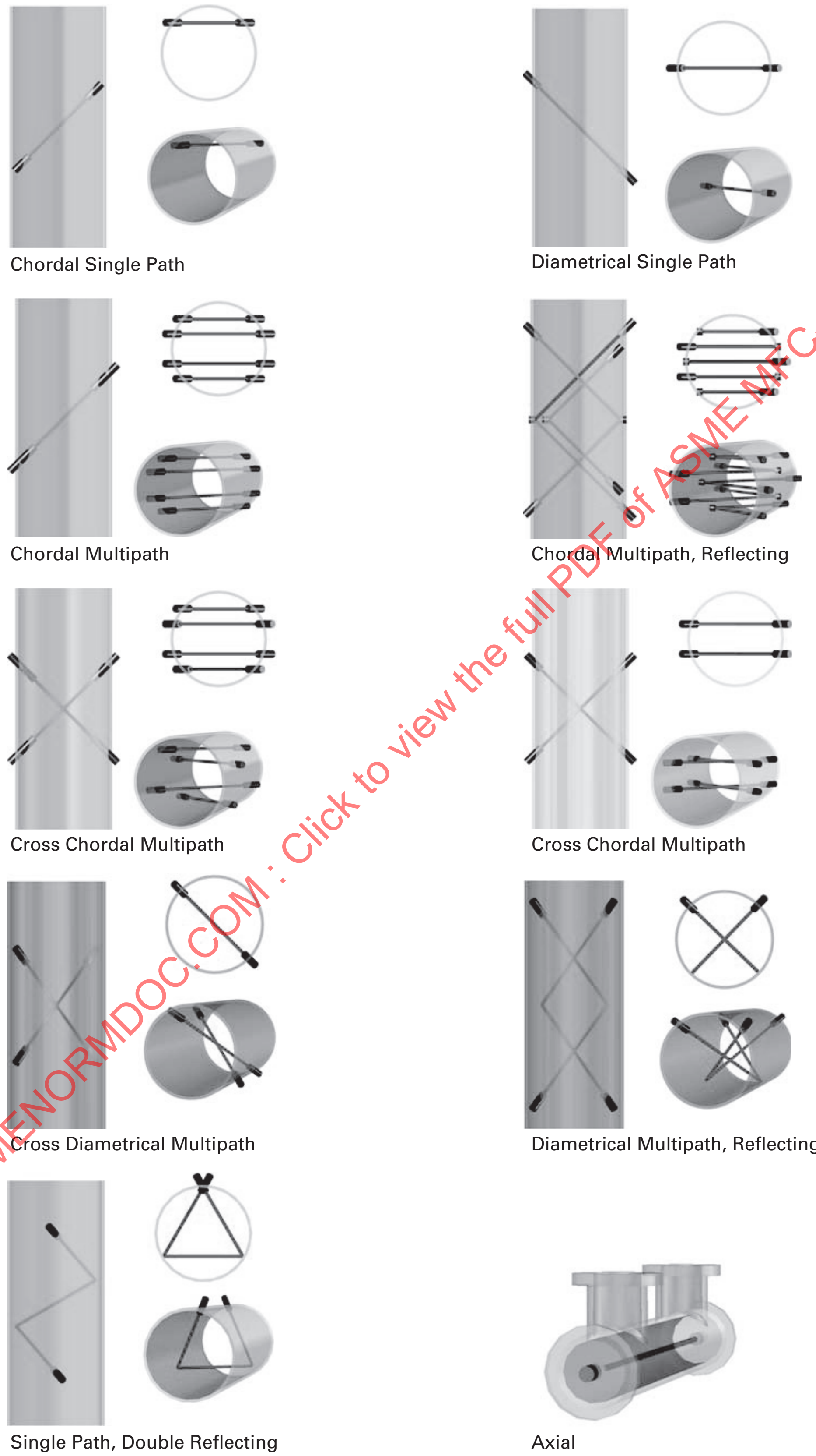
where
- A = average cross-sectional area of the measurement section
- i = "i-th" acoustic path
- n = number of acoustic paths
- Q = measured volumetric flow rate in the measurement section
- S = velocity profile correction factor
- $\bar{v}_x$ = average axial flow velocity along acoustic path line
- w = weighting factor for each acoustic path

Note that increasing n can reduce the uncertainty associated with flow profile variations.

The path configuration can be either single or multipath. Figure 3-3 shows common techniques for both types of configuration.

NOTE: The actual design of a commercial ultrasonic transit-time flowmeter may be a combination of these configurations.

Fig. 3-3 Acoustic Path Configurations



(a) *Single Path*
– Chordal
– Diametrical
– Double reflecting
– Axial
(b) *Multipath*
– Chordal multipath
– Chordal multipath reflecting
– Cross chordal multipath (2)
– Cross chordal multipath (4)
– Cross diametric multipath
– Cross diametric multipath Reflecting

3.6 Operation of Transducers

Transducers may be excited nearly simultaneously or alternately with one or more transmissions in each direction. The acoustic frequency and pulse repetition rate may vary.

3.7 Measurement Method

The transit time of an acoustic pulse is usually taken to be the time interval between initial excitation of the transmitter and some characteristic point of the received signal. Exact details vary from one manufacturer to another.

4 UNCERTAINTY SOURCES AND UNCERTAINTY REDUCTION

The purpose of this section is to describe possible uncertainty sources for transit-time ultrasonic flowmeters. These components should be addressed in detail when doing an uncertainty analysis for a particular installation.

According to eq. (10), the volume flow is calculated as a product of three factors: a weighted sum of the velocities, v_x, measured on all acoustic paths; the flow profile correction factor, S; and the cross section, A, of the measurement section. This means that the sources of the uncertainty can be grouped into three classes: flow velocity uncertainty, flow profile related uncertainty, and uncertainty due to the pipe geometry.

4.1 Uncertainty in the Flow Velocity Measurement

4.1.1 Acoustic Path Length and Angle. With nonrefractive systems, the determination of axial flow velocity, $\overline{v}_x$, from the transit times, according to eq. (5), is based on the acoustic path length, L, and angle, θ. The uncertainty in $\overline{v}_x$ is in direct proportion to the uncertainty in the acoustic path length and angle.

Uncertainty in the acoustic path length or angle for nonrefractive systems can be reduced by accurate geometric and acoustic measurements.

Compensation for changes in acoustic path length and angle which result from temperature- or pressure-induced pipe deformation may be provided for in either refractive or nonrefractive systems.

With refractive systems, the flow velocity is calculated by eq. (9) from the transit times; the sound speed, c_1; and the angle, φ_1, in the coupling wedge. A temperature influence from the temperature dependency of the sound speed, c_1, may be compensated for.

4.1.2 Sound Speed Dependency. The speed of sound in the liquid and in any intervening materials along the acoustic path varies with composition, temperature, and pressure. Depending upon a particular ultrasonic flowmeter design; L, θ, and t_o [eqs. (5) and (7)] may be affected.

In nearly all cases, the uncertainty caused by sound speed variation in the liquid is negligible for a properly implemented, nonrefractive, wetted transducer system.

In refractive systems, changes in the speed of sound in intervening materials and the process liquid affect the acoustic angle and thereby the optimum transducer position. It is possible to compensate for these effects. In rare cases, changes in the speed of sound in the liquid may refract the beam so much that the signal misses the receiving transducer and is not received. Accurate knowledge of the speed of sound in a particular liquid can reduce this possibility. (This condition is more prevalent when a refractive flowmeter is utilized to measure multiple liquid types at a single installation location. The speed of sound difference between two liquids may cause a large enough change in the refraction angle that the sound may miss the receiving transducer.)

4.1.3 Timing. Uncertainty in the transit-time measurement will result in a corresponding uncertainty in $\overline{v}_x$. This timing uncertainty can be associated with limitations in the electronic timing circuitry, such as from clock jitter or drift, and from the detection of an aberrant receive signal caused by excessive flow velocity or high percentage of gas and/or solids.

The cables between the secondary and primary devices are important as these can influence the timing calculations. The manufacturer's recommendations should be followed.

Timing calculations can also be affected by the different intervening materials (see para. 3.3).

Uncertainty in the measurement of time may be reduced by the use of stable and accurate high frequency oscillators, averaging of many individual transit-time measurements and by selectively rejecting receive signals that are considered unacceptable for reliable time measurement.

4.1.4 Noise. Noise sources may be either electrical or acoustic, and either random or synchronous with respect to the received signal. The effect of random noise is an increased standard deviation of the measurement result. The degree of this effect depends on the signal-to-noise ratio (SNR). Random noise contribution to uncertainty in the long-term average of the measurement result should be negligible, as long as the noise level is not so high that the signal is not detectable

Synchronous noise can cause an uncertainty in measurement.

4.1.4.1 Random Noise. As all electronic components produce noise, a certain level of self-synchronous electrical noise is unavoidable. External sources of electrical noise are, for instance, DC/DC converters and VFDs (variable frequency drives) driving electrical machines. Possible sources of external acoustic noise are pumps and flow restricting plumbing components such as regulator valves (see section 5).

External electrical noise can be attenuated by appropriate shielding and grounding according to the manufacturer's recommendations. Receive signal level can be increased by increasing the transmitted signal level.

4.1.4.2 Synchronous Noise. A portion of the acoustic signal from the transducer can be transmitted and received through the pipe wall, instead of the fluid, and interfere with the measurement. This noise is also called "short circuit noise" or "pipe noise." The signal-to-noise ratio, in these cases, may be improved by acoustically isolating the transducers from the measurement section, by application of damping materials and/or signal processing techniques, such as digital filtering. In the case of refractive externally mounted systems it may be possible to change the transducer mounting mode (altering the number of sound reflections within the pipe), effectively changing the wave propagation time in the liquid as compared to the propagation time in the pipe wall.

4.1.5 Fluid-Induced Variation. The turbulence of the flow, like random noise, causes a random variation in the time difference and the signal amplitude and thus increases the standard deviation of the measurement result. Also, cavitation and other inhomogenities of the fluid have a similar effect.

4.1.6 Signal Detection. Acoustic measurements may be affected by inconsistencies in recognition of the received acoustic signal caused by variations in received signal level or waveform distortion and noise. In systems where sound wave propagation time is measured by detecting a threshold potential or zero-cross on the received signal, an extreme condition can occur if the received signal becomes distorted or attenuated. The time difference measured for a single measurement will encompass a large uncertainty — equal to one period of the propagated waveform — leading to a large contribution to uncertainty in flow measurement. Methods can be provided that will reject those signals which are excessively attenuated or which are distorted by noise.

4.2 Flow Profile Related Uncertainties

The ultrasonic flowmeter calculates the mean velocity based on a fully developed, symmetrical velocity profile. When this assumption is valid, the Reynolds number and pipe roughness (which determine the friction factor) are sufficient to determine the velocity profile correction factor, S.

Disruption of the flow profile can be caused by upstream and downstream pipe disturbances such as pumps, elbows, tees, reducers, and valves, or by pipe intrusions such as thermowells or sampling probes. Velocity profile variations can also be caused by changes in flow rates (including transients), wall roughness, temperature, viscosity, transducer projections, and transducer cavities.

Disturbances upstream of the flowmeter installation location usually have a greater influence on the flow profile than those that are located downstream.

The flow profile related uncertainty can be reduced by increasing the flow tube length, increasing the number of acoustic paths, by choosing an appropriate path configuration and by the use of flow conditioners. However, be aware that the flow conditioner can become fouled and may adversely influence the velocity profile that it was meant to correct. (See ASME MFC-3Ma–2007, Nonmandatory Appendix 1C.)

4.2.1 Acoustic Path Location and Integration. The ultrasonic flowmeter calculates the area averaged flow velocity from the line average path velocities $\overline{v}_{xi}$, A, S, and w_i as shown in eq. 3.15.

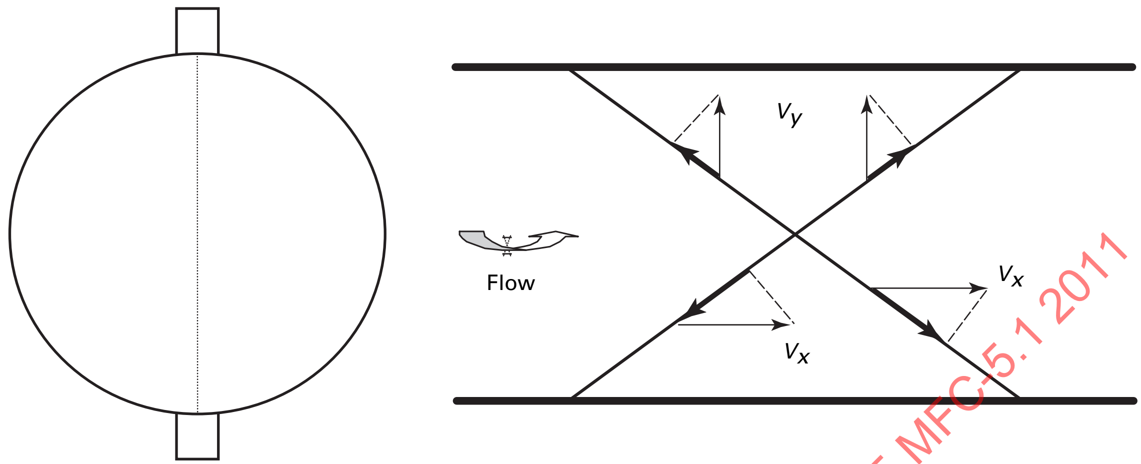
$$Q = SA \sum_{i=1}^{n} w_i \overline{v}_{xi}$$

The acoustic path location, particularly in multipath flowmeters, is important. The position, orientation, number of paths, and direct or reflecting paths affect the meter sensitivity to velocity profile. The path locations can affect the sensitivity of the meter to nonaxial velocity components (swirl and cross flow) and distortion. The uncertainty in the position of the acoustic path can cause flow uncertainty through improper assignment of a weighting factor, w_i, by causing unnecessary sensitivity of $\overline{v}_x$ to the velocity profile and the integration technique.

4.2.2 Nonaxial Flow. Velocities that are normal or not axial do not contribute to the flow rate, but they can cause uncertainty in the ultrasonic flowmeter response due to the location and orientation of the paths. However, non-axial flow uncertainty can be reduced by the use of an appropriate acoustic path orientation or by computing line velocities on appropriate multiple acoustic paths, for example, by crossed paths as illustrated in Fig. 4-1.

V_x = axial velocity and V_y = nonaxial velocity. The V_y component along one path is in the same direction as the V_x component, but in the opposite direction on the crossed path, thus cancelling the non-axial flow component.

Fig. 4-1 A Typical Cross Path Ultrasonic Flowmeter Configuration



4.3 Cross Section Dimensional Uncertainty

Uncertainty in the assumed cross-sectional area of the measurement section causes an uncertainty in the volume flow rate estimate. This uncertainty may be due to initial measurement section shape irregularities, such as out-of-roundness or manufacturing tolerances; or it may be due to changes in the initial shape caused by temperature, pressure, or structural loading.

In the case of clamp-on flowmeters, pipe configuration parameters (diameter and wall thickness measurements) are typically taken from tables. The flowmeter utilizes this configuration data to calculate the cross-sectional area of the pipe as well as transducer spacing. Nominal measurements taken from these tables will match the pipe within a certain tolerance, but the best performance is achieved if actual pipe measurement information is entered. The pipe outside diameter can be calculated from a circumference measurement. An ultrasonic wall thickness gauge can be used to reduce uncertainty associated with the pipe inside diameter, although these devices typically will not detect or measure a pipe lining or material buildup, if present.

Cross section uncertainty may also be due to the formation of deposits or growths, such as erosion, corrosion, scale, wax, hydrates, and algae in the measurement section.

Cross section dimensional uncertainty can be reduced by manufacturing or choosing a measurement section which has constant dimensions along its length, can be accurately measured, and has a stable surface so that cross section changes with time due to corrosion, material buildup, or loss of protective coatings will be small. Additionally, if temperatures or pressures are expected to be substantially different from reference conditions, it may be necessary to adjust the measured dimensions to compensate for dimensional changes that may occur under operating conditions.

In circular pipes, cross section dimensional uncertainty can be reduced by minimizing the effects of out-of-roundness through averaging of diameter measurements made at the upstream, middle, and downstream ends of the measurement section.

The measurement section should be inspected or measured with instrumentation periodically to determine if the dimensional factor should be adjusted to compensate for observed changes.

4.4 Installation Effects

4.4.1 Temperature. Temperature can affect the acoustic path length and cause uncertainty in the speed of sound measurement. The effects can be compensated for with the use of algorithms that account for changes in the pipe dimensions (i.e., cross-sectional area).

4.4.2 Vibration. With clamp-on transducers, vibration can interrupt the mechanical coupling to the pipe. The use of a secure transducer mounting assemblies and dry coupling materials can minimize the impact of vibration on clamp-on meter operation.

4.4.3 Pulsating Flow. Uncertainty can occur if the sampling rate of the flowmeter is not at least two times faster than fluid pulsation frequency.

4.4.4 Two or More Phase Flow. Transit-time ultrasonic flowmeters are tolerant of a certain volume fractions of gas or solid in the liquid flow. The presence of a second phase will result in erroneous or no measurement due to the scattering and absorption of the ultrasound by the second phase as the concentration increases.

4.4.5 Equipment Degradation. Fouling or physical degradation of the equipment can increase the measurement uncertainty. Equipment design should include reasonable tolerance to changes in component values and process conditions. The equipment should also indicate when degradation of flowmeter performance occurs. The probability of uncertainty can be reduced considerably by including suitable self-test or diagnostic circuits in the equipment.

4.4.6 Computation. There is a degree of uncertainty associated with the computations made by the electronic circuits because of the finite limits in processing accuracies. However, this uncertainty will normally be negligible.

5 INSTALLATION AND SELECTION GUIDELINES

5.1 Installation Considerations

Some of the uncertainty sources listed in section 4 can be reduced or eliminated by proper installation. Uncertainties the user should address during the design phase of a project are listed below.

5.1.1 Partially Filled Pipe. The ultrasonic meters referenced in this Standard do not incorporate a means to compensate for portions of a fluid conduit that may not be entirely filled with liquid.

A primary consideration of the installation of any ultrasonic flowmeter should include mounting of the transducer in a section of the piping system where the liquid will completely fill the conduit when measurements are to be made. Installation locations where the conduit potentially is not completely filled with liquid, such as spilling into an open container or at the uppermost point in a piping system, should be avoided. Manufacturers will typically recommend that installation of transducers on horizontal pipes be limited to the sides — avoiding the top of the pipe, as gas may accumulate and cause the flowmeter to lose signal.

Installations on vertical pipes should be limited to sections where flow is traveling in the upward direction unless sufficient backpressure is present that ensures a completely filled pipe at all times.

5.1.2 Uncertainties With Entrained Gas. Velocity/area flowmeters, such as ultrasonic transit-time flowmeters, do not have an absolute means to compensate for the volume of gases that may be suspended within the carrier liquid. As an example, if entrained gases make up 2% of the volume of the liquid/gas composition passing through the flowmeter measuring region, a 2% volumetric *liquid* measurement uncertainty will result, assuming that the bubbles are dispersed and moving with the same velocity as the liquid.

5.2 Selection Guidelines

This paragraph is intended to assist in selecting the most appropriate ultrasonic flowmeter for a particular application. Since there are many variations and differences even among the same types of flowmeters, this paragraph addresses only the major differences between the types. It is suggested that the application conditions be discussed with the manufacturer prior to a decision on a particular type of flowmeter.

5.2.1 Single-Path Versus Multipath Instruments. Single-path instruments are usually lower in cost than multipath instruments. Multipath flowmeters can exhibit lower uncertainty than single-path meters under the variable and/or non-ideal velocity profile distribution conditions caused by changing Reynolds number, changes in friction factor, and the effects caused by upstream and downstream elbows, valves, or other sources of flow disturbance. The choice of path orientations varies among manufacturers. It can be crossed or parallel, chordal or diametrical, and direct or reflective. Choice of the most appropriate path distribution should be made after a full evaluation of the application conditions.

5.2.2 Externally Mounted Versus Insert-Type Transducers. Externally mounted (clamp-on) transducers can be installed on existing pipe and, since they do not require any extensive pipe preparation, are less expensive to install than insert systems. Since the pipe inner wall is undisturbed, there is no flow disturbance in the vicinity of the transducers. They can also be easily removed without requiring shutdown of the process. Since these systems utilize a beam that refracts into the liquid, they may be affected by variations in the sonic properties of the liquid, pipe, transducer coupling wedge, liner if applicable, and other materials that are in the acoustic path.

Externally mounted transducers can utilize one of three different modes of wave propagation in the pipe wall. A shear wave transducer is the most common type since it can be applied universally to most pipe materials and wall thicknesses. For steel and most metallic pipes, the longitudinal wave inside the transducer is mode converted into a shear wave at the transducer/pipe wall interface. This shear mode conversion is weak in plastic materials; therefore, the longitudinal wave is the primary propagation mode for plastic pipes.

Another externally mounted transducer type uses the Lamb or Plate wave propagation mode, where the acoustic beam remains coherent as it travels down the length of the pipe wall. One advantage of this type of propagation is that a wider range of fluid sound velocities can be measured without the need for re-positioning the transducers. However, the transducer frequency and wedge angle must be matched to the pipe wall thickness and acoustic properties in order to establish a correct Lamb wave propagation.

The use of refraction in an externally mounted transducer system generally limits the acoustic path to the diametrical orientation, limiting its ability to compensate for non-ideal flow profile conditions. The manufacturer should be contacted to ensure that the expected application conditions can be handled with satisfactory performance.

Insert-type systems (generally installed, by manufacturers, into a flanged length of pipe that can be bolted into the process piping) can be of two types: those using wetted transducers and those where the transducers are installed in a protective well. Where the transducer faces and protective surfaces are orthogonal to the acoustic path, these systems can offer greater immunity to changes in the sonic velocity of the liquid because refraction of the beam does not take place. Since these systems usually have either the transducer recessed in a cavity or protruding into the liquid beyond the pipe wall, a local flow disturbance results that may affect the meter's performance. Although reportedly rare, the transducer cavities could collect debris and should therefore be installed in a plane or orientation that reduces this possibility.

Insert-type systems where the well is filled with a protective window results in refraction of the beam into the liquid and requires either relatively constant sonic velocity or compensation in the secondary device.

NOTE: If very large changes in sonic velocity occur, refraction may cause the ultrasonic beam to miss the opposing transducer.

Insert-type systems may provide greater acoustic power since they avoid the transmission loss through pipe wall. They may also, in some cases, offer a greater signal-to-noise ratio since they avoid some of the pipe-borne synchronous noise that may affect externally installed systems.

6 CALIBRATION, VERIFICATION, AND DIAGNOSTICS

Calibration is the primary means to provide the optimum accuracy with the lowest uncertainty. Velocity profile uncertainty can be reduced with in situ calibration or by properly simulated field installations.

The ultrasonic flowmeter should be calibrated using standardized procedures from national or international standards, such as those issued by ASME, ISO, API, and AGA, in order to minimize uncertainty from procedural mistakes.

The three principal methods of meter calibration factor determination are

(a) laboratory determination of a calibration factor
(b) field determination of a calibration factor
(c) analytical determination of a meter factor

Analytical procedures may sometimes be the only available technique for meter factor determination. This is particularly true for very high flow rates and large line sizes. Extreme pressures and temperatures that cannot be achieved at calibration facilities may require analytical corrections. This procedure requires physical measurements and data supplied by the manufacturer. The uncertainty in the meter performance should reflect uncertainties associated with these procedures, as well as those uncertainty sources outlined in section 3.

There are two general methods of laboratory calibration: gravimetric (mass) and volumetric. Ultrasonic meters are velocity-measuring devices. The integration technique gives an average velocity, which when multiplied by the cross-sectional area yields a volume flow rate. This can be used to infer either standard volume or mass flow by the application of additional density, pressure, temperature, and fluid-composition data. The uncertainty of the calibration will increase when more data is required.

Maintaining as-found and as-left calibration records is recommended to help understand the flowmeter's long-term performance and to provide an audit trail.

6.1 Laboratory Calibration

The calibration tests should generally be run using liquid that is free from acoustically interfering entrained air or solid particles. The calibration liquid should preferably have properties close to that used in the field.

For applications where installation effects are known to occur (i.e., less than 10*D* straight pipe upstream), it is recommended to consider calibration of the complete flowmeter piping section. A flowmeter piping section typically consists of a flow conditioner, 10*D* section upstream straight pipe, ultrasonic flowmeter, and 5*D* section of downstream straight pipe.

NOTE: Straight run requirements may vary depending on the type of flow conditioner and flowmeter used.

Alternatively, for an application that does not allow the flow conditioner and straight pipe lengths to be installed (i.e., due to limited space or pressure loss), it is recommended that the ultrasonic flowmeter be calibrated in the laboratory with the actual field piping or with piping that duplicates the field piping.

In all cases, the flowmeter calibration facility should ensure that the inlet flow to its calibration system is stable and as free as possible from swirl, asymmetry, and pulsation. The ideal is to have fully developed flow, which does not change with additional straight pipe length.

The extent to which the above conditions have been achieved can be determined by noting the sensitivity of the meter factor to rotation and translation of the primary device, or by evaluating the relative path behavior in a multipath instrument.

Flowmeter accuracy, within the uncertainty of the laboratory standards, should be determined by the combined random and systematic uncertainties in the measurement of the volumetric flow rate.

6.2 Field Calibration

Field calibration (often called "proving"), as opposed to laboratory calibration, has the advantage that true operating conditions are encountered. The disadvantage is that there is much less control over the stability and