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Measurement of fluid flow in closed conduits — Methods using transit-time ultrasonic flowmeters

Mesure de débit des fluides dans les conduites fermées — Méthodes utilisant des débitmètres à ultrasons à temps de transit

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The main task of technical committees is to prepare International Standards, but in exceptional circumstances a technical committee may propose the publication of a Technical Report of one of the following types:

— type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;

— type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;

— type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example).

Technical Reports of types 1 and 2 are subject to review within three years of publication, to decide whether they can be transformed into International Standards. Technical Reports of type 3 do not necessarily have to be reviewed until data they provide are considered to be no longer valid or useful.

ISO/TR 12765, which is a Technical Report of type 2, was prepared by Technical Committee ISO/TC 30, *Measurement of fluid flow in closed conduits*.

This document is being isssued in the type 2 Technical Report series of publications (according to subclause G.4.2.2 of part 1 of the ISO/IEC Directives, 1992) as a "prospective standard for a provisional application" in the field of ultrasonic flowmeters because there is an urgent need for guidance on how standards in this field should be used to meet an identified need.

This document is not to be regarded as an "International Standard". It is proposed for provisional application so that information and experience of its use in practice may be gathered. Comments on the content of this document should be sent to the ISO Central Secretariat.

A review of this type 2 Technical Report will be carried out not later than three years after its publication with the options of: extension for another three years; conversion into an International Standard; or withdrawal.

Annexes A, B and C of this Technical Report are for information only.

Measurement of fluid flow in closed conduits — Methods using transit-time ultrasonic flowmeters

1 Scope

This Technical Report gives guidance on the principles and main design features of ultrasonic flowmeters based on the measurement of the difference in transit time for volume flowrate measurement of fluids. It covers their operation, performance and calibration. It primarily covers wetted transducers but briefly refers to clamp-on transducer arrangements.

Annex A of this Technical Report shows the calculation of volume flowrate by transit-time measurement using pulse techniques.

Annex B covers the recommendations for use and installation.

Annex C gives a list of information to be supplied by the manufacturers.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this Technical Report. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 4006:1991, *Measurement of fluid flow in closed conduits — Vocabulary and symbols.*

ISO 4185:1980, *Measurement of liquid flow in closed conduits — Weighting method.*

ISO 8316:1987, *Measurement of liquid flow in closed conduits — Method by collection of the liquid in a volumetric tank.*

ISO 9300:1990, *Measurement of gas flow by means of critical flow Venture nozzles.*

ISO 9951:1993, *Measurement of gas flow in closed conduits — Turbine meters.*

International Vocabulary of Basic and General Terms in Metrology (VIM), BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, 1993.

3 Definitions

For the purposes of this Technical Report, the definitions given in the *International Vocabulary of Basic and General Terms in Metrology (VIM)*, ISO 4006 and the following definitions apply.

3.1
transit-time difference method
time-of-flight method
method of flowrate measurement in which the average fluid velocity along the acoustic path $\bar{v}$ is determined from the transit-time difference of two ultrasonic signals, one travelling upstream and one downstream, over the same distance in the flowing fluid

3.2
leading-edge method
method of flowrate measurement in which the transit times of ultrasonic pulses are measured based on triggering at a predetermined amplitude level of the received signal

See Figure 1.

Key
1 Trigger point at leading edge

Figure 1 — Principle of transit-time measurement using leading-edge method

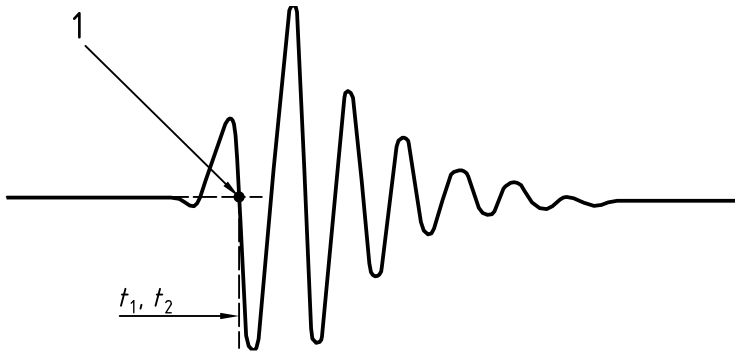
3.3
pulse-repetition frequency method
sing-around method
frequency-difference method
method of flowrate measurement used in ultrasonic flowmeters whereby two independent streams of pulses are transmitted in opposite directions, each pulse being emitted immediately after the detection of the preceding pulse in the stream, and the difference between the pulse-repetition frequencies in the two directions is measured

NOTE The difference between the pulse-repetition frequencies in the two directions is a function of the fluid velocity.

3.4
phase control method
lambda-locked-loop method
method of flowrate measurement in which a measure of the average fluid velocity along the acoustic path $\bar{v}$ is derived from the difference in frequency of sound with the same wavelength travelling in opposite directions through the flowing fluid

3.5
zero-crossing method
method of flowrate measurement in which transit times of ultrasonic pulses are measured using the first (or another predetermined) "zero-crossing" of the received signal following the first half alternance

See Figure 2.



Key

1 Trigger point at zero crossing

Figure 2 — Principle of transit-time measurement using zero-crossing method

3.6
multi-path method
method of flowrate measurement in which the average fluid velocity over a number of different paths is determined

3.7
simultaneous pulse method
method of flow measurement by which the transit times and transit-time difference are determined from signals which are transmitted simultaneously upstream and downstream over the same acoustic path

3.8
phase shift method
method of flow measurement in which the average fluid velocity along the acoustic path $\bar{v}$ is determined from the phase shift of ultrasonic signals in a fluid flow

3.9
ultrasonic flowmeter
USM
flowmeter which generates ultrasonic signals and receives them again after they have been influenced by the flow in such a way that the observed result can be used as a measure of the flowrate

NOTE An ultrasonic flowmeter normally consists of the ultrasonic transducers and equipment which evaluates the flowrate measurement from the emitted and received ultrasonic signals and converts these signals to a standard output signal proportional to the flowrate.

3.10
flowrate integrator
device for volume measurement by time-integration of volume flowrate

3.11
ultrasonic transducer
element that converts acoustic energy into electrical signals and/or vice versa

NOTE Ultrasonic transducers used in transit-time flowmeters usually work as both transmitter and receiver.

3.12
clamp-on arrangement
arrangement by which the transducers are attached to the outside wall of the conduit in which the flowrate is to be measured

3.13
meter tube
specially fabricated section of conduit containing the ultrasonic transducers and conforming in all respects to the specification of the standard

3.14
measurement section
section of conduit consisting of the meter tube, the inlet section and the outlet section

3.15
acoustic path
actual path of the ultrasonic signal between both transducers

3.16
path length
L_p
length of acoustic path, in fluid at rest, from the faces of both transducers

See Figure 3 a) and b).

3.17
interrogation length
L
length of that part of the acoustic path, in fluid at rest, inside the conduit

See Figure 3 a) and b).

3.18
interrogation distance
d
projection of the interrogation length on the line parallel to the axis of the conduit or of the flow

See Figure 3 a) and b).

3.19
inclination angle
ϕ
angle between the axes of the ultrasonic transducers and a line parallel to the axis of the conduit

See Figure 3 a).

3.20
phase angle
phase position of an oscillation

3.21
propagation velocity
c
velocity of acoustic signals relative to an observer at rest

3.22
velocity of sound
c_0
velocity of acoustic signals in the fluid at rest

3.23
average fluid velocity along the acoustic path
$\bar{v}$
fluid velocity in the plane which is formed by the acoustic path and the direction of flow

3.24
mean axial fluid velocity
$\bar{v}_A$
ratio of the volume flowrate (q_V) [the integral over a cross-section of the meter tube of the axial components of the local fluid velocities (v)] to the area of the measurement cross-section (A)

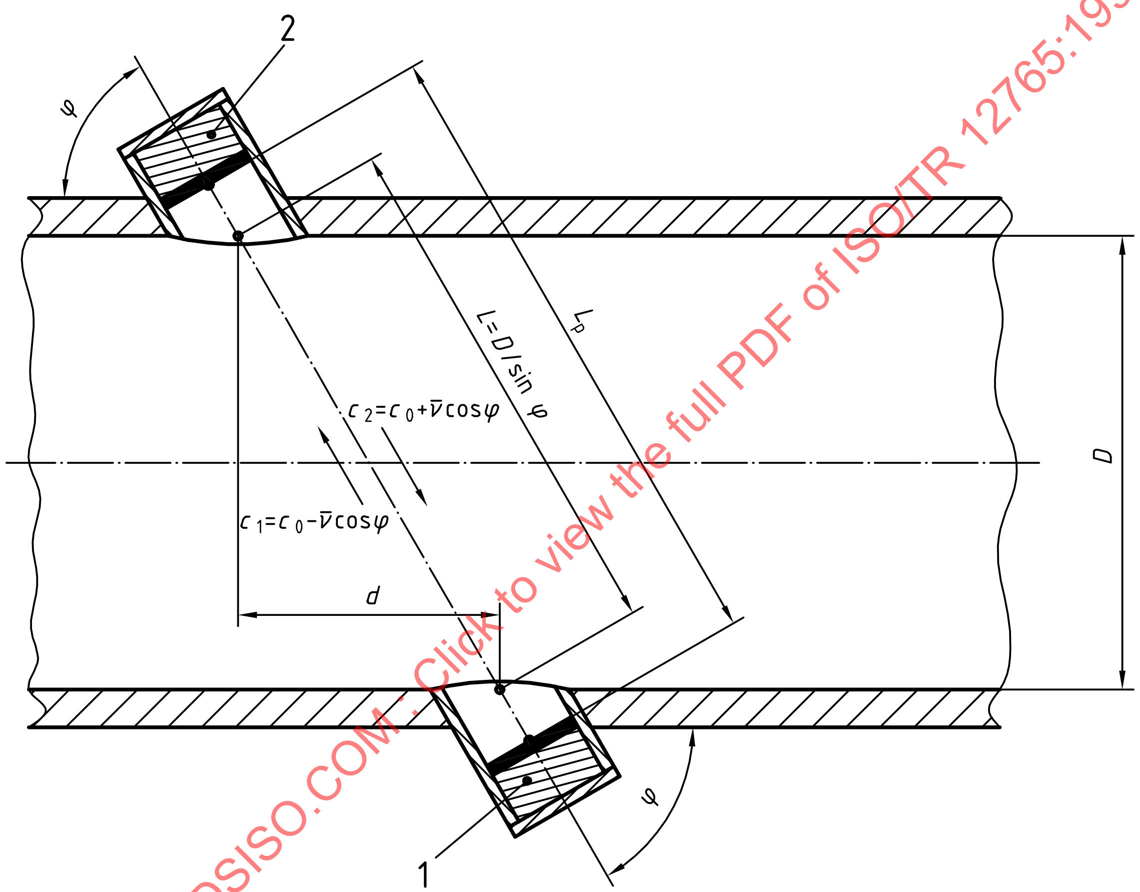
3.25
velocity distribution correction factor
k_h
ratio of the mean axial fluid velocity $\bar{v}_A$ in the meter run to the average axial flow velocity $\bar{v}$ along the acoustic path

3.26
ultrasonic pulse
signal generated by finite-duration electrical excitation of an ultrasonic transducer

3.27
continuous-wave ultrasound
signal generated by continuous electrical excitation of an ultrasonic transducer

3.28
transit time
t
time needed by an ultrasonic pulse to traverse the acoustic path

3.29
transit-time difference
Δt
difference between the transit times of the ultrasonic signals propagated upstream and downstream



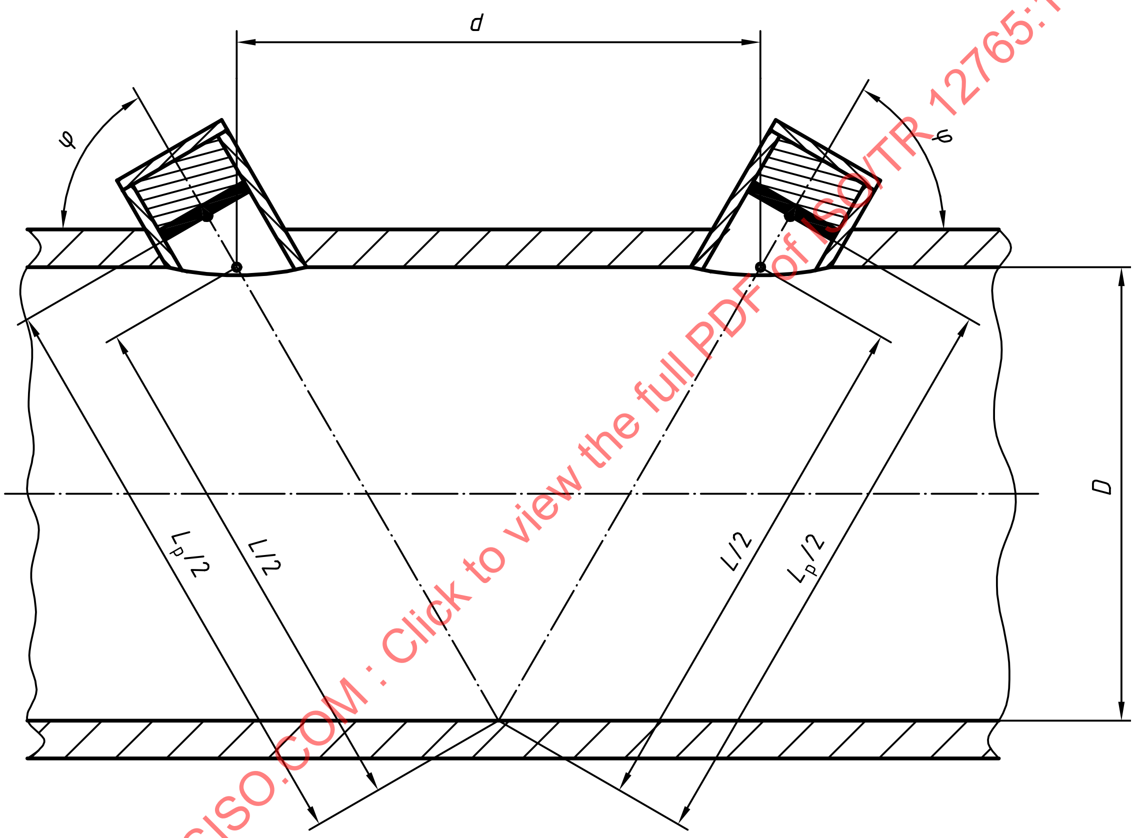
Key

1 Receiver/emitter

2 Emitter/receiver

a) Diagonal-direct beam meter

Figure 3 — Arrangements of single-path beam meter (wetted transducers)



b) Diagonal-reflected indirect beam meter

Figure 3 — Arrangements of single-path beam meter (wetted transducers)

4 Symbols and subscripts

Table 1 — Symbols

Quantity	Symbol	Dimensions[1)]	Corresponding SI unit
Cross-sectional area	A	L^2	m^2
Propagation velocity in the flowing fluid	c	LT^{-1}	m/s
Velocity of sound in fluid at rest	c_0	LT^{-1}	m/s
Inside diameter of pipe	D	L	m
Interrogation distance	d	L	m
Frequency	f	T^{-1}	s^{-1}
Relative uncertainty	E	2)	
Absolute uncertainty	e	3)	
Integer	i	2)	
Velocity distribution correction factor	k_h	2)	
Interrogation length	L	L	m
Path length	L_p	L	m
Integer	m	2)	
Integers (1, 2, 3, ...)	n	2)	
Volume flowrate	q_V	L^3T^{-1}	m^3/s
Reynolds number (related to D)	Re_D	2)	
Transit time	t	T	s
Transit-time difference	Δt	T	s
Local velocity of the fluid	v	LT^{-1}	m/s
Average fluid velocity along the acoustic path	$\bar{v}$	LT^{-1}	m/s
Mean axial fluid velocity	$\bar{v}_A$	LT^{-1}	m/s
Weight of measurement	w_i	2)	
Phase angle	γ	2)	rad
Wavelength of an ultrasonic oscillation	λ	L	m
Inclination angle	ϕ	2)	rad
Cyclic frequency	ω	T^{-1}	$rad \cdot s^{-1}$
Density of the fluid	ρ	ML^{-3}	kg/m^3

1) M = mass, L = length, T = time.
2) Dimensionless quantity.
3) The dimension of this parameter is the dimension of the quantity to which it relates.

Table 2 — Subscripts

1	upstream
2	downstream

5 General principles of measurements

The basic principle used by the ultrasonic flowmeters described in this Technical Report is that sound travelling with the fluid flow will travel faster than sound travelling against the flow. The transit times and the time difference are functions of the fluid velocity. The measurement can be made either by measuring transit times directly or by using frequency or phase measurement. Ultrasonic flowmeters are inherently bidirectional.

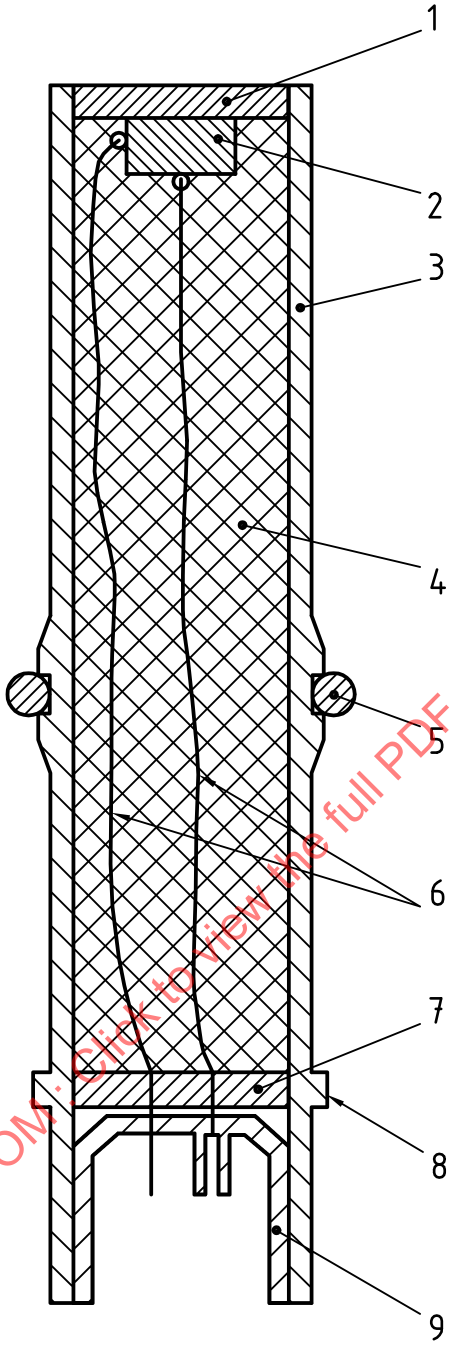
Volume flowrate (q_V) is determined by the product of the cross-sectional area (A) and the mean axial fluid velocity $\bar{v}_A$.

5.1 Generation of ultrasonic signals

The ultrasonic signals required for the flow measurement are generated and received by ultrasonic transducers (e.g. using piezoelectric crystals).

Piezoelectric transducers employ crystals or ceramics which are sent into vibration when alternating voltage is applied to their terminals. The vibrating element thus generates longitudinal pressure waves (sound waves) in the fluid. Sound waves incident on such piezoelectric elements will produce electric signals at their terminals, as the piezoelectric effect is reversible.

The acoustic properties of the transducer (beam pattern, resonance frequency, bandwidth, etc.) depend strongly on the construction of the transducer. Figure 4 shows a possible transducer design, and the beam pattern of a transducer is shown in Figure 5.

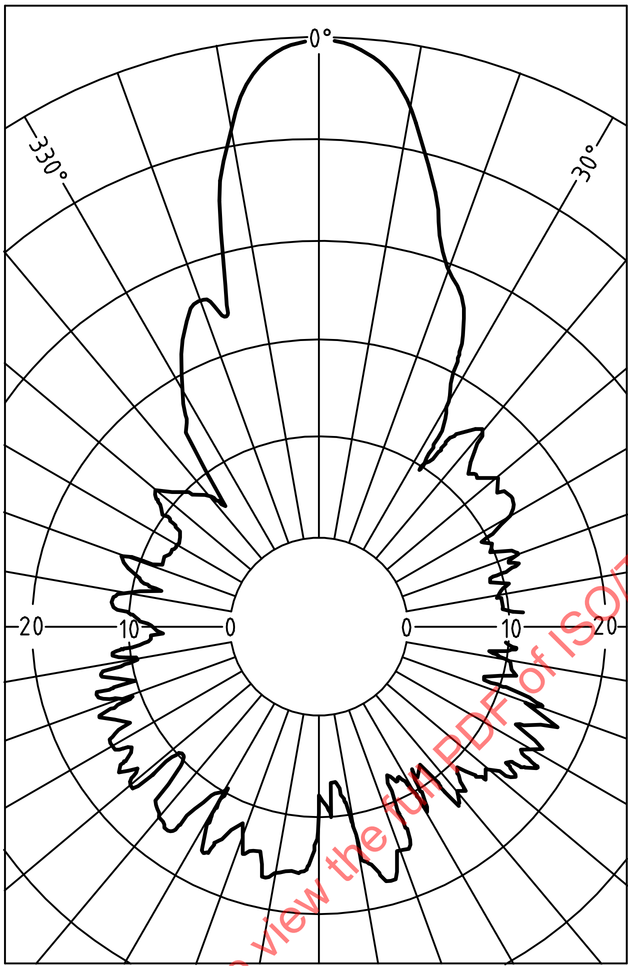


Key

1	Possible matching layer	6	Wires
2	Piezoelectric element	7	Possible pressure seal
3	Transducer housing	8	Mounting flange
4	Backing material	9	Plug for transducer cable
5	O-ring seal		

NOTE The transducer housing material can be metal, plastics etc. depending on the application.

Figure 4 — Possible design of a piezoelectric transducer



NOTE 1 The transducer employs a matching layer as in Figure 4.

NOTE 2 One division of the radial scale in the polar diagram corresponds to 10 dB.

Figure 5 — Measured beam pattern of a transducer with an outer diameter of 2 cm at an operating frequency of 162 kHz

5.2 Transit-time method

5.2.1 Direct transit-time method

The propagation velocity c will be the sum of the velocity of sound c_0 and the fluid velocity component $v \cos\phi$ in the direction of the acoustic path [see Figure 3 a) and b)].

$$c = c_0 \pm \bar{v} \cos\phi \quad \text{. . . (1)}$$

If ultrasonic transducers are mounted flush with the inside of the meter tube [see Figure 8 b)], ultrasonic signals can propagate downstream and upstream in the flowing fluid. The upstream and downstream transit times of the ultrasonic pulses in the fluid flow are given by

$$t_1 = \frac{L}{c_0 - \bar{v} \cos\phi} \quad \text{. . . (2)}$$

$$t_2 = \frac{L}{c_0 + \bar{v} \cos\phi} \quad \text{. . . (3)}$$

$$\frac{1}{t_2} - \frac{1}{t_1} = \frac{2\bar{v}\cos\phi}{L} \qquad \text{. . . (4)}$$

where

$$\cos\phi = \frac{d}{L} \qquad \text{. . . (5)}$$

$$\bar{v} = \frac{L^2}{2d}\frac{\Delta t}{t_1 t_2} \qquad \text{. . . (6)}$$

$$\Delta t = t_1 - t_2 \qquad \text{. . . (7)}$$

If the transducers are set back from the pipe wall, the interrogation length (L) is replaced by the path length (L_p). The transit times (t_1) and (t_2) are defined as the signal transit times over $L_{p.}$

$$\bar{v} = \frac{L_p^2}{2d}\frac{\Delta t}{t_1 t_2} \qquad \text{. . . (8)}$$

Equation (8) compensates directly the time which the signal spends in the pockets, under the assumption that the velocity of sound in the stationary fluid is the same as in the flowing fluid (see annex A.3).

The following equations (10), (14) and (15c) are for flush-mounted transducers. For retracted transducers, L shall be changed to L_p [see equation (8)].

5.2.2 Pulse repetition method (sing-around method)

Instead of the direct transit times (t_1) and (t_2) above, in the case of the pulse-repetition frequency method the frequencies (f_1) and (f_2) are measured. The frequencies occur when an ultrasonic pulse reaching the receiver triggers a new signal at the emitter.

$$f_2 - f_1 = \frac{1}{t_2} - \frac{1}{t_1} = \frac{\Delta t}{t_1 t_2} \qquad \text{. . . (9)}$$

Instead of equation (7) it follows that

$$\bar{v} = \frac{L^2}{2d}(f_2 - f_1) \qquad \text{. . . (10)}$$

5.2.3 Phase shift methods

5.2.3.1 Phase difference methods

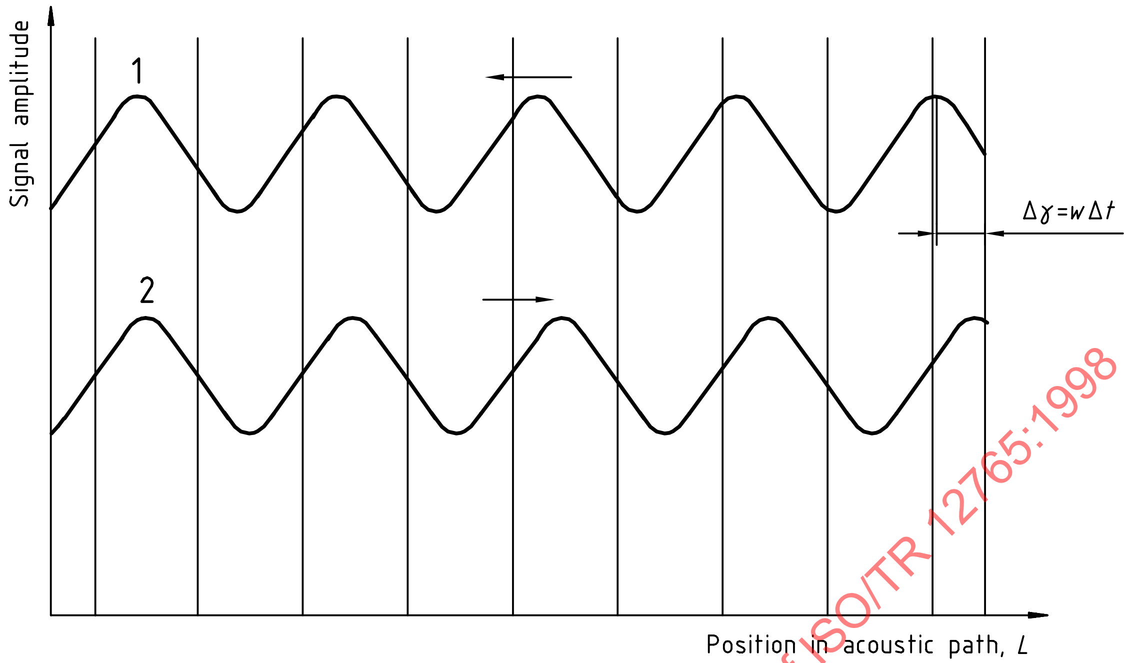
Instead of the direct measurement of the signal transit times, the phase angles γ_1 and γ_2 of two continuous signals with the cyclic frequency

$$\omega = 2\pi f \qquad \text{. . . (11)}$$

can be used to determine t_1 and t_2 (see Figure 6):

$$\gamma_1 = \omega t_1 = 2\pi f t_1 \qquad \text{. . . (12)}$$

$$\gamma_2 = \omega t_2 = 2\pi f t_2 \qquad \text{. . . (13)}$$



Key

1 Signal upstream

2 Signal downstream

Figure 6 — Phases of the ultrasonic signals upstream and downstream

From equations (12) and (13) and equation (6) it follows that

$$\bar{v} = \frac{L^2 \pi f}{d} \frac{\gamma_1 - \gamma_2}{\gamma_1 \gamma_2} \qquad \text{. . . (14)}$$

5.2.3.2 Phase control method

The constant frequency (f) can be replaced in both directions by variable frequencies (f_1) and (f_2). Through phase control it is possible to have signals in both directions with constant wavelengths at identical phase $\gamma_1 = \gamma_2 = 2\pi m$ (m preferably an integer).

In this case the transit times will be

$$t_1 = \frac{m}{f_1} \quad t_2 = \frac{m}{f_2} \quad \frac{\Delta t}{t_1 t_2} = \frac{1}{m}(f_2 - f_1) \qquad \text{. . . (15)}$$

Instead of equation (6) it follows that

$$\bar{v} = \frac{L^2}{2md}(f_2 - f_1) \qquad \text{. . . (15a)}$$

Since the "lambda-locked-loop" sets $\lambda = L/m$, it follows that

$$\bar{v} = \frac{\lambda L}{2d}(f_2 - f_1) \qquad \text{. . . (15b)}$$

The wavelength λ depends on the instantaneous velocity of sound in the fluid at rest (c_0) as well as the flow velocity. Even if the "lambda-locked-loop" is broken (e.g. by loss of signal or change in the direction of signal transmission), the loop may be re-established with a different number of cycles, i.e. a different m. Provided m is the same in both transmission directions, λ can be determined from $\lambda = c_0 / \bar{f}$ where $\bar{f} = (f_1 + f_2)/2$.

Thus

$$\bar{v} = \frac{c_0 L}{2 \bar{f} d}(f_2 - f_1) \qquad \text{. . . (15c)}$$

5.3 Calculation of volume flowrate q_V

5.3.1 Using diametrical paths only

The volume flowrate q_V is determined by

$$q_V = A \bar{v}_A \qquad \text{. . . (16)}$$

In the transit time method, only the average fluid velocity along the acoustic path $\bar{v}$ is determined.

In order to determine the mean axial fluid velocity $\bar{v}_A$ over the cross-section (A) and therefore the volume flowrate (q_V), the velocity distribution correction factor (k_h) must be known. The factor k_h is a result of the velocity profile in the meter tube and is given by

$$k_h = \frac{\bar{v}_A}{\bar{v}} \qquad \text{. . . (17)}$$

thus leading to

$$q_V = k_h A \bar{v} \qquad \text{. . . (18)}$$

The value k_h is a function of the Reynolds number (Re_D) (see Figure 7) and can be calculated approximately for fully developed velocity distribution in an axi-symmetric nonswirling flow (see annex A.4). k_h cannot be defined without ambiguity for the transition from laminar to turbulent flow. Diametrical meters employing dynamic profile correction require values for bore roughness, diameter and viscosity to be assumed in order that Re_D and hence k_h can be evaluated on the basis of the measured v.

If the conditions deviate from above, a flow calibration would be necessary (see 7.2).

5.3.2 Using multiple paths in parallel planes

When $\bar{v}$ is measured in different parallel planes (using multi-path arrangement of acoustic paths) $\bar{v}_A$ can be evaluated using suitable integration techniques over the cross-sectional area A (see 6.2.2 and annex A.4). For example, with a set of transit times (t_{1i}) and (t_{2i}) measured upstream and downstream in n parallel planes and the resulting $\bar{v}_i$ the volume flowrate may be calculated using

$$q_v = A \sum_{i=1}^{n} w_i \bar{v}_i \qquad \text{. . . (19)}$$

where the velocities $\bar{v}_i$ are measured at the planes i (i = 1 to $i = n$) and w_i depends on the integration technique used (see annex A.4).

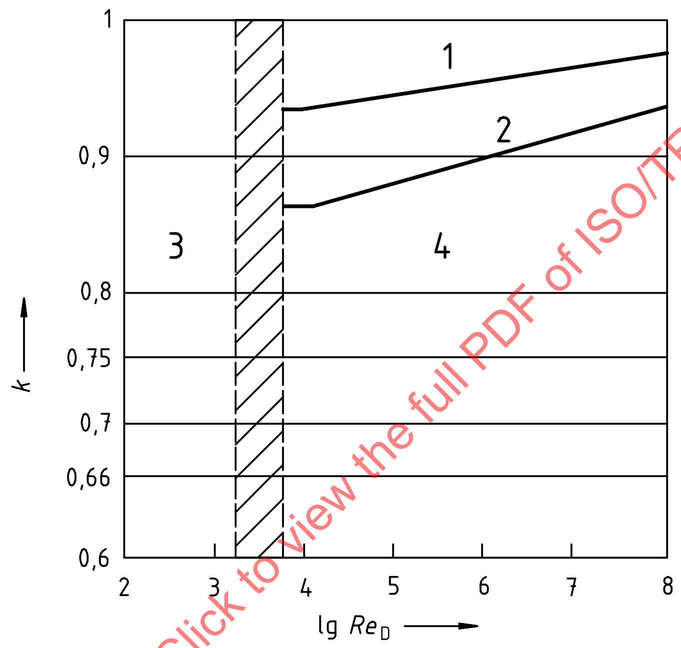
Multi-path arrangements help to reduce the errors in the estimation of flow velocity due to flow profile.

6 Types of design

The present status of ultrasonic flowmeters is characterized by the following features.

a) Meter tube and ultrasonic transducers (primary device) with specified arrangement of acoustic paths and specified method for attaching the transducers to the conduit;

b) control unit (secondary device) for signal processing, which comprises all or part of the necessary electronics. The control unit comprises the electronic equipment required to operate the transducers and make the measurements, means for processing the measured data, and for the display, output and/or recording of the results.



Key

1 Circular cross-section

2 Rectangular cross-section

3 Laminar flow

4 Turbulent flow

Figure 7 — Approximate value for k_h depending on Re_D

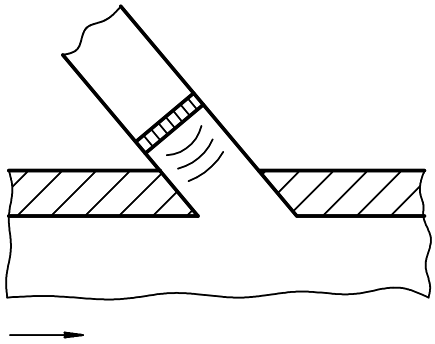
6.1 Ultrasonic transducer

6.1.1 Arrangement of the transducers

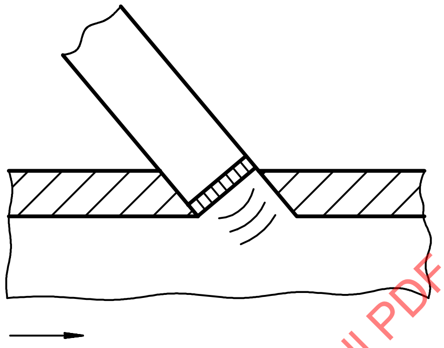
A minimum of two ultrasonic transducers are applied in an ultrasonic flowmeter using the transit-time method.

The transducers will be either inserted into the conduit in contact with the fluid or, for liquid measurements only, attached to the outside wall of the conduit (clamp-on arrangement) (see Figure 8).

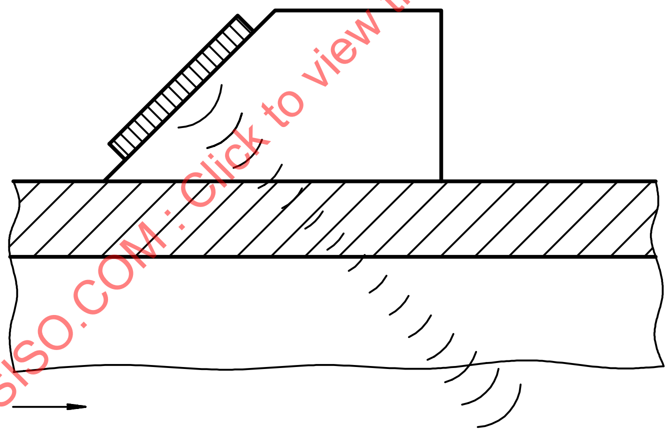
Ultrasonic transducers inserted into the conduit are mounted either at an oblique angle or normal to the conduit wall. In any case the angle between the axial flow direction and the straight line(s) running between the transducers is never 90°. The transducers may protrude into the conduit or be set back into the conduit wall.



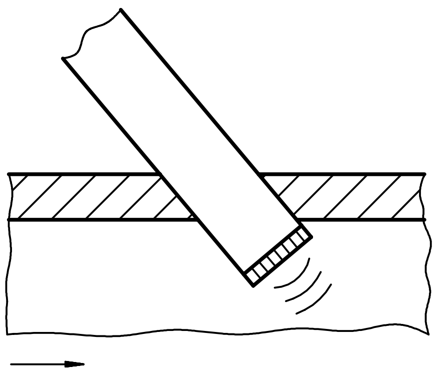
a) Transducer in contact with the fluid (retracted)



b) Transducer in contact with the fluid (flush)



c) Transducer mounted outside the conduit (clamp-on arrangement)



d) Transducer intruding into flow path

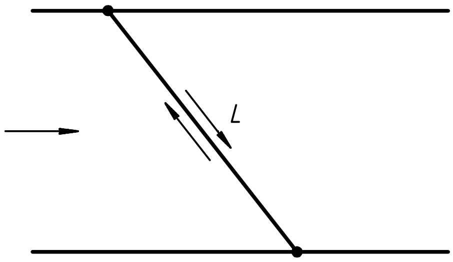
Figure 8 — Typical transducer arrangements

6.1.2 Single-path arrangement

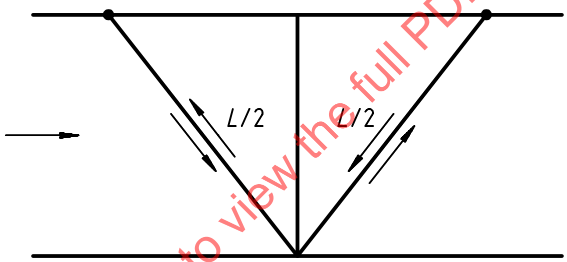
The acoustic transmission between the transducers can be either direct or indirect. Using the inner conduit wall as a reflector [see Figure 9 a), b) and c)] helps to increase the acoustic path length.

This implies that the transducers are mounted either on the same or "opposite" sides of the conduit [see Figure 9 a), b) and c)].

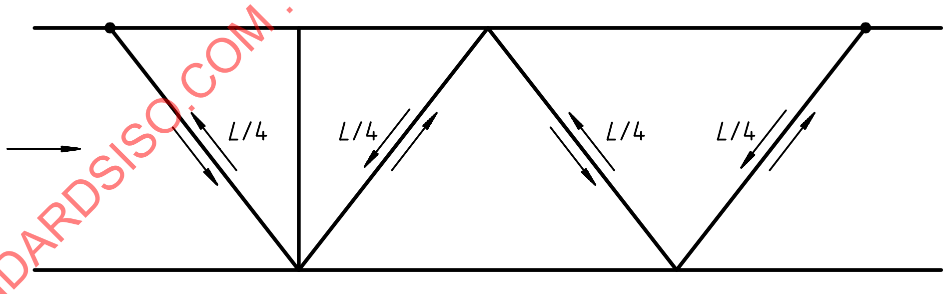
In a single-path meter with direct transmission, the transducers can be located along a tilted diameter or a tilted chord [see Figure 9 d) and e)]. For small conduits, the transducers may be mounted axially as shown in Figure 9 f).



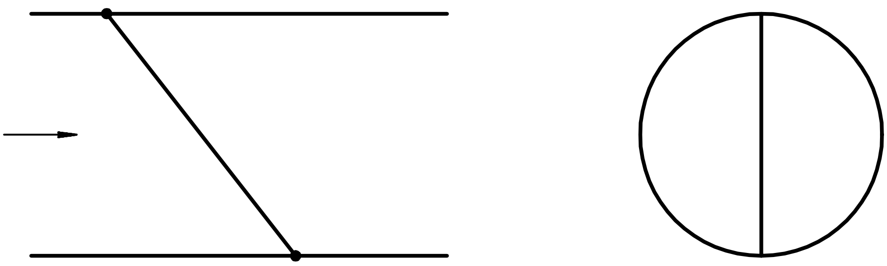
a) Direct transmission



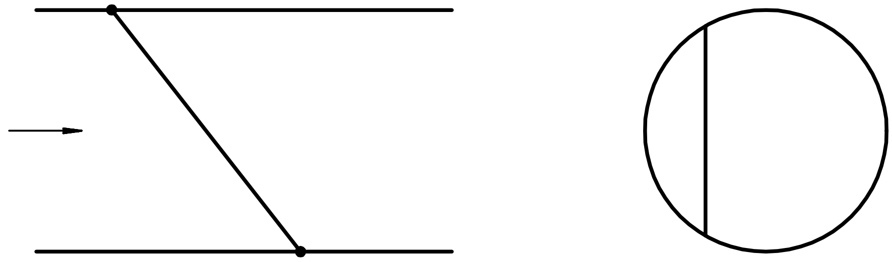
b) Indirect transmission (reflected by the conduit wall) (V-path)



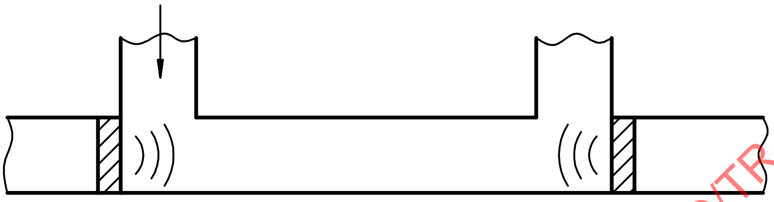
c) Indirect transmission (reflected by the conduit wall) (W-path)



d) Tilted diameter



e) Tilted chord



f) Axially mounted transducers

Figure 9 — Single-path arrangements

6.1.3 Multi-path arrangement

A multi-path meter is normally based on direct transmission along two or more tilted chords or diameters. The transducers can be arranged in many different ways in order to minimize the sensitivity to swirl and other disturbed flow profiles. Examples [see Figure 10 a) to d)] include:

— single-plane arrangement;

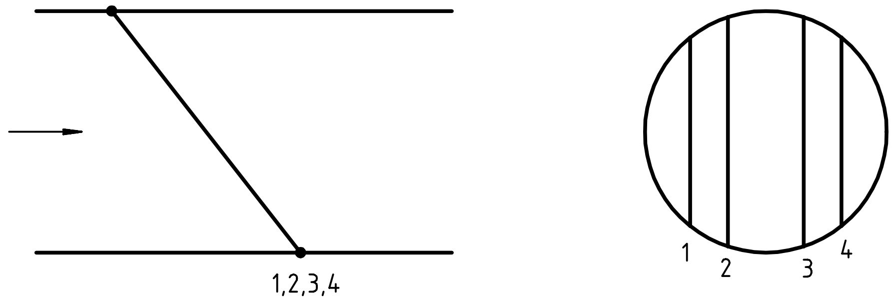
— symmetric criss-cross arrangement;

— asymmetric criss-cross arrangement;

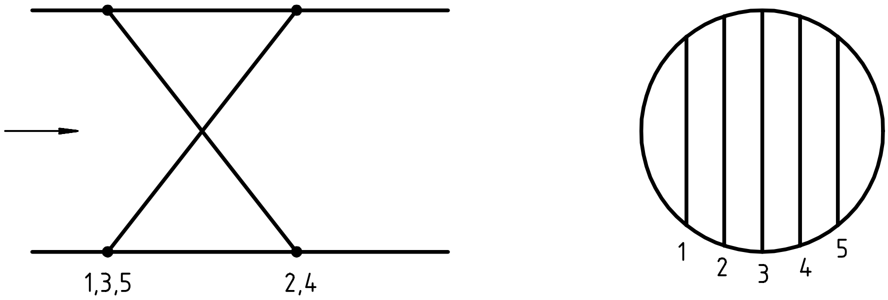
— twin-pair arrangement.

The criss-cross arrangement eases the mechanical arrangement in configurations employing a large number of paths.

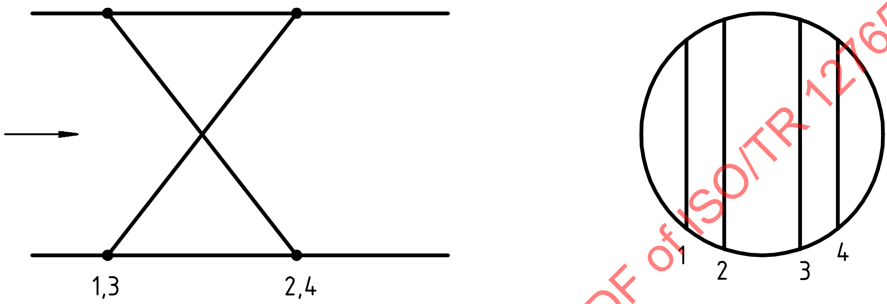
A multi-path meter can also be based on a spaced acoustic path network (see annex A.6).



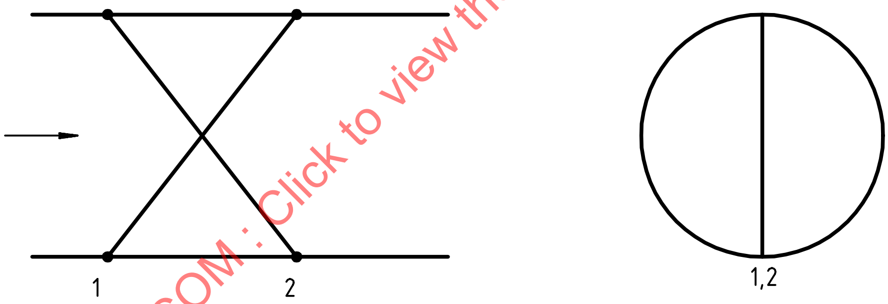
a) Single plane



b) Symmetric criss-cross



c) Asymmetric criss-cross



d) Twin-pair

Figure 10 — Multi-path arrangements

6.1.4 Design of transducers

The following criteria are, among others, significant in the design of the transducers:

— acoustic and mechanical adaption to the conduit as well as the fluid;

— for transducers in contact with the fluid, selection of a mechanical mounting with a minimum acoustic coupling from the transducers to the conduit wall;

— for clamp-on arrangements, good acoustic coupling from the transducers to the conduit wall;

— possibility of mounting and removal under operating conditions;

— suitability for the required temperature and pressure ranges;

— moisture protection;

— corrosion protection;

— safety requirements.

The transducers are critical components in a flowmeter and their performance affects the accuracy of the ultrasonic flowmeter.

If the physical characteristics of transducers change with time, the signal-to-noise ratio could deteriorate. The transducers should undergo strictly quality control in the manufacturing process. Indications of possible changes in performance of the transducers should be provided by the manufacturer.

6.1.5 Interconnecting cables

Any interconnecting cable length between the transducer and the control units is an important consideration, and both the maximum length and data to determine the resulting time delay (see 6.2.4) in such cables should be defined by the manufacturer.

6.2 Control unit

6.2.1 Operation of transducers

Paired transducers may be excited simultaneously or alternately with one or more transmissions in each direction. The acoustic frequency, pulse length and pulse repetition rate may vary mainly depending on the flowing fluid and path length (L_p). Each transducer pair in a multi-path configuration may operate independently, or multiplexed operation may be used.

In a multi-path meter, transit-time measurements for each path are performed before the mean axial fluid velocity $\bar{v}_A$ is determined.

6.2.2 Processing of data

The processing section, in addition to estimating the volume flowrate from measured transit times, should be capable of rejecting invalid measurements, noise etc. The indicated volume flowrate may be the result of one or more individual fluid velocity determinations.

6.2.3 Displays and outputs

Most ultrasonic flowmeters have several outputs available, either as standard or optional features. Displays may show flowrate, integrated fluid volume and/or directions of flow, and may be analog or digital. Signal outputs may include one or more of the following: current, voltage, digital output and a pulse rate proportional to flowrate. These outputs may or may not be electrically isolated. Control units may also include alarms and diagnostic facilities.

7 Uncertainty of measurement

The sources of uncertainty include:

— the uncertainty associated with the flow and the velocity distribution correction factor (k_h) or the weight of measurement (w_i);

— the uncertainties associated with geometrical parameters of the meter tube;

— the uncertainties associated with the time measurement.

7.1 Calculation procedure

7.1.1 Measurement of volume flowrate using single-path arrangement

The measured average fluid velocity along an acoustic path is given by equation (7). The volume flowrate is given by equation (18). Combining both for a conduit of inner diameter D, with $A = \pi D^2/4$ leads to

$$q_v = k_h \frac{\pi}{4} D^2 \frac{L^2}{2d} \frac{\Delta t}{t_1 t_2} \qquad ...(20)$$

The relative uncertainty in q_v is obtained by determining the total differential of the equation and dividing it by q_v:

$$\frac{\delta q_v}{q_v} = \frac{\delta k_h}{k_h} + 2\frac{\delta D}{D} + 2\frac{\delta L}{L} - \frac{\delta d}{d} + \frac{1}{(t_1 - t_2)\, t_1 t_2}(t_2^2\, \delta t_1 - t_1^2\, \delta t_2) \qquad ...(21)$$

The squares of the components are added to obtain

$$E_{q_v}^2 = E_{k_h}^2 + 4E_D^2 + 4E_L^2 + E_d^2 + \frac{1}{(t_1 - t_2)^2}(t_2^2\, E_{t_1}^2 + t_1^2\, E_{t_2}^2) \qquad ...(22)$$

where

E_{q_v} is the relative uncertainty in the measured volume flowrate;

E_{k_h} is the relative uncertainty in the velocity distribution correction factor:

E_D is the relative uncertainty in the pipe diameter (area);

E_d is the relative uncertainty in the interrogation distance;

E_L is the relative uncertainty in the interrogation length;

E_{t_1} is the relative uncertainty in the transit time t_1;

E_{t_2} is the relative uncertainty in the transit time t_2.

In the derivation above it is assumed, that all parameters are independent and hence their uncertainties may be squared and added to obtain the square of the resulting relative uncertainty.

7.1.2 Measurement of volume flowrate using multi-path arrangement

The volume flowrate (q_v) can be obtained by measurements on several paths by approximate integration, given by equation (19). In this case the combination of equation (19) with equation (7) leads to

$$q_v = \frac{\pi}{4} D^2 \sum_{i=1}^{n} w_i \left(\frac{L_i^2}{2d_i}\right)\left(\frac{\Delta t_i}{t_{1i}\, t_{2i}}\right) \qquad ...(23)$$

The relative uncertainty in q_v is obtained by determining the total differential of equation (23) and dividing it by q_v:

$$\frac{\delta q_v}{q_v} = \frac{2\delta D}{D} + \sum_{i=1}^{n}\left[\frac{\delta w_i}{w_i} + 2\frac{\delta L_i}{L_i} - \frac{\delta d_i}{d_i} + \frac{(t_{2i}^2\, \delta t_{1i} - t_{1i}^2\, \delta t_{2i})}{(t_{1i} - t_{2i})(t_{1i}\, t_{2i})}\right] \qquad ...(24)$$

The squares of the components, assumed independent, are added to obtain

$$E_{q_v}^2 = 4E_D^2 + \sum_{i=1}^{n}\left[E_{w_i}^2 + 4E_{L_i}^2 + E_{d_i}^2 + \frac{1}{(t_{1i} - t_{2i})^2}(t_{2i}^2\, E_{t_{1i}}^2 + t_{1i}^2\, E_{t_{2i}}^2)\right] \qquad ...(25)$$

where the components of the relative uncertainties are defined in the same way as stated in 7.1.1 and E_{w_i} are the relative uncertainties in w_i.

7.2 Influence factors

7.2.1 Factors related to disturbed flow

Disturbed flow causes uncertainty in measurement of $\bar{v}$ and calculation of $\bar{v}_A$.

The uncertainty is influenced by:

— flow around the transducer;

— the existence of transverse flow components (swirling flow);

— the shape of the axial velocity profile;

— pulsations.

The uncertainty can be reduced by:

— increasing the length of upstream and downstream straight pipes;

— using flow conditioners;

— using multipath meter with integration techniques suited for the actual conditions;

— carrying out flow calibrations under conditions similar to actual conditions.

7.2.2 Factors related to geometry

Errors in D and L cause constant percentage error in the volume flowrate and velocity, respectively, of twice the percentage error in D and L. Errors in d cause constant percentage error in velocity of the same value as the percentage error in d.

The uncertainty is influenced by:

— method of determination of D and roundness;

— measurement accuracy;

— expansion of measurement section due to pressure and temperature.

The uncertainty can be reduced by:

— a proper method for determining D (see 8.1.1);

— precise machining of the roundness of the meter tube;

— use of accurate devices for geometrical measurements;

— compensation for measurement section expansion due to temperature and pressure effects;

— carrying out flow calibration under conditions similar to actual conditions.

7.2.3 Factors related to signal detection

Velocity measurements can be influenced considerably when the acoustic signal gets corrupted. The signal detection then becomes increasingly difficult, which can lead to errors in transit-time measurement and hence to reduction in the accuracy of measurement. It can also lead to inconsistencies in the recognition of the correct timing point due to changes in received amplitude, distorted waveform or noise. Corrupted signals, however, may be rejected using appropriate validity tests. The following three sources of signal corruption can be encountered: electrical problems, flow-induced problems and acoustic problems.

More specifically:

— electrical noise;

— secondary flow (cross- and swirling flow):

— multiple phases in the measurement section;

— contaminants on the transducers and around the transducer area;

— extreme density gradients in the measuring section;

— excessive turbulence;

— excessive environmental noise (flow-generated or from external sources such as control valves);

— self-generated noise;

— installation close downstream of supercritical valves.

Generally the problems are best identified by sufficient self-diagnostics, self-checking features and alarm status indications. Flow-induced problems are best overcome with careful location of the measurement section and control of fluid conditions.

Acoustic problems are best solved by providing a high signal-to-noise ratio. Random background noise (electrical, flow-induced, acoustic) will generally average out. Self-generated noise may be more difficult to detect and may not average out, thus causing timing errors in transit-time measurements.

7.2.4 Factors relating to measurement and processing of time

The uncertainties in t_1, t_2 and Δt are influenced by:

— signal detection technique;

— method of time measurement (transit time, frequency shift);

— time resolution;

— non-fluid time estimates, including time delay along cables, electronics, transducers and pipewall;

— internal computational precision;

— influence of ambient condition on electronics;

— flow-induced timing errors (turbulence, swirl and pulsation);

— time delays in transducer pockets.

The uncertainties can be reduced by:

— insulating meter tube to avoid temperature gradients;

— zero checks at actual operating conditions.

8 Calibration

8.1 Dry calibration

8.1.1 Geometrical parameters

For high accuracy, the value of D should be the mean of the internal diameter over the length of meter tube. The internal mean diameter should be the arithmetic mean of measurements of at least twelve diameters, namely four diameters positioned at approximately equal angles to each other, distributed in each of three cross-sections evenly distributed over the length of meter tube containing all transducers. No diameter shall differ by more than 0,3 % from the average of the twelve diameters.

8.1.2 Timing and time delay

The time delays can be measured for a certain set of electronics and transducers.

One method among others is to mount two transducers in a test cell. The distance between the transducers is accurately measured. The test cell is filled with a fluid in which the velocity of sound is known. In this test cell a zero-flow condition is present.

NOTE A change in delay time does not cause a zero error, but an exchange of transducers can introduce a zero error due to change in orientation or change in transducer frequency.

The actual transit time of the signals in the fluid can be calculated by the equations (2) and (3). The transit times for "upstream" (t_1) and "downstream" (t_2) signals are equal (zero-flow) and can thus be calculated. The ultrasonic measurement system gives the transit times (t_1') and (t_2') that include the time delay in the electronics, transducers, cables, etc. These time delays are easily calculated from the difference of $t_1' - t_1$ and $t_2' - t_2$.

This method requires accurate knowledge of the velocity of sound in the fluid filling the test cell. Any errors in the velocity of sound affect the flowmeter performance. This causes a systematic shift of the performance curve, since errors in the velocity of sound cause a systematic offset in the applied time delays. The same method can be used for testing transducers and in the field as a check on the initial calibration.

NOTE It should be stated that this test requires thermal equilibrium, a very well known fluid (especially for gases) precise linear measurement, etc.

Another method for determining the time delay in the electronic cables and transducers is given below. The method requires a setup where the transit times of a pair of transducers can be measured at two different path lengths, (L_a) and (L_b) at still conditions. The measurements should be performed under the same ambient conditions for both path lengths. The USM will measure the transit times (t_a') and (t_b') that include for both equal lengths an equal time delay, t_d.

$$t_a' = t_a + t_d \qquad \text{. . . (26)}$$

$$t_b' = t_b + t_d \qquad \text{. . . (27)}$$

The transit times (t_a) and (t_b) in the fluid are equal to L_a/c_0 and L_b/c_0. Provided the distances L_a and L_b are known accurately, equations (27) and (28) have two unknowns, namely c_0 and t_d. This set can be solved explicitly so that the time delay t_d and c_0 can be calculated using:

$$t_d = \frac{(t_b' L_a - t_a' L_b)}{(L_a - L_b)} \qquad \text{. . . (28)}$$

$$c_0 = \frac{(L_a - L_b)}{(t_a' - t_b')} \qquad \text{. . . (29)}$$

This method does not require the knowledge of the velocity of sound in the fluid, since it is calculated.

8.1.3 Velocity distribution

8.1.3.1 k_h-factor

The k_h-factor can be calculated, based on the Reynolds number, the assumed flow profile and the integration technique used. However, errors in the correction factor may cause nonlinearity and/or systematic error. These errors are not considered in dry calibration.

8.1.3.2 Weight of measurement

In a multi-path arrangement, the number of chords, chord positioning and the integration technique used reduce the measurement uncertainty considerably and also the effect of changes in the flow profile (see Table A.1).

8.2 Flow calibration

In some cases a flow calibration is dictated by application, requirements or legal metrology. Any flow calibration has a degree of uncertainty, depending on the fluid, methods of calibration and the type of calibration facility. Two principal methods of flow calibration are used to test meter performance:

— laboratory flow calibration;

— field flow calibration (not commonly used for gases).

A flow calibration can be used to reduce uncertainties still prevailing after a dry calibration.

Usually the flow calibration results in a set of systematic errors, as function of flowrates, that can be used to correct meter output. The calibration should be performed in such a way to ensure that the test rig does not influence the test results and at conditions as close as possible to the envisaged installation. As a minimum, the manufacturer's reference to the installation conditions shall be observed.

8.2.1 Laboratory flow calibration

To improve the accuracy, the calibration should be conducted according to good laboratory practice and in accordance with methods recognized by International Standards (e.g. ISO 4185, ISO 8316, ISO 9300). The calibration should be made over a statistically significant number of runs and over a range of flowrates (for gases see ISO 9951).

The calibration accuracy of the flowmeter is determined by the random and systematic errors in the measurement of the volume flowrate and by the random and systematic errors associated with the measurements in the laboratory.

8.2.2 Field flow calibration

The effects of the actual installation in the field on the meter factor can be corrected with a field calibration or by properly simulated field conditions in a laboratory. The calibration should be performed at a Reynolds number as close as possible to the Reynolds number encountered in the actual application.

Annex A
(informative)

Calculation of volume flowrate by transit-time measurement using pulse techniques

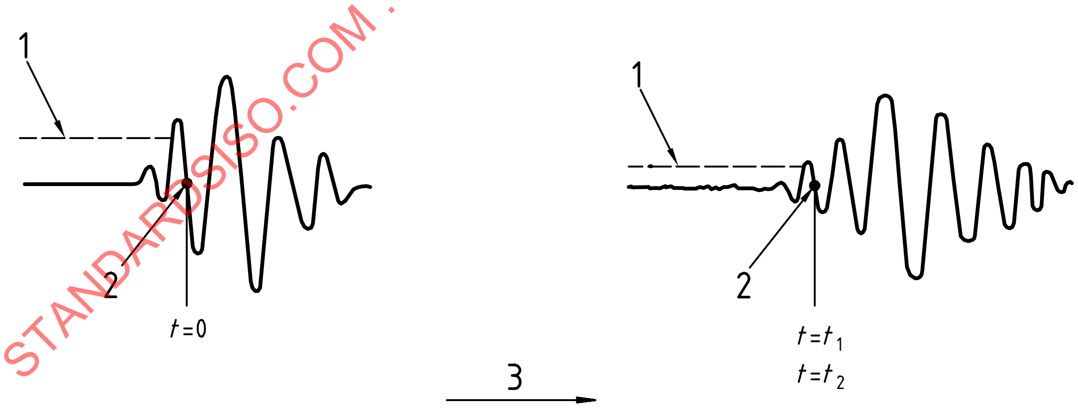
A.1 Transit-time measurement techniques

It is necessary to measure the transit time for an acoustic pulse travelling from an emitter to a receiver. Each transducer is required to serve both as an emitter and a receiver if the transit time is to be measured in both directions, i.e. downstream and upstream.

Direct measurement of acoustic transit times can be carried out in different ways in the flowmeter electronics. The basic principles are, however, common to all the techniques and will be summarized in the following without going into the details of how the detection techniques are incorporated using various electronic design strategies.

Pulse techniques employed for direct transit-time measurement are based on emitting and receiving acoustic pulses and measuring the time between pulse emission and pulse reception. Figure A.1 illustrates the emitted and received pulses, as an example where the transit time is taken as the time interval between the third zero-crossing in the emitted pulse and third zero-crossing in the received pulse. The problem, which in essence is addressed by virtually all the detection techniques, is to identify one or several predetermined zero-crossings or periods in the received pulse. This is not straightforward due to the limited bandwidth of the acoustic transducers and the modulation of the pulse by the flowing fluid.

A widely used technique is to trigger on a predetermined amplitude level of the received pulse and then detect the first subsequent zero-crossing, as shown in Figure A.1. This technique may be refined by using a longer pulse and detecting several zero-crossings in the more stable part of the pulse, see Figure A.2. In this way one avoids the transient part of the pulse where the pulse period varies. Further, for every pulse the transit time is computed as an average of the individual transit times corresponding to each zero-crossing.



Key

1 Trigger level

2 First zero-crossing

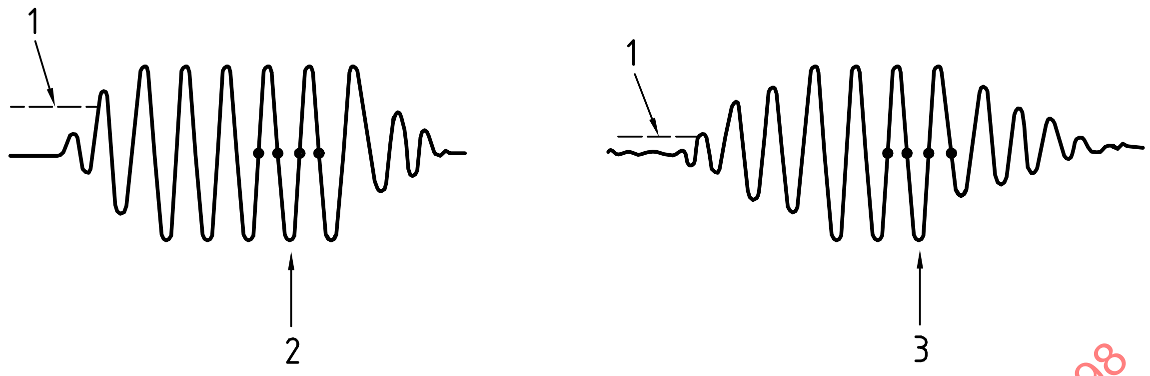
3 Time

a) Emitted pulse **b) Received pulse**

NOTE 1 Pulse transit times = t_1 or t_2

NOTE 2 The transit time is given as the time interval between the 3rd zero-crossing in the received and emitted pulses.

Figure A.1 — Pulse detection by triggering on a predetermined amplitude level subsequent detection of first zero-crossing



Key

1 Trigger level

2 Zero-crossings in stable part of pulse, $t = 0$

3 Zero-crossing in stable part of pulse, $t_1 = t$ or $t = t_2$

a) Emitted pulse **b) Received pulse**

NOTE 1 Pulse transit times $t_1 = \frac{1}{M}\sum_{i=1}^{M} t_{1i}$ or $t_2 = \frac{1}{M}\sum_{i=1}^{M} t_{2i}$

NOTE 2 The transit time is given as the mean of the time intervals between the zero crossings in the received and emitted pulses.

Figure A.2 — Pulse detection by triggering on a predetermined amplitude level and detection of zero-crossings in the stable part of the pulse

Another method of identifying a given zero-crossing or pulse period is to shape the pulse or to make use of the relatively fixed amplitude pattern in the transient part of the pulse.

A somewhat different approach is to use a correlation technique, e.g. to cross-correlate the received pulse with a digital representation of the excitation waveform used (see Figure A.3). The transit time is then calculated by determining the peak of the cross-correlation function. In a variation of this method, the transit time difference is determined directly by cross-correlating the upstream received pulse with the downstream received pulse.

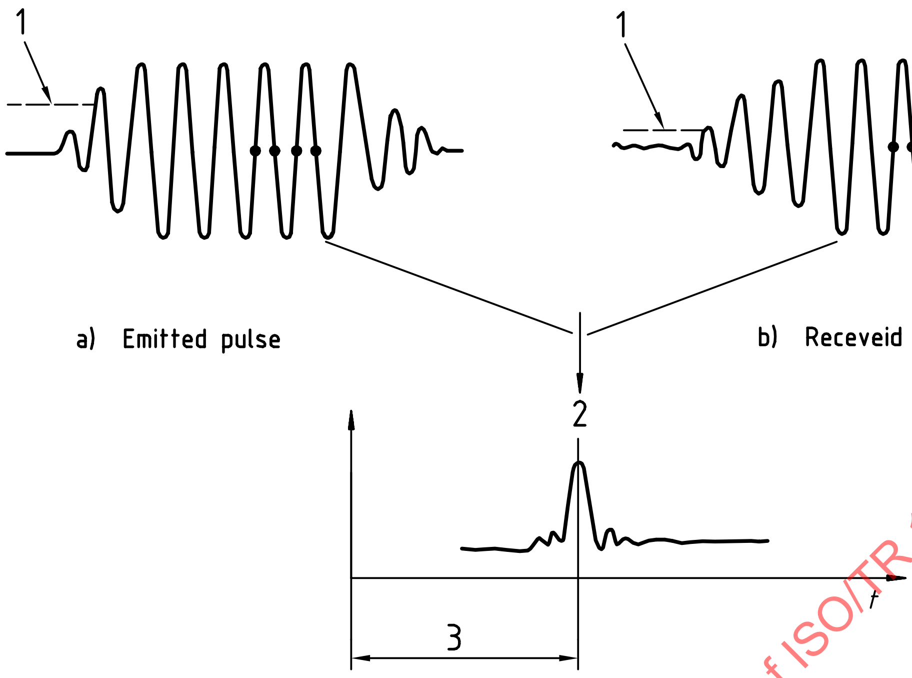
In a single-path meter, the upstream and downstream transit times have to be measured either simultaneously or alternately.

In a multi-path meter, the two transit times for each path, e.g. upstream and downstream, are usually measured once for all paths before the transit time velocity measurement for any of the paths is performed.

A.2 Calculation of mean transit time

Based on a set of n upstream and n downstream measured transit times, the mean upstream and downstream transit times (t_1) and (t_2) are to be calculated.

The transit times should be checked for spurious values, which should be discarded from the data set. A number of alternative methods are possible. The values should always be checked to ensure that the velocity of the fluid and the velocity of sound which these values suggest are possible.



Key

1 Trigger level

2 Autocorrelation function

3 Pulse transit time

Figure A.3 — Transit-time measurement by a correlation technique

The mean of t_1 and t_2 and the standard deviation σ of the n transit times may be computed:

$$t_1 = \frac{1}{n}\sum_{i=1}^{n} t_{1i} \qquad \text{... (A.1)}$$

$$t_2 = \frac{1}{n}\sum_{i=1}^{n} t_{2i} \qquad \text{... (A.2)}$$

$$\sigma(t_1) = \left[\frac{1}{n-1}\sum_{i=1}^{n}(t_{1i} - t_1)^2\right]^{1/2} \qquad \text{... (A.3)}$$

$$\sigma(t_2) = \left[\frac{1}{n-1}\sum_{i=1}^{n}(t_{2i} - t_2)^2\right]^{1/2} \qquad \text{... (A.4)}$$

The mean and the standard deviation of the velocity of sound can be computed according to:

$$c_{0i} = \frac{L^2}{2d t_1 t_2}\left[(t_{1i} + t_{2i})^2 \cos^2\phi + (t_{1i} - t_{2i})^2 \sin^2\phi\right]^{1/2} \qquad \text{... (A.5)}$$

$$c_0 = \frac{1}{n}\sum_{i=1}^{n} c_{0i} \qquad \text{... (A.6)}$$

$$\sigma(c_0) = \left[\frac{1}{n-1} \sum_{i=1}^{n} (c_{0i} - c_0)^2 \right]^{1/2} \qquad \text{. . . (A.7)}$$

Based on the mean and the standard deviation of the transit times and the mean and standard deviation of the velocity of sound, a suitable filtering technique may be established. For example, transit times leading to unrealistic estimates of the velocity of sound may be rejected. Similarly, transit times outside a specified interval around the mean transit times may also be rejected. Such a procedure will apply to unimodal transit-time distributions only.

The mean transit times and the mean velocity of sound are then calculated using the filtered set of transit times.

A.3 Extented theory for the transit-time flowmeter

A.3.1 The wave equation

A formal solution of the wave equation can be obtained for the case of transducers at the pipe wall and a uniformly flowing fluid. This gives the following more rigorous alternatives to equations (2) and (3) for the upstream and downstream transit times.

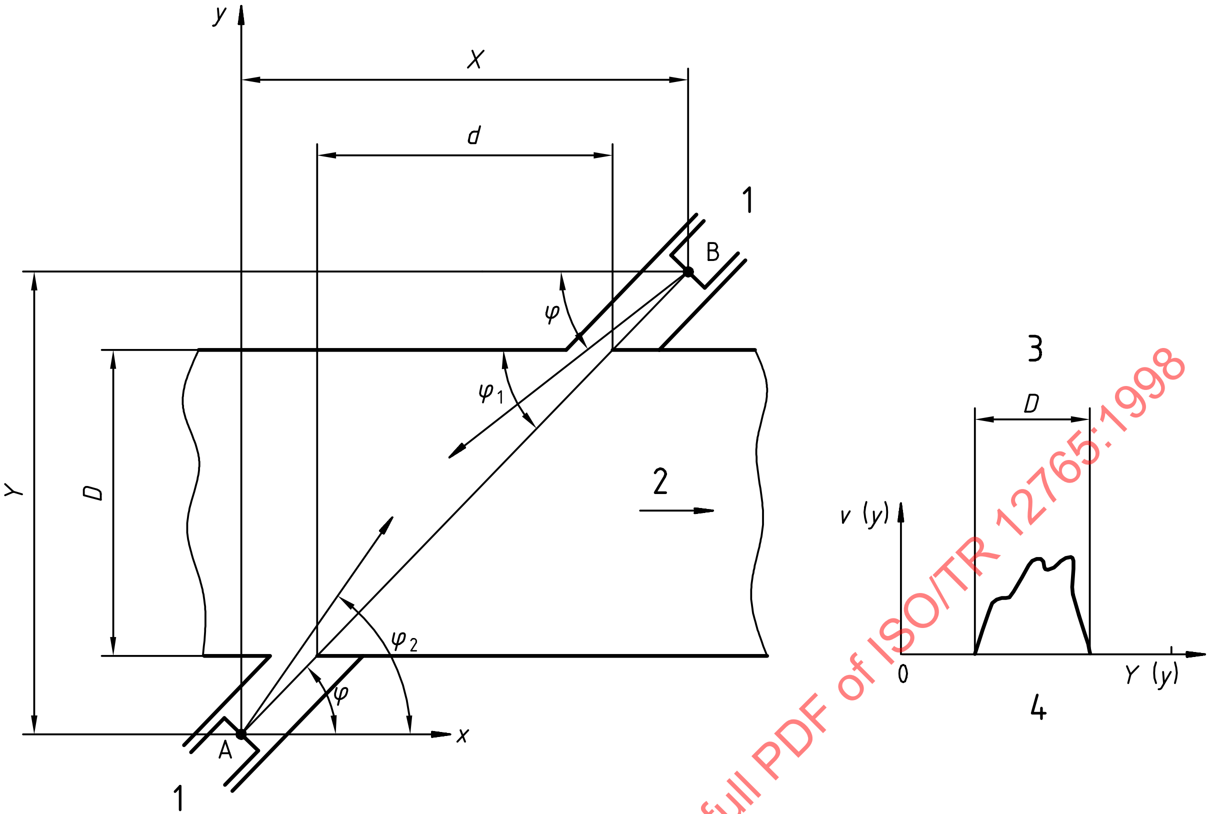
$$t_1 = \frac{L}{(c_0^2 - \bar{v}^2 \sin^2\phi)^{1/2} - \bar{v}\cos\phi} \qquad \text{. . . (A.8)}$$

$$t_2 = \frac{L}{(c_0^2 - \bar{v}^2 \sin^2\phi)^{1/2} + \bar{v}\cos\phi} \qquad \text{. . . (A.9)}$$

These equations, however, still lead to the same equation (7) for the fluid velocity $\bar{v}$.

A.3.2 Transducers set back from the pipe wall

In the following, the configuration is studied in which the transducers are set back clear of the fluid flow, as shown in Figure A.4, which defines the axes and shows many of the symbols.



Key

1 Transducer

2 Fluid flow, where $L_p^2 = X^2 + Y^2$; L_p = AB; $D/Y = d/X$

3 Illustrative distribution

4 Fluid velocity zero except in the flow

Figure A.4 — Transit-time flowmeter with transducers set back

Consider an ultrasonic pulse leaving transducer A at an angle ϕ_2 to the pipe axis, with the fluid flowing in the x direction with a velocity $v(y)$. Resolving the distance travelled by the pulse in the time τ in a fluid with velocity of sound c_0, we get, in the y direction,

$$y = c_0 \sin\phi_2 \,\tau \quad \text{. . . (A.10)}$$

and for x the increment

$$\mathrm{d}x = \left[c_0 \cos\phi_2 + v(y)\right] \mathrm{d}\tau \quad \text{. . . (A.11)}$$

After the transit time t_2

$$y = c_0\, t_2 \sin_2 \quad \text{. . . (A.12)}$$

and if the pulse is to arrive at B, it must travel a distance X in the x direction in transit time t_2, so

$$X = \int_0^X \mathrm{d}x = \int_0^{t_2} \left[c_0 \cos\phi_2 + v(y)\right] \mathrm{d}\tau \quad \text{. . . (A.13)}$$

$$= c_0\, t_2 \cos\phi_2 + \int_0^{t_2} v(y)\, \mathrm{d}\tau \quad \text{. . . (A.14)}$$

$$= c_0\, t_2 \cos\phi_2 + \int_0^y \left[\frac{v(y)}{c_0 \sin\phi_2} \right] \mathrm{d}y \qquad \text{. . . (A.15)}$$

Since the fluid velocity is zero outside the flow and has a mean of $\bar{v}$ over the flow section width D, then

$$\int_0^Y v(y)\, \mathrm{d}y = \bar{v} D \qquad \text{. . . (A.16)}$$

Thus

$$X = c_0\, t_2 \cos\phi_2 + \frac{\bar{v} D}{c_0 \sin\phi_2} \qquad \text{. . . (A.17)}$$

$$= c_0\, t_2 \cos\phi_2 + \frac{\bar{v} D t_2}{Y} \qquad \text{. . . (A.18)}$$

Since $D/Y = d/X$, the above equation can be rearranged to give

$$c_0 \cos\phi_2 = \frac{X}{t_2} - \frac{\bar{v} d}{X} \qquad \text{. . . (A.19)}$$

where d is the projection of the part of AB in the flow in the x direction.

From (A.12) and (A.19) with $\sin^2\phi_2 + \cos^2\phi_2 = 1$

$$c_2^0 = \frac{Y^2}{t_2^2} + \frac{X^2}{t_2^2} + \frac{\bar{v}^2 d^2}{X^2} - \frac{2\bar{v} d}{t_2} = \left(\frac{L_\mathrm{p}}{t_2} - \frac{\bar{v} d}{L_\mathrm{p}} \right)^2 + \frac{\bar{v}^2 d^2}{X^2} - \frac{\bar{v}^2 d^2}{L_\mathrm{p}^2} \qquad \text{. . . (A.20)}$$

where L_p is the transducer separation and $L_\mathrm{p}^2 = X^2 + Y^2$. Thus

$$\frac{L_\mathrm{p}}{t_2} = \left(c_0^2 - \frac{\bar{v}^2 d^2}{X^2} + \frac{\bar{v}^2 d^2}{L_\mathrm{p}^2} \right)^{1/2} + \frac{\bar{v} d}{L_\mathrm{p}} \qquad \text{. . . (A.21)}$$

Consider pulses travelling from B to A, with transit time t_1, and leaving B at an angle ϕ_1 to the pipe axis. The equations corresponding to (A.9), (A.12) and (A.19) above are

$$y = c_0\, t_1 \sin\phi_1 \qquad \text{. . . (A.22)}$$

$$c_0 \cos\phi = \frac{X}{t_1} + \frac{\bar{v} d}{X} \qquad \text{. . . (A.23)}$$

$$\frac{L_\mathrm{p}}{t_1} = \left(c_0^2 - \frac{\bar{v}^2 d^2}{X^2} + \frac{\bar{v}^2 d^2}{L_\mathrm{p}^2} \right)^{1/2} - \frac{\bar{v} d}{L_\mathrm{p}} \qquad \text{. . . (A.24)}$$

Subtracting (A.24) from (A.21) and rearranging gives:

$$\bar{v} = \frac{L_\mathrm{p}^2 (t_1 - t_2)}{2d\, t_1 t_2} \qquad \text{. . . (A.25)}$$

It can be seen that this equation involves only quantities which can be measured, namely the spool dimensions L_p and d shown in Figure A.4, and the transit times (t_1) and (t_2). There are no empirical constants involved.

However, it is assumed that the velocity of sound in the stationary fluid (c_0) is the same as in the flowing fluid, i.e. that the fluid is isothermal.

A.4 Calculation of mean axial fluid velocity $\bar{v}_A$

For single-path meters, the mean axial fluid velocity $\bar{v}_A$ averaged over the cross-sectional area of the conduit can be computed according to

$$\bar{v}_A = k_h \bar{v} \quad \text{... (A.26)}$$

For a single-path meter of diametric type, k_h may be calculated according to

$$k_h = \frac{1}{1{,}12 - 0{,}011 \lg Re_D} \quad \text{... (A.27)}$$

for a fully developed turbulent flow, and

$$k_h = 0{,}75 \quad \text{... (A.28)}$$

for laminar flow.

For a single-path meter of the chordal type, i.e. the acoustic path is along a tilted chord, where the lateral position of the ultrasonic transducers from the centreline is r, k_h may be calculated as follows:

$$k_h\,(Re_D) = \frac{\bar{v}_A}{v(r)} \quad \text{... (A.29)}$$

where $\bar{v}(r)$ is the average axial flow velocity at r. Calculating $\bar{v}_A$ and $\bar{v}(r)$ for the power law velocity distribution

$$v(r, Re_D) = v_{r=0}\left(1 - \frac{r}{R}\right)^{\frac{1}{n}} \quad \text{... (A.30)}$$

$$\frac{1}{n} = 0{,}250 - 0{,}023 \lg Re_D \quad \text{... (A.31)}$$

for $r = R/2$, the average value of k_h for Reynolds numbers in the range 10^4 to 10^8 is 0,996.

For this particular lateral path position, the variation of k_h is less than 0,4 % over the specified Reynolds number range. For chordal-type meters, the recommended lateral position of the transducers is at $r = R/2$.

Since the assumed conditions for the calculation of k_h are very seldom fulfilled, a flow calibration should be performed on a test rig or at the final installation if this can be arranged.

For a circular pipe, the theoretical expression for $\bar{v}_A$ is given by

$$\bar{v}_A = \left(\frac{1}{A}\right)\int_{-R}^{R} D(r)\,\bar{v}(r)\,\mathrm{d}r = \left(\frac{2}{A}\right)\int_{-R}^{R} (R^2 - r^2)^{1/2}\,\bar{v}(r)\,\mathrm{d}r \quad \text{... (A.32)}$$

where $\bar{v}(r)$ is the average flow velocity along the chord $D(r)$ having a lateral position r, and A is the cross-sectional area of the pipe.

In a multi-path meter $\bar{v}(r)$ is calculated for a set of discrete values of r. By applying a suitable numerical integration technique, $\bar{v}_A$ can be computed based on the calculated $\bar{v}$ for each path. Thus, $\bar{v}_A$ may be computed e.g. by the Gaussian integration technique with

$$\bar{v}_A = \left(\frac{2}{A}\right) \sum_{i=1}^{n} w_i \, \bar{v}_i(r_i) \qquad \text{. . . (A.33)}$$

where w_i are weighting factors depending on the applied integration technique, and r_i are the lateral positions of the ultrasonic transducers.

This is a widely used technique for numerical integration. This method has been implemented in various ways in multi-path ultrasonic flowmeters.

As examples, Table A.1 shows weight of measurement and lateral transducer positions for two Gaussian integration techniques with weighting function $f(r) = 1$ (Gauss) and $f(r) = (R^2 - r^2)^{1/2}$ (Gauss-Jacobi).

Table A.1 — Examples for normalized transducer positions and weight of measurement for Gaussian integration with weighting functions $f(r) = 1$ (Gauss) and $f(r) = (R^2 - r^2)^{1/2}$ (Gauss-Jacobi), respectively

Below F_i is defined as: $F_i = R^2 \cdot \left[1 - \left(\frac{r_i}{R}\right)^2\right]^{1/2}$

Integration technique	2 paths		3 paths		4 paths	
	$\frac{r_i}{R}$	w_i	$\frac{r_i}{R}$	w_i	$\frac{r_i}{R}$	w_i
Gauss	– 0,577 4	F_i	– 0,774 6	0,555 5 F_i	– 0,861 1	0,347 9 F_i
	0,577 4	F_i	0,000 0	0,888 8 F_i	– 0,340 0	0,652 1 F_i
			0,774 6	0,555 5 F_i	0,340 0	0,652 1 F_i
					0,861 1	0,347 9 F_i
Gauss-Jacobi	– 0,5	0,785 4 R^2			– 0,809 0	0,217 1 R^2
	0,5	0,785 4 R^2			– 0,309 0	0,568 3 R^2
					0,309 0	0,568 3 R^2
					0,809 0	0,217 1 R^2
NOTE Gauss-Jacobi method is applied to configurations with even numbers of paths.						

In addition, $\bar{v}_A$ may also be computed by fitting a polynomial to the calculated velocities $\bar{v}$ for each path, and then integrating the fitted polynomial to obtain $\bar{v}_A$.

A.5 Calculation of volume flowrate

The volume flowrate is calculated from

$$q_V = A\bar{v}_A \qquad \text{. . . (A.34)}$$

A.6 Path configurations

Basically there are three types of multipath flowmeters, based upon their configuration:

— the diagonal-path flowmeter;

— the parallel-path flowmeter;

— the reflecting-path flowmeter.

The diagonal-path flowmeter employs a number of diagonally arranged flow paths. The discharge is calculated with the mean value of the individual velocity measurements.

The parallel-path flowmeter employs a number of paths (generally no more than five) parallel to each other. For the positioning of the paths and calculation of the flowrate, applying weighting factors for the different flow velocities, numerical integration methods (e.g. the Gauss integration method) are used.

The matrix flowmeter employs reflecting acoustic-path networks (see Figure A.5). These networks of acoustic paths give additional information on velocities and flow distortions.

The mean axial fluid velocity, and thus the volume flowrate, are processed by combining the different information received from the different paths.

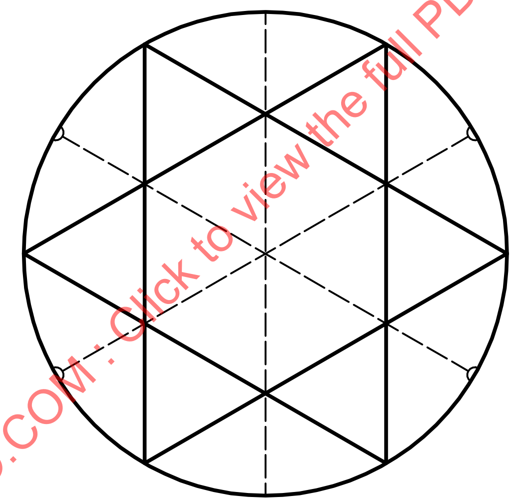


Figure A.5 — Matrix configuration of acoustic paths