



BSI Standards Publication

Use of clamp-on (externally mounted) ultrasonic flow-metering techniques for fluid applications – Guide

NO COPYING WITHOUT BSI PERMISSION EXCEPT AS PERMITTED BY COPYRIGHT LAW

raising standards worldwide™

Publishing and copyright information

The BSI copyright notice displayed in this document indicates when the document was last issued.

© BSI 2010

ISBN 978 0 580 60891 9

ICS 17.120.10

The following BSI references relate to the work on this standard:

Committee reference CPI/30/5

Draft for comment 10/30173459 DC

Publication history

First published February 2005

Second (present) edition December 2010

Amendments issued since publication

Date	Text affected
------	---------------

Contents

Foreword *iii*

Introduction 1

- 1 Scope 1
- 2 Symbols and abbreviations 2
- 3 Clamp-on ultrasonic flow-meters 3
- 4 Application areas 10
- 5 Performance measures 12
- 6 Calibration – general 19
- 7 Installation effects 20
- 8 Pipe work effects 26
- 9 Fluid effects 30
- 10 Operational effects 39

Annexes

- Annex A (normative) Reference data 49
- Annex B (normative) Variants to base technologies 62
- Annex C (normative) Detailed equations 66
- Annex D (informative) Installation effects 68

Bibliography 71

List of figures

- Figure 1 – Refraction of ultrasound signals through pipe wall 4
- Figure 2 – Schematic of a clamp-on transit time ultrasonic flow-meter 6
- Figure 3 – A typical clamp-on TTUF 6
- Figure 4 – Cross-correlation ultrasonic flow-meter (CCUF) 8
- Figure 5 – Basic operation of a DUF 9
- Figure 6 – Repeatability for installation after a single elbow at 23D 15
- Figure 7 – Acoustic energy coupled into pipe and fluid for liquid clamp-on (top) and gas clamp-on (bottom) 18
- Figure 8 – Oscillogram of received signal 18
- Figure 9 – Profile correction factor (k_h) against Reynolds number for fully developed flow in smooth pipes 21
- Figure 10 – Refraction angles 22
- Figure 11 – Effects of flow distortion 24
- Figure 12 – Two-path measurement 25
- Figure 13 – Effect of pipe wall roughness on profile correction factor 29
- Figure 14 – TTUF transducer configurations 41
- Figure B.1 – Leading edge measurement 62
- Figure B.2 – Phase measurement system 63
- Figure B.3 – Cross-correlation tag time meter 65
- Figure B.4 – Signal set demodulated 65
- Figure B.5 – Demodulated signals and cross-correlation function 66
- Figure 3 – A typical clamp-on TTUF (*repeated*) 67
- Figure D.1 – Errors downstream of a conical contraction 68
- Figure D.2 – Errors downstream of a conical expansion 68
- Figure D.3 – Errors downstream of a single 90° bend 68
- Figure D.4 – Errors downstream of two 90° bends in “U” configuration 69
- Figure D.5 – Errors from two 90° bends in perpendicular planes 69
- Figure D.6 – Errors downstream of a butterfly valve $\frac{2}{3}$ open 69
- Figure D.7 – Errors downstream of a globe valve $\frac{2}{3}$ open 70
- Figure D.8 – Errors downstream of a gate valve $\frac{2}{3}$ open 70

List of tables

Table 1 – Clamp-on meter selection table – liquids	11
Table 2 – Clamp-on meter selection table – gases	11
Table 3 – Comparison of gas clamp-on flow-metering methods	17
Table 4 – Acoustic impedances of important materials	17
Table 5 – Required straight lengths between fittings and USM	23
Table 6 – Additional requirements for reporting flow in standard volume and mass terms	26
Table 7 – Ranges of pipe size, material, wall thickness and lining material with which clamp-on TTUFs can be used	28
Table A.1 – Reference clamp-on calibrations	50
Table A.2 – Disturbance calibrations	51
Table A.3 – Solid sound speeds	52
Table A.4 – Fluid sound speeds	53

Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 74, an inside back cover and a back cover.

Foreword

Publishing information

This British Standard is published by BSI and came into effect on 31 December 2010. It was prepared by Subcommittee CPI/30/5, *Velocity based methods*, under the authority of Technical Committee CPI/30, *Measurement of fluid flow in closed conduits*. A list of organizations represented on this committee can be obtained on request to its secretary.

Supersession

This British Standard supersedes BS 8452:2005, which is withdrawn.

Information about this document

This guide now covers gas and liquid applications. It draws on practical user experience and various pieces of research work funded by DTi and other bodies.

Use of this document

As a guide, this British Standard takes the form of guidance and recommendations. It should not be quoted as if it was a specification and particular care should be taken to ensure that claims of compliance are not misleading.

Any user claiming compliance with this British Standard is expected to be able to justify any course of action that deviates from its recommendations.

Presentational conventions

The provisions in this standard are presented in roman (i.e. upright) type. Its recommendations are expressed in sentences in which the principal auxiliary verb is "should".

Commentary, explanation and general informative material is presented in smaller italic type, and does not constitute a normative element.

Contractual and legal considerations

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Compliance with a British Standard cannot confer immunity from legal obligations.

Introduction

This British Standard identifies factors likely to affect the performance of clamp-on (externally mounted) ultrasonic flow-meters for closed conduits running full. One of the significant advantages in employing ultrasonic techniques in fluid flow-metering is that not only can the meters be used non-intrusively, i.e. the sensors do not intrude into the flow path, but they can also be used non-invasively, i.e. with the transducers mounted onto the outside of the pipe work. Such methods are commonly referred to as clamp-on ultrasonic techniques because the transducers are clamped or held onto the outside of the pipe work.

These methods enable measurements to be made without breaking into the pipe work; therefore, measurements can be made where, for reasons of safety, hygiene, continuity of supply or cost, it is not possible to break containment.

Non-invasive ultrasonic metering techniques can thus provide a basis for checking existing meters, and be used as a temporary, semi-permanent or permanent method of measurement.

1 Scope

This British Standard identifies factors, including installation effects, pipe work and fluid effects, operational effects and supplier specific effects, which are likely to affect the performance of clamp-on (externally mounted) ultrasonic flow-meters. This includes hybrid spool type clamp-on meters where the clamp-on transducers are permanently mounted to a spool piece of precisely known physical dimensions. In doing so it also identifies best operational practice for such meters and provides estimates of the overall uncertainty that can be achieved when employing best practice.

This standard provides a description of the non-invasive clamp-on meter, typical application areas, the measures which should be used in assessing the likely performance in terms of error, repeatability and reproducibility when used under ideal flow, pipe, fluid and operational conditions based upon available data.

There are currently three commonly used non-invasive ultrasonic flow measurement technologies. These are the transit time ultrasonic flow-meter (TTUF), Doppler ultrasonic flow-meter (DUF) and the cross-correlation ultrasonic flow-meter (CCUF). However, technological innovation has seen variants of these techniques developed to improve the operation of the meters. The scope of this British Standard is restricted to the use of base technology employed in the meters so as not to preclude further developments. Each technique has its advantages and disadvantages depending upon the application. In order to provide the reader with as much information as possible the different ultrasonic technologies hybrids and their applications are discussed in Annex B to provide a comparative overview of the additional capabilities they offer.

2 Symbols and abbreviations

2.1 Symbols

Symbol	Meaning	Units
C_f	velocity of sound in fluid	m/s
C_p	velocity of sound in pipe wall	m/s
C_w	velocity of sound in transducer wedge	m/s
D	pipe internal diameter	m
E	indicated flow rate error	%
$\bar{E}$	average flow rate error for all test runs	%
E_i	flow rate error of the i^{th} test run	%
f_d	Doppler frequency shift	Hz
f_t	transmission frequency	Hz
h	height of wedge	m
K	meter factor	—
k_h	profile correction factor	—
k_r	uniform equivalent roughness	m
n	number of test runs	—
Q_v	volumetric flow rate	m ³ /s
R	repeatability	—
Re	Reynolds number	dimensionless
ρ	density of fluid	kg/m ³
μ	viscosity	Poise
v	velocity	m/s
S	transducer separation	m
S_f	separation through the fluid	m
S_p	separation through the pipe wall	m
S_w	separation through the transducer wedge	m
t	pipe wall thickness	m
t_{12}	transit time for ultrasound to travel from transducer 1 to transducer 2	s
t_{21}	transit time for ultrasound to travel from transducer 2 to transducer 1	s
Δt	time difference $t_{12} - t_{21}$	s
v_{pipe}	mean pipe velocity	m/s
V_{ind}	volume indicated by test meter	m ³
V_{std}	volume indicated by reference meter	m ³
α	angle between the direction of ultrasound in the transducer wedge and the pipe axis	° (degrees)
θ	angle between the direction of ultrasound in the liquid and the pipe axis	° (degrees)
λ	wavelength	m
λ_l	wavelength of ultrasound in the fluid	m

Symbol	Meaning	Units
v_{path}	averaged axial component of velocity along path between transducers	m/s
v_s	velocity of scatterers	m/s
Z	acoustic impedance	MRayls

2.2 Abbreviations

ABS	Acrylonitrile butadiene styrene
CCUF	cross-correlation ultrasonic flow-meter
CPVC	Chlorinated polyvinyl chloride
DUF	Doppler ultrasonic flow-meter
GRP	Glass Reinforced Plastic
HDPE	High Density Polyethylene
LDPE	Low Density Polyethylene
MDPE	Medium Density Polyethylene
PP	Polypropylene
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl Chloride
PVDF	Polyvinylidene Fluoride
RTV	Room Temperature Vulcanizing (elastomer sealant)
TTUF	transit time ultrasonic flow-meter
UFS	Ultrasonic Flow Meter System
USM	Ultrasonic Meter

3 Clamp-on ultrasonic flow-meters

3.1 General

A typical clamp-on ultrasonic flow-meter comprises three elements:

- The transducers and associated cables.
- The clamping arrangement.
- The signal processing and user interface electronic package.

The transducers are generally piezoelectric devices generating ultrasound that penetrates through the pipe wall and is transmitted through the fluid.

The clamping arrangements enable the transducers to be in good sonic contact with the pipe wall and correctly positioned, given the particular clamp-on technology employed and the specific pipe and fluid application.

3.2 Beam refraction – Snell's law

It is worth reiterating the impact of Snell's law as it applies to all forms of clamp-on ultrasonic meter. This is shown graphically in Figure 1 and in the following analysis.

Refraction of ultrasound is governed by Snell's law, which can be presented as:

$$\frac{\cos \alpha}{c_1} = \frac{\cos \beta}{c_2} = \frac{\cos \theta}{c_f} \quad (1)$$

where:

c_1 is...velocity of sound of the transducer

c_2 is...velocity of sound in the pipe

c_f is...velocity of sound in the fluid

If the transducers are configured such that $\alpha_t = \alpha_r = \alpha$ then Equation 1 can be rewritten as:

$$\delta f = 2f_t \left(\frac{v \cos \theta}{c_f} \right) \quad (2)$$

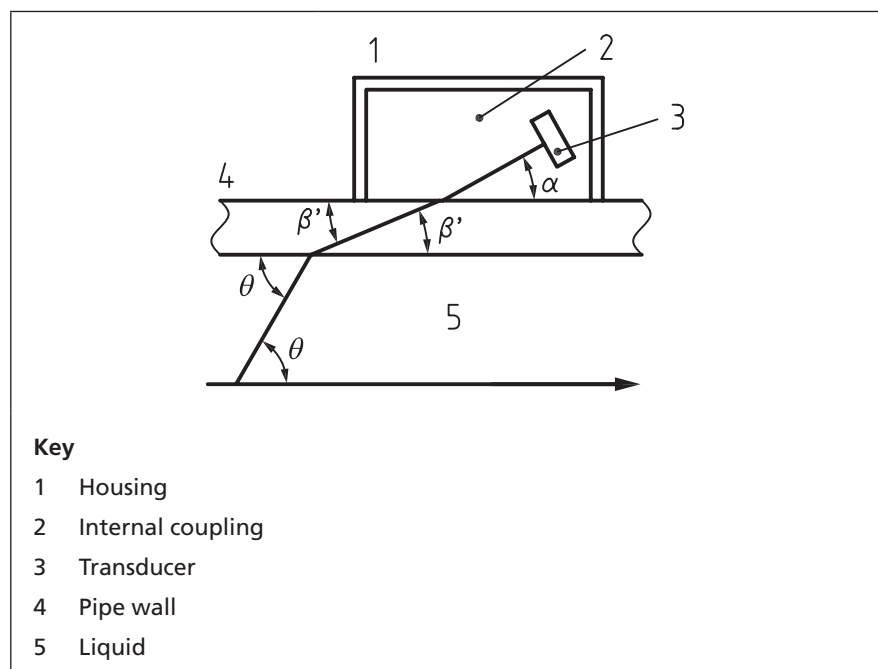
substituting $\frac{\cos \alpha}{c_1}$ for $\frac{\cos \theta}{c_f}$ and rearranging for v yields:

$$v = \frac{\delta f c_1}{2f_t \cos \alpha} \quad (3)$$

i.e. the measured velocity is proportional to δf and independent of the acoustic properties of the fluid and the pipe wall. The angle α and velocity of sound c_1 are assumed to have known values.

However, temperature dependence of c_1 , the velocity in the transducer "potting" or internal coupling material, can give rise to errors in the measurement of velocity. The USM manufacturer should be consulted regarding the temperature dependence of the particular transducers employed and the likely impact of temperature variation.

Figure 1 Refraction of ultrasound signals through pipe wall



3.3 Transit time ultrasonic flow meter

Figure 2 shows the principle of operation of the clamp-on TTUF measuring the flow rate of a fluid whose velocity of sound is c_f in a pipe of internal diameter D . This technology is applicable to both liquid and gas applications. Figure 3 illustrates a typical TTUF configuration. The signal processing electronics measures the time taken for ultrasonic waveforms to be alternately passed upstream and downstream. Any resulting difference in times (Δt) is directly related to the velocity of the fluid. The velocity is converted to a flow rate, which is typically displayed on a user interface either in numerical or graphical format. An analogue and/or digital output might be provided. A means is also provided for the user to enter application specific data.

Although different manufacturers undertake the measurement in a variety of ways and employ different algorithms to compute the flow rate from the measurements they make, the following gives in generic form the basis of the measurement.

The flow rate is determined using the transit time difference between the time taken for ultrasound to travel upstream from Transducer 1 to Transducer 2 and the time taken to travel downstream from Transducer 2 to Transducer 1. If the ultrasonic beam in the fluid is at an angle θ to the pipe axis and the path orientation is as shown in Figure 2 the individual transit times would be defined as Equation 4 and Equation 5.

$$T_{up} = P / (c - \bar{V} \sin \theta) \quad (4)$$

$$T_{dn} = P / (c + \bar{V} \sin \theta) \quad (5)$$

where:

$\bar{V}$ is the average flow velocity along the acoustic path

c is fluid soundspeed

Combining (1) and (2) gives:

$$\bar{V} = \frac{P}{2 \sin \theta} \cdot \frac{\Delta t}{T_{up} \cdot T_{dn}} \quad (6)$$

where:

$$\Delta t = T_{up} - T_{dn}$$

The volumetric flowrate is given by:

$$Q = K \cdot \bar{V} \cdot A \quad (7)$$

where:

K is a meter factor to take profile effects into account

A is the cross-sectional area of the pipe

Also by combining (1) and (2) the velocity of sound can also be calculated directly from the equation:

$$c = \frac{P}{2} \cdot \left(\frac{1}{T_{up}} + \frac{1}{T_{dn}} \right) \quad (8)$$

A detailed account of the flow algorithm is given in Annex C.

Figure 2 Schematic of a clamp-on transit time ultrasonic flow-meter

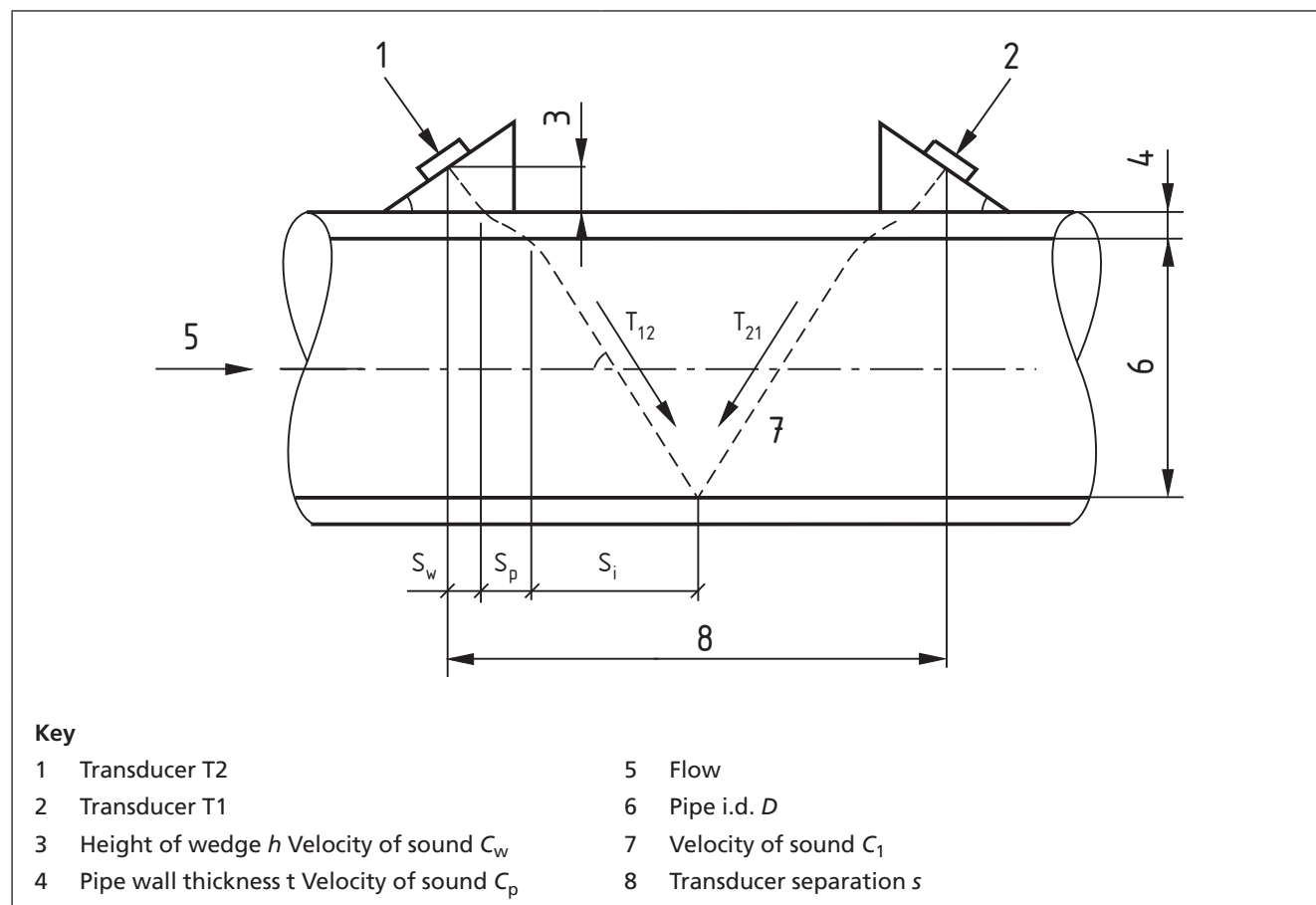
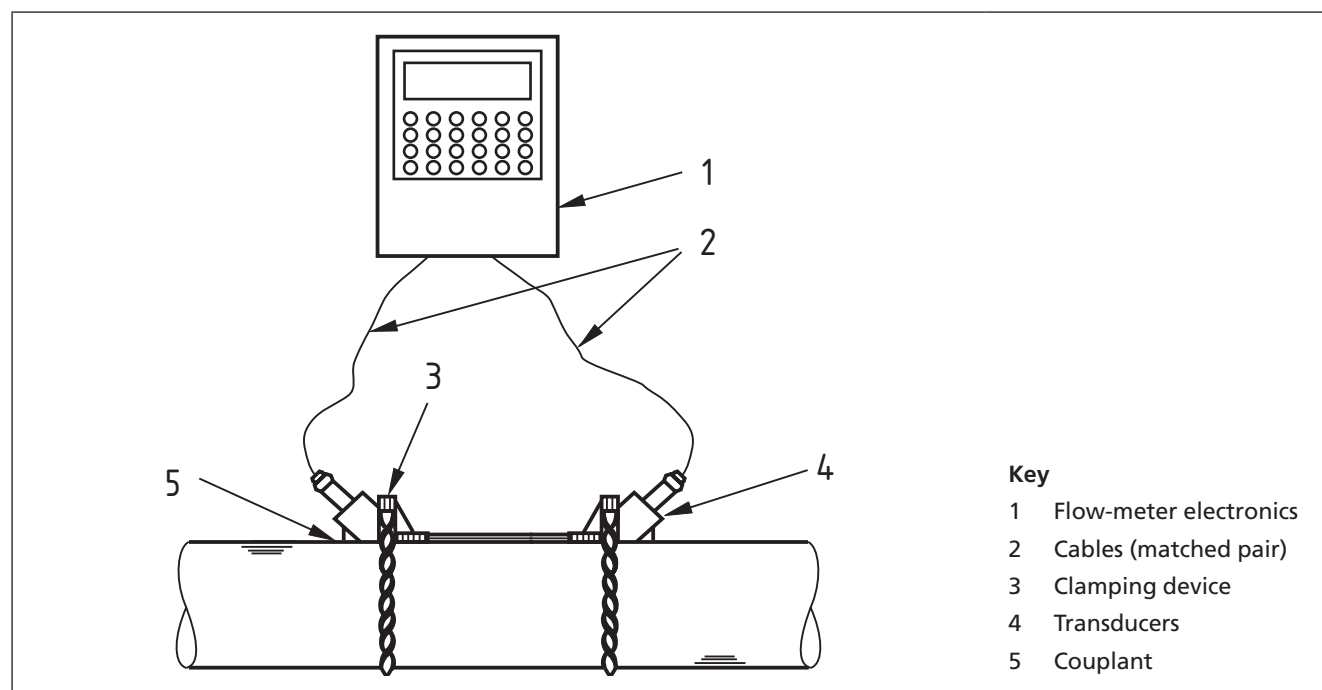


Figure 3 A typical clamp-on TTUF



3.4 Cross-correlation ultrasonic flow meter

Cross-correlation ultrasonic flow-meters (CCUFs), although not widely used, are commercially available from some manufacturers. Figure 4 shows the basis of operation of a cross correlation ultrasonic flow meter.

Modulation of the ultrasound by particulate matter, gas bubbles or turbulence is detected at two stations axially separated by a distance, L , which is typically between $0.5D$ and D . The flow velocity is estimated by cross-correlation of the noise signals generated by modulation phenomenon. The time delay between the arrival of similarly modulated signals provides a peak in the cross-correlation function of the noise at each receiver and provides an estimate of the time for a particular distribution of scatterers to travel along the pipe from one beam to another.

In two-phase flow, the signal is affected by factors such as the number of scatterers per unit volume, the distribution of scatterer sizes, their spatial arrangement and the velocity profile across the pipe. Consequently, a calibration obtained under a particular set of operating conditions might not apply to another.

Cross-correlation technology is applicable to both liquid and gas applications, but commercially CCUFs are mostly applied to gases. A CCUF requires a 2-channel meter and two pairs of transducers. Approximate purchase price would be 50% more than a TTUF for the equivalent line size. It is therefore advised that the manufacturer be consulted regarding selection of CCUF over TTUF.

3.5 Clamp-on DUFs

As the majority of CUF applications involve liquid as opposed to gas, a potential user of a CUF is most likely to encounter either TTUF or DUF technology. A TTUF operates in the time domain and a DUF in the frequency domain. The areas of application are essentially different, but there is an overlap, and the potential user might be drawn to the lower price of a DUF. It should be understood that DUF performance, e.g. accuracy, will inherently be inferior to that of a TTUF.

Figure 5 shows the basic operation of a DUF, whereby gas bubbles or solid particles are necessary to reflect or scatter the propagated ultrasound. Assuming that all the scatterers are moving with a velocity, v_s , then the Doppler shift, f_d , of the transmitted ultrasound is given by:

$$f_d = 2f_t \frac{v_s}{C_l} \cos \theta$$

where

- f_t is the transmission frequency;
- C_l is the velocity of sound in the liquid; and
- θ is the angle of the ultrasonic beam with respect to the pipe axis.

The different frequency is known as the Doppler shift and is linearly proportional to the fluid velocity.

In general, the Doppler shift is not a single frequency because broadening of the spectrum occurs as the suspended bubbles or particles, i.e. scatter sources, have a range of velocities and are further

affected by turbulence, the ultrasonic beam has a finite width, and the angle of the beam relative to the direction of liquid flow has a range of values. An estimate therefore has to be made of the average Doppler shift from a spectrum, which typically looks like that in Figure 5.

Figure 4 Cross-correlation ultrasonic flow-meter (CCUF)

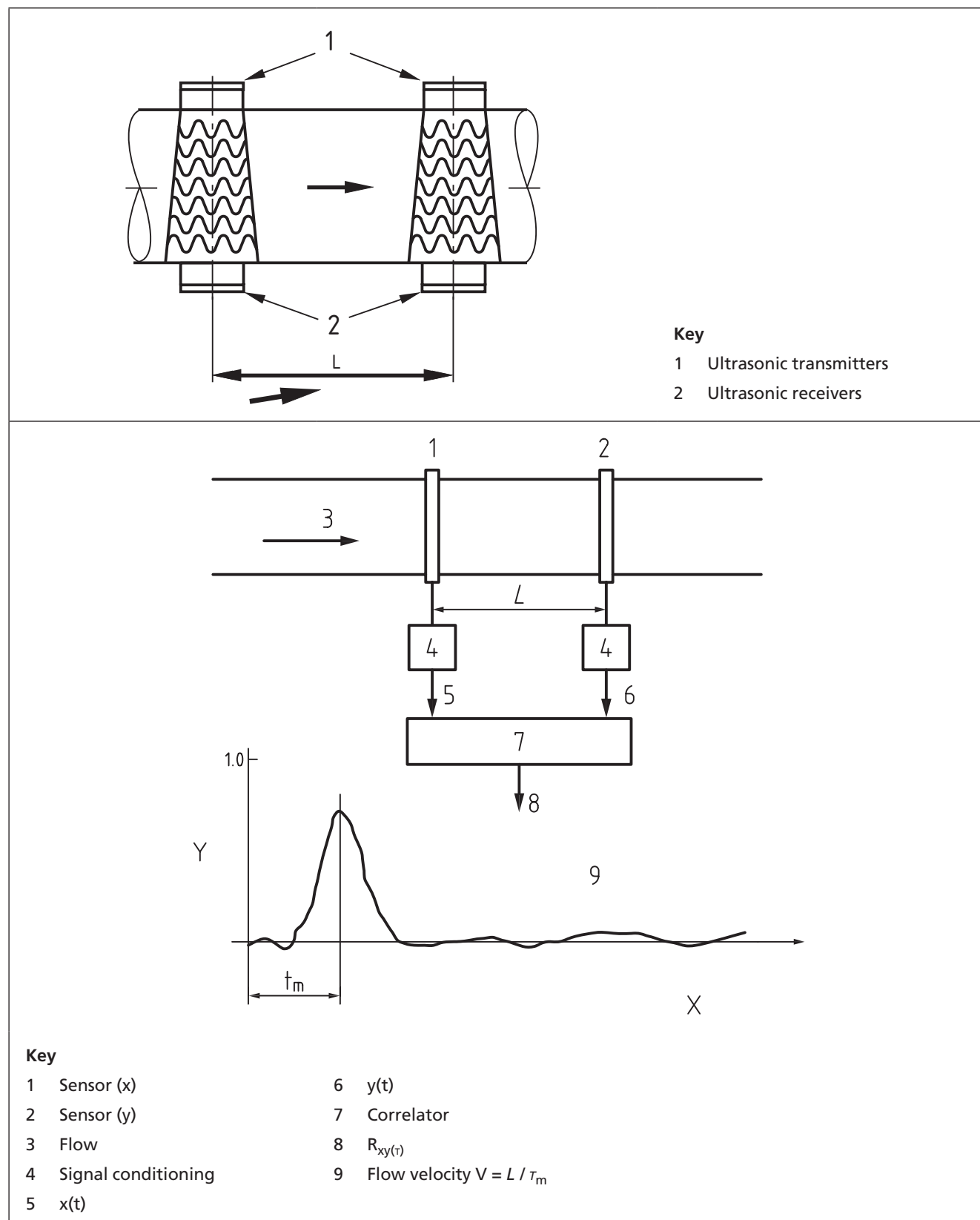
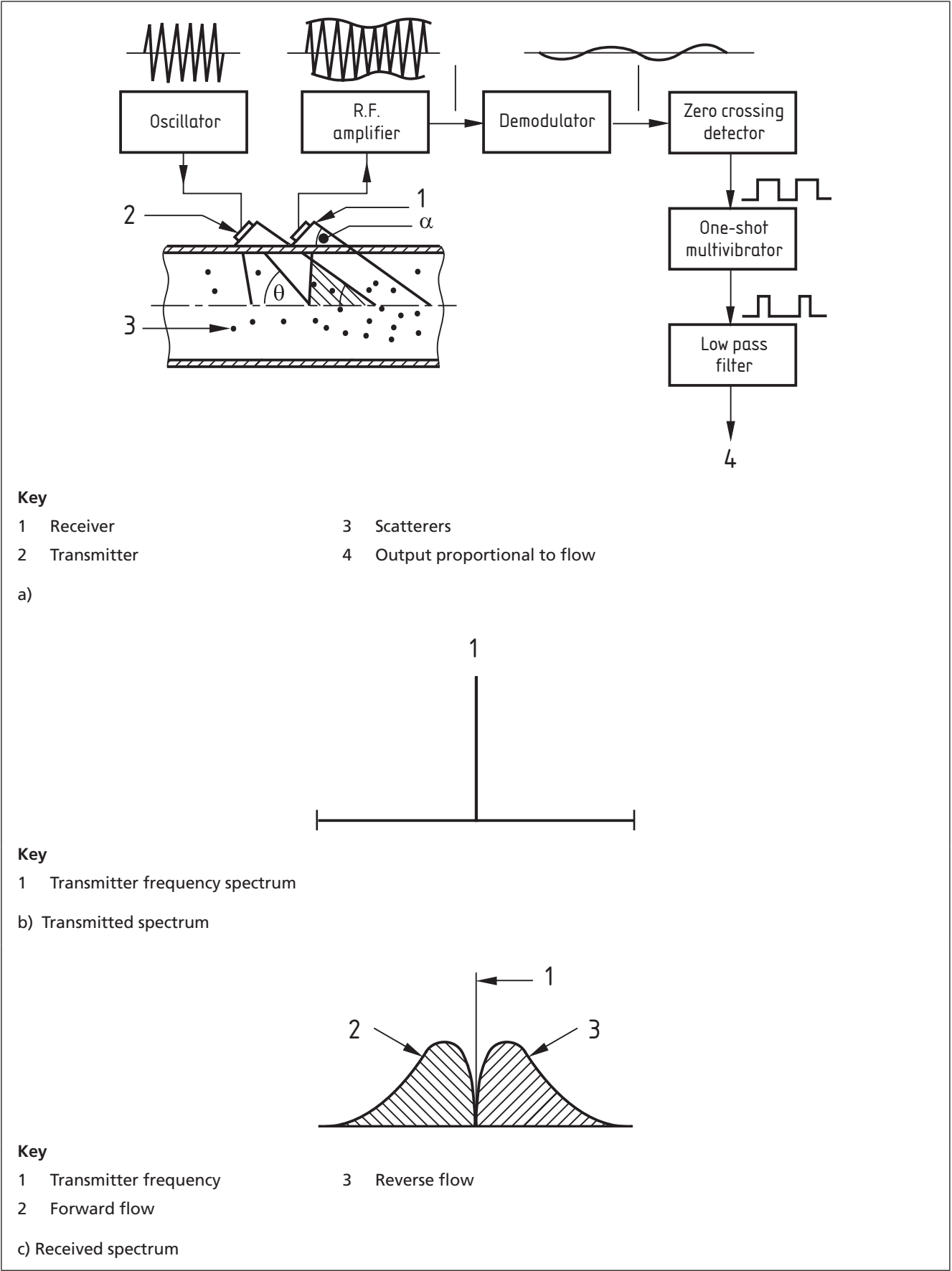


Figure 5 Basic operation of a DUF



The performance of Doppler flow-meters (DUFs) is limited due to the nature, size, spatial distribution of the scatterers which varies the attenuation of the ultrasonic beam. The zone that contributes to the velocity measurement is not well defined. In large pipes it is likely to be close to the wall. The relationship between the sensed velocity and the mean velocity in the pipe is unknown. The velocity being sensed is that of the scatterers and, because of slippage, it might not correspond to the liquid velocity.

Generally, DUFs are application specific and require considerable product and application knowledge if the use of this technology is to be successful. Variants of the technology are used by manufacturers and include pure Doppler, gated Doppler and speckle-tracking methods.

Upstream disturbances, in the form of bends, valves, pipe work and probes causing vortices can all cause the meter to read in error. Errors can also be caused by vibration. In order to obtain an accurate volumetric flow rate measurement, the internal diameter of the pipe work needs to be measured accurately. Typical application areas for DUFs are raw sewage, sludge, slurries and paper pulp.

Some manufacturers of clamp-on TTUFs provide dual modes of operation. In the absence of scatterers, the meters operate as conventional TTUFs. When the scatterers in the form particulate matter or gas bubbles rise above a certain level, the meter changes its mode of operation and it then operates as a DUF.

4 Application areas

4.1 General

4.1.1 Typical applications

Table 1 and Table 2 identify typical applications for the various clamp-on technologies, drawn from manufacturer's application data, identifies typical application areas to which clamp-on meters are being applied.

This is not meant to be an exhaustive list and, for specific areas of application outside those identified in Table 1 and Table 2, potential users should consult meter manufacturers.

The application areas for clamp-on meters, where they show significant advantages over other techniques, are those where:

- the pipe cannot be cut for reasons of safety or hygiene or possible process contamination;
- the cost of breaking into the pipe work and installation are too high;
- for reasons of continuity of supply, maintenance or service, flow measurement must be achieved without a process shut-down;

on larger pipes, the cost-benefit over other in-line meters is greatest.

In Table 1 and Table 2 there is an indication P or T which relates to either permanent or temporary installations. These are categorized in 4.1.2 and 4.1.3.

Table 1 Clamp-on meter selection table – liquids

Technology selection for liquid applications					
Industry	Application	P/T	Transit time	Doppler	Cross-correlation
Water	Leak detection	P/T	Yes	Yes	
	Network analysis	T	Yes		
Oil and gas	Fire pump test	T	Yes		
	Crude oil	P	Yes		
	Water injection	P	Yes		
	Diesel flow	P	Yes		
	Produced water	P	Yes	Yes	Yes
	Condensate	P	Yes		
Food	Food blending	P	Yes	Yes	
	Food batching	P	Yes	Yes	
Semiconductor	High purity liquid	P	Yes	No	
	Aggressive liquid	P	Yes		
Pharmaceutical	—	P/T	Yes		
Chemical	Check metering	T	Yes	Yes	
Power	Coolant flow	P	Yes		Yes
	Nuclear feed water	P	Yes		Yes
	Hydro electric turbine flows	P	Yes		
	Coal slurry	P		Yes	Yes
Miscellaneous	Cold utility water	P	Yes		
	Hot utility water	P	Yes		
	Heat metering	P	Yes		
	Air conditioning	P	Yes		
	Raw sewage	P	Yes	Yes	

Table 2 Clamp-on meter selection table – gases

Technology selection for gas applications					
Industry	Application	P/T	Transit time	Doppler	Cross-correlation
Oil and gas	Hydrocarbon processing	p	Yes	No	No
	Gas transmission	P	Yes	No	Yes
	Check metering	T	Yes	No	Yes
	Network analysis	T	Yes	No	Yes
Food	Food blending	P	Yes		
	Food batching	P			
Semiconductor	High purity gas	P	Yes	No	Yes
	Aggressive gas	P	Yes	No	Yes
Pharmaceutical	—	P/T	Yes	Yes	
Chemical	Process air	T	Yes	No	Yes
Miscellaneous	Heat metering	P/T	Yes		
	Air conditioning	P/T	Yes	No	Yes

4.1.2 Permanent installation

Applications where hygiene or contamination; operation, e.g. supply interruption; high purity; aggressive substances; maintenance and cost are of major consideration resulting in the provision of a permanently installed meter.

4.1.3 Temporary/Semi-permanent installation

Applications where the requirement for the meter is short term or periodic, e.g. validating other installed meters; leakage determination; pump testing or network analysis.

Gas clamp-on TTUFs are designed to be used with dry gases, although they can operate in the presence of limited amounts of either particulate matter or liquid droplets. (Guidance on operating in the presence of particulate matter or liquid droplets is found in Clause 8.)

4.2 Specific considerations

4.2.1 TTUF

Liquid clamp-on TTUFs are designed to be used with clean liquids, although they can operate in the presence of limited amounts of either particulate matter or gas bubbles. (Guidance on operating in the presence of particulate matter or gas bubbles is found in Clause 8.)

4.2.2 Cross-correlation

The application areas to which such flow-meters have been employed are in the measurement of single phase liquids; liquid–solid mixtures; liquid–gas mixtures; liquid–liquid mixtures; low pressure gas and high pressure gas.

4.2.3 Doppler

Applications might be limited by the lack of scatterers requiring each application to be considered on its own merits.

5 Performance measures

5.1 General

Clamp-on meters generally provide outputs indicative of volumetric flow rate or totalized volume flow. In assessing the performance of the meter, three measurements are of interest. These are:

- the percentage error of the indicated volumetric flow rate or totalized volume flow (see 5.2);
- the repeatability of the measurement (see 5.3); and
- the reproducibility of the measurement (see 5.4).

In employing these terms, it is important that they should correspond to standard usage. The following sub clauses define the three terms.

5.2 Percentage error

The percentage error of the volumetric flow rate measurement is given by:

$$E = \left(\frac{V_{\text{ind}} - V_{\text{std}}}{V_{\text{std}}} \right) \times 100\% \quad (9)$$

where:

V_{ind} is the volume of fluid passed as indicated by the meter under test during the duration of the test

V_{std} is the recorded reference volume of fluid passed during the same time.

It is usually expressed as a function of flow velocity through the meter.

5.3 Repeatability

The repeatability of the measurement is a measure of the ability to provide repeatable measurements under the same set of conditions. It is a measure of the random uncertainty in the measurement, R , which is defined as:

$$R = 2.83ms_E$$

and:

$$s_E = \sqrt{\frac{\sum_{i=1}^n (E_i - \bar{E})^2}{n-1}} \quad (10)$$

Where:

E_i is the error of the i^{th} run within the test series

$\bar{E}$ is the average error of all the runs in the test series

n is the number of runs in the test series

m is a scaling factor

The use of the scaling factor enables comparisons of repeatability to be made between test series which are different in length by normalizing all the repeatabilities to a standard length of test run.

$$m = \frac{\sqrt{T_{\text{test set}}}}{\sqrt{T_{\text{std}}}} \quad (11)$$

where:

$T_{\text{test set}}$ is the average length of the test run in a particular set of runs

T_{std} is the time to which the uncertainty is to be normalized.

5.4 Reproducibility

The reproducibility of the measurement is concerned with the degree to which the measurement can be reproduced if the conditions of measurement are changed. Of particular importance in clamp-on meters is the degree to which the readings of the meter are reproducible under unclamping and re-clamping conditions. The reproducibility (r) of the

measurements can then be measured by measuring the difference between the average errors in the two sets of tests, one taken before unclamping and re-clamping and the other after, i.e.

$$r = \bar{E}_1 - \bar{E}_2 \quad (12)$$

where:

$\bar{E}_1$ is the average error of the initial tests

$\bar{E}_2$ is the average error of the test undertaken after unclamping and re-clamping

If more than two sets of tests are available, it might be possible to express the reproducibility as a function of the standard deviation of the errors across the whole range of tests. In this case, reproducibility would then be defined as:

$$r = 2.83s_{\text{reproducibility}} \text{ where } s_{\text{reproducibility}} = \sqrt{\frac{\sum_{i=1}^n (\bar{E}_i - \bar{E}_{\text{all}})^2}{n-1}} \quad (13)$$

where:

$\bar{E}_i$ is the average error obtained in the i^{th} reproducibility test series

$\bar{E}_{\text{all}}$ is the error average overall the reproducibility test series

N is the number test series undertaken to assess the reproducibility

Reproducibility is generally expressed as a function of flow velocity.

5.5 Uncertainty under ideal flow, pipe fluid and operational conditions

5.5.1 General

Clamp-on USMs are likely to be used over a very wide range of pipe sizes, materials, wall thicknesses and fluids. Because the overall performance achievable in the field depends on the care with which the operators prepare the pipe work and mount the transducers, coupled with an inability to provide traceable calibrations of clamp-on meters in the field, it is difficult to obtain figures for the uncertainty, repeatability and reproducibility of such flow-meters in the field.

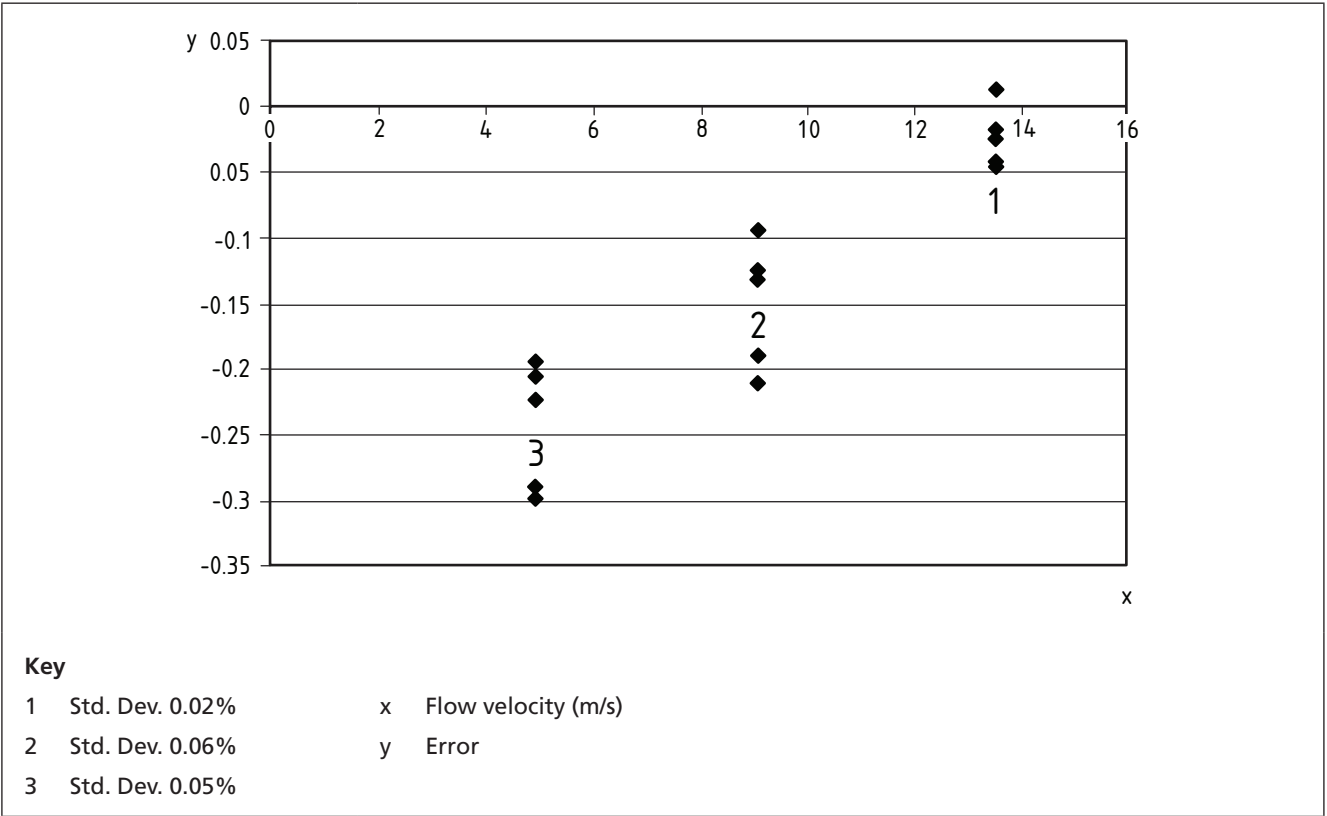
5.5.2 Transit time

The values manufacturers quote for the typical accuracy of clamp-on TTUFs range between $\pm 1\%$ to $\pm 5\%$ of reading with this performance being over a restricted flow range that is generally specified in terms of flow velocity. At the lower flow rates, the performance is generally specified as a fixed uncertainty expressed as a velocity which can range from ± 0.01 m/s to ± 0.03 m/s, depending on the pipe size and the particular manufacturer. In addition to these accuracy specifications, manufacturers often specify what is termed a calibrated accuracy. This means the accuracy which is achievable in situations where the meter is capable of being calibrated in situ by some other means or where the clamp-on transducers are being used as part of a spool piece.

Typical values for the uncertainty under these conditions range between $\pm 0.5\%$ to $\pm 2\%$ of reading, dependent on manufacturer and pipe size. Repeatabilities quoted by manufacturers typically lie in the range $\pm 0.15\%$ to $\pm 0.5\%$ of reading, depending on application.

A repeatability test was carried out for this to show the results at three flow rates downstream from one elbow; the results are shown in Figure 6.

Figure 6 Repeatability for installation after a single elbow at 23D



5.5.3 Cross-correlation

The overall accuracy of the technique is estimated to be $\pm 2\%$ to $\pm 5\%$ of reading, although for a particular application where the meter can be calibrated under similar conditions improved accuracy might be expected. Typical repeatability should be 0.5% of reading.

5.5.4 Doppler

The uncertainty with such flow-meters can be high and in some cases likely to be greater than $\pm 10\%$ of reading with a dependency on the size of scatterers in the fluid. However, under closely defined flow conditions, it is possible for the DUF to provide an overall uncertainty of $\pm 2\%$ of reading. Typical manufacturers' specifications indicate that some devices have an expected accuracy of $\pm 2\%$ of full scale, as opposed to % of reading. This must be considered carefully when assessing performance in the lower flow velocity range. Reliable performance further demands minimum scatterer concentrations, often requiring solids or bubbles of minimum size 100 μm , and minimum solids concentration 100 ppm. Typical repeatability expectation is $\pm 0.5\%$ to $\pm 1.0\%$ of reading.

5.6 Factors affecting uncertainty

5.6.1 General

Errors in measurement by clamp-on ultrasonic meters are in the region of 2% to 5% in respect of TTUF and CCUF, and 2% to 10% for DUF, when set up with due care and attention in favourable application conditions. In general the performance of the meters tends to degrade as the fluid velocity decreases and is typically most noticeable below 0.5 m/s.

A USM manufacturer may express performance in terms of device error under reference conditions, as distinct from additional anticipated installation error, the latter being in the form of bias error derived from such sources as incorrect pipe wall thickness, pipe diameter, pipe material, transducer positioning, etc. and as such are beyond the manufacturer's control. For example a 1% error in internal pipe diameter directly creates a 2% error in flow rate as calculated by the USM from flow velocity. This relationship naturally has greater practical implication with smaller pipes than large. For example a pipe with 50 mm diameter needs only a 0.25 mm error in assumed pipe wall thickness to create the aforesaid 1% error in internal diameter and the consequential 2% error in calculated flow rate. Conversely, a 2.5 mm error in wall thickness applies for the same error scenario for a 500 mm diameter pipe.

It is not normal for the effects of flow profile to be accounted for in performance specifications. As is the case with the majority of flow measurement technologies, it is assumed that the meter will be installed in accordance with recommended guidelines e.g. sufficient straight inlet and outlet run, distance from sources of flow disturbance etc. No manufacturer can legislate for the many causes and effects possible in any particular installation.

Even with sound knowledge of the set-up and installation conditions where a clamp-on meter is used, or where there is excessive signal attenuation, it might not be possible in some circumstances to evaluate the uncertainty with acceptable confidence.

There is an assumption that pipes are generally round but on large diameter pipes there is a tendency for them to be slightly oval and if this is not accounted for during set-up and subsequent use of the meter then errors in the measurement will be present.

5.6.2 Comparison of techniques for gas use

Table 3 compares the two methods of transit time and cross-correlation tag meters.

5.6.3 Operational impacts

Irrespective of the meter type (Transit time or Cross-correlation) the fundamental challenge with clamp-on gas measurement is the extremely small amount of ultrasonic energy that can be coupled from transmitter to the pipe and then to the fluid, and back to the receiver, resulting in poor signal-to-noise ratio. A second, but less severe problem is the relatively high acoustic attenuation in the gas compared with most liquids. This is discussed in more detail in 5.6.6.

Table 3 Comparison of gas clamp-on flow-metering methods

Characteristic	Transit time	Cross-correlation TAG
Flow range:		
Low flow limit	Can measure to zero (low flows with reduced accuracy)	Good for $Re \geq 10\,000$ Possible for $Re \geq 4\,000$
High flow limit	Typically limited to 10 m/s to 15 m/s, maximum is 30 m/s	Up to 80 m/s or higher
Profile effects	Sensitive to cross-flow. Other profile effects similar to liquid transit time. Reflective mount resists abnormal flow profile conditions such as cross-flow	Relatively insensitive to cross-flow and swirl. Other profile effects similar to transit time meters in theory
Pressure range	Typically > 10 Bar (gage) Possible ≥ 4 Bar (gage) Possible > atmospheric on plastic pipes	Atmospheric pressure and above for most gases including air, irrespective of pipe material
Ease of setup	Spacing coupling etc. generally more critical than liquid apps	Potentially very simple

Table 4 Acoustic impedances of important materials

Material	Velocity of sound (c) m/s	Density (ρ) kg/m ³	$Z = \rho c$, MRayls
Air	343	1.3	0.000 4
Water	1 482	1 000	1.5
PVC	2 395	1 400	3.4
Steel	5 890	7 710	45

5.6.4 As a result of the very large difference in acoustic impedances between steel and air (and most gases), see Table 4, only a tiny fraction of the transmitted energy travels through the pipe wall and the gas to reach the receiving transducer. Only about 5×10^{-9} of the energy reaches the receiver for gas compared to water in a steel pipe.

5.6.5 A significant amount of the transmitted acoustic energy is coupled into the pipe wall, and travels around the pipe wall as coherent noise or "cross-talk". This cross-talk for gases at low or moderate pressures overwhelms the gas-borne signal.

5.6.6 The attenuation of ultrasound in air is also much greater than water at equivalent frequencies. This is also true for most gases versus most liquids. Except for larger pipes, this effect is relatively insignificant compared to the coupling losses described in 5.6.3. This is demonstrated in Figure 7 and Figure 8.

In spite of these difficulties, clamp-on gas flow-meters using both the transit time methods and the tag cross-correlation method are commercially available, [1]. Methods to mitigate the poor ratio of the gas-borne signal to the pipe-borne short circuit have included damping materials on the outside of the pipe [2], [3], the use of coded signals,

quadrature demodulation, and special transducer configurations [4], e.g. those using Lamb or Rayleigh wave propagation. Generally speaking the transit time method has seen greatest success in higher pressure gases and steam, and the tag cross-correlation method has seen success even down to atmospheric pressure, but requires a Reynolds number above about 10000.

Figure 7 **Acoustic energy coupled into pipe and fluid for liquid clamp-on (top) and gas clamp-on (bottom)¹⁾**

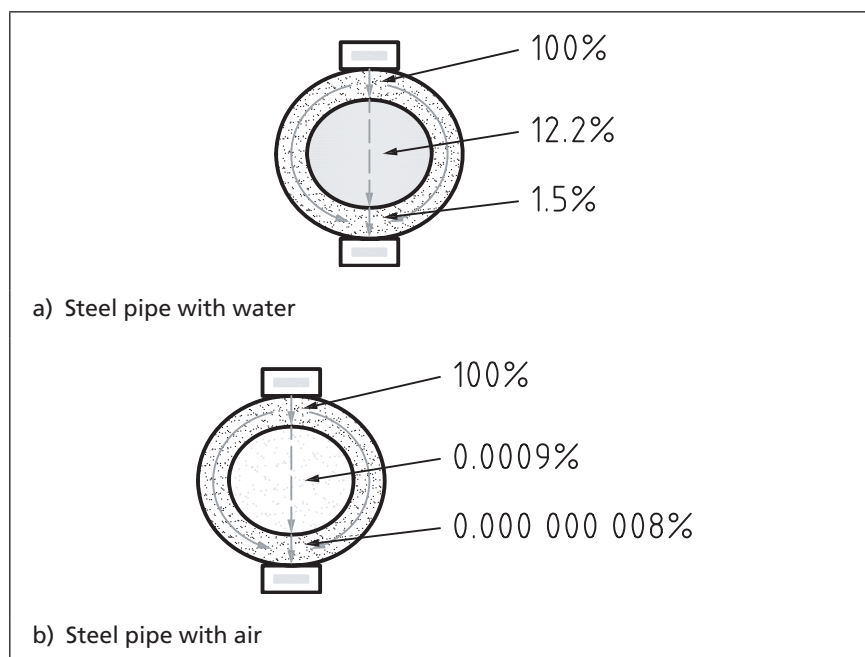
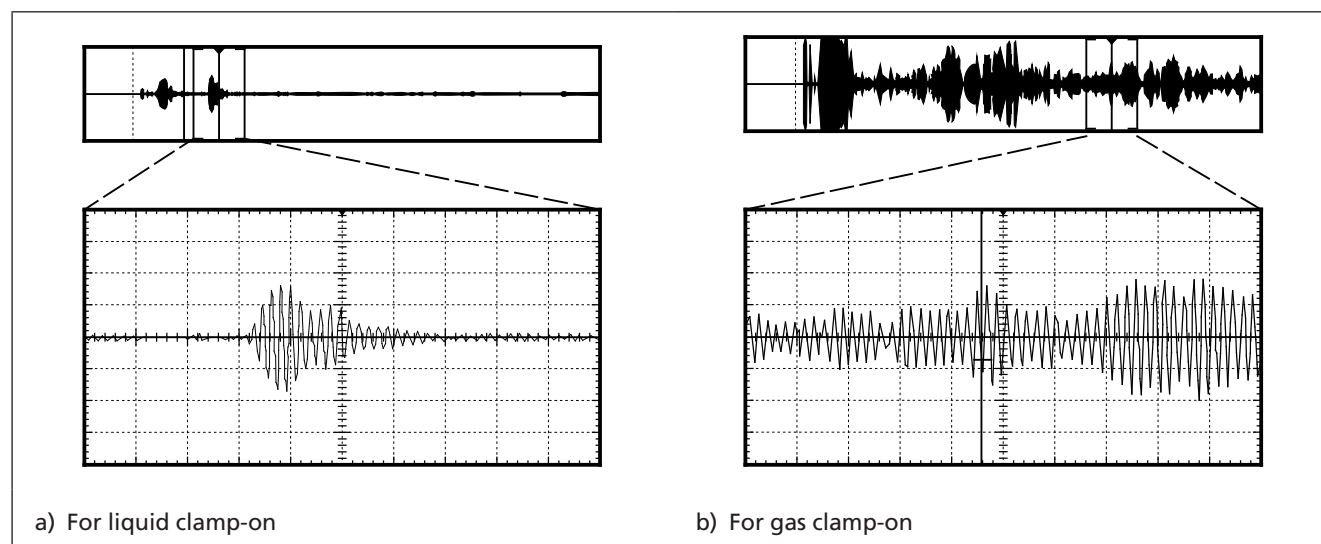


Figure 8 **Oscillogram of received signal¹⁾**



¹⁾ © 2008 IEEE, reproduced with permission.

6 Calibration – general

Laboratory calibration is of more limited use for clamp-on ultrasonic meters than it is for many other meter types. This is because when the meter is removed from the laboratory and set up in the field, the conditions (physical attachment to the pipe, the pipe properties, piping configuration, fluid properties and flow profile) will be different. The pipe and transducers together form an integral part of the flow-meter and as a result it is currently not possible for a true calibration certificate (e.g. a UKAS certificate) to be issued for an ultrasonic clamp-on meter.

However, a verification utilising the meter's signal diagnostics is very useful for confirming that a given unit and/or sets of transducers are performing to specification. Such an exercise can be readily performed. (Refer also to 10.12 Diagnostics). The results would also help to evaluate more accurately the uncertainty in measurement of the clamp-on meter itself. For TTUFs, it is possible to assess USM flow measurement performance (notwithstanding velocity profile effects) by correlating known fluid velocity of sound with the diagnostic value from the USM.

When manufacturing a spool piece for permanent mounting of clamp-on transducers to form a hybrid, and where actual calibration is to be performed, potential problems arising from pipe material variations can be avoided by reserving an off-cut of process pipe for dedicated use during manufacture. The user should be cautioned that clamp-on transducers should of course not be moved once installed on a manufactured spool piece and thereafter calibrated, as any such movement would invalidate the calibration. It is recommended that the manufacturer employs mechanical means to prevent such movement.

Furthermore, the user is advised that if a calibration is performed using water at a given temperature, this will prescribe particular transducer positioning (see 3.2). If the intended use of the calibrated spool piece hybrid involves a significantly different temperature and/or fluid then USM performance, and even function, may be impaired. A calibration using a fluid with properties that differ significantly from those of the process, or where flow rates differ greatly, should be viewed with caution. Particular attention should be paid to the actual range of Reynolds numbers for the process conditions compared to those of the calibration. The manufacturer should be consulted in this regard. It is unlikely that a DUF would be the subject of such a hybrid given the practical difficulty involved in generating precise volumes of liquid with adequate control of the requisite scatter source.

This standard suggests that calibrations which have been undertaken under laboratory conditions for transit time ultrasonic flow-meters should not be taken as the basis for a judgement as to the likely performance that could be achieved in the field under actual operating conditions. Performance obtainable in the field is unlikely to be better than that achieved under reference conditions in a calibration laboratory. Additional uncertainty is likely to result when the USM is installed in the field, due to variation in pipe dimensions and material, transducer location and mounting. Whether the transducers are normally field installed, or form part of a hybrid solution described earlier, the actual flow profile of the process fluid may not be fully developed at the installation point.