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Hydrometry — Measurement of discharge by the ultrasonic (acoustic) method

Hydrométrie — Mesure du débit à l'aide de la méthode ultrasonique (acoustique)

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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.

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 6416 was prepared by Technical Committee ISO/TC 113, *Hydrometry*, Subcommittee SC 1, *Velocity area methods*.

This third edition cancels and replaces the second edition (ISO 6416:1992), which has been technically revised.

Hydrometry — Measurement of discharge by the ultrasonic (acoustic) method

1 Scope

This International Standard describes the establishment and operation of an ultrasonic (transit-time) gauging station for the continuous measurement of discharge in a river, an open channel or a closed conduit. It also describes the basic principles on which the method is based, the operation and performance of associated instrumentation and procedures for commissioning.

It is limited to the "transit time of ultrasonic pulses" technique, and is not applicable to systems that make use of the "Doppler shift" or "correlation" or "level-to-flow" techniques.

This International Standard is not applicable to measurement in rivers with ice.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 772:1996, *Hydrometric determinations — Vocabulary and symbols*

ISO 4373:1995, *Measurement of liquid flow in open channels — Water-level measuring devices*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 772 apply.

4 Applications

4.1 Open channels

4.1.1 The method is suitable for use in river flow measurement, a significant advantage being additional freedom from siting constraints in comparison with other available techniques. In particular, the method does not demand the presence of a natural control or the creation of a man-made control at the proposed gauge location, as it does not rely upon the establishment of a unique relation between water level and discharge.

4.1.2 Gauges using the method are capable of providing highly accurate flow determinations over a range of flows contained within a defined gauge cross-section. They are tolerant of the backwater effects created by tides, downstream tributary discharges, downstream weed growth, reservoir or head-pond water level manipulation, and periodic channel obstruction.

NOTE For locations subjected to significant bed level or profile instability, it may not be possible to use gauges.

4.1.3 Use of the method usually creates no obstruction to navigation. It creates no significant hazard or loss of amenity for other channel users or riparian interests. However, some species of fish may be sensitive to some types of ultrasonic signal. The gauge can be designed to be physically unobtrusive.

4.1.4 For use in remote locations, the electronic equipment can be designed to operate from battery power. To economise on power consumption, the system is usually set to sample the flow for short periods and to return to a quiescent condition between samples. (see 10.1.3 and 13.9.5).

4.1.5 The method is not really suitable for use when the channel is covered with ice, because of the difficulty of determining the cross-sectional area of the water. Although this is a limitation of use, the method may still have value in determining water velocity under the ice, if transducers can be positioned in unfrozen water.

4.2 Multiple channels

4.2.1 At locations where the total flow is divided between two or more physically separate channels, such as under a multiple-arched bridge, the instrumentation can be configured to determine individual channel flows separately and then to combine these to create a single unified determination of flow.

4.2.2 If flow may not readily be contained within a single well-defined cross-section, and in particular if there is significant flow that bypasses the main gauge cross-section by way of an extensive flood plain, it may be possible to subdivide the flood plain into a series of “channels” in which the flow can be measured.

4.2.3 A station designer may decide to provide a comprehensive flood-plain measurement capability by this means or may, alternatively, simply provide a flow or velocity sampling facility. In the latter situation, gauged cross-sections may be constructed in the flood plain. These do not normally provide total coverage, but merely provide locations at which flood-plain flow can be sampled for subsequent examination and analysis.

4.2.4 It should be noted that systems designed to determine flood-plain flow may suffer from the practical difficulties of

a) inability to commission the system due to there being no water in the measurement section,

b) maintenance of the section, including weed cutting, debris clearance and repair of vandalism.

4.3 Closed conduits

The ultrasonic method can also be applied to the measurement of flow in closed conduits, including both storm-water and foul sewers, under both free-flowing and surcharged conditions.

For systems used in foul sewers, special attention should be paid to the following:

a) the source of the water, especially whether it is from an aeration tank or from a section of channel containing aerators or from a hydro-electric plant. The air dissolved in the water from such sources may cause bubbles to form, and these may inhibit the operation of the flow gauge (see 10.3.1);

b) possible aeration of the water caused by a hydraulic jump or weir upstream of the measurement section, especially under storm conditions (see 10.3.1);

c) the design of transducer mountings, to eliminate the risk of fouling by grease, rags and paper;

d) the need for the system to meet local codes of practice for electrical equipment installed in potentially explosive atmospheres. This usually requires a certified intrinsically safe design for both the transducers (which can be piezo-electric sources of ignition) and for the electronic unit (see for example EN 50014);

e) the change in the flow computation algorithm when the conduit is surcharged.

For foul sewers which are less than about 4 m in width, a high loading of suspended solids is unlikely to present a serious problem of signal attenuation (see 6.2.3).

5 Method of measurement

5.1 Discharge

5.1.1 Discharge, as defined in ISO 772, is the volume of liquid flowing through a cross-section in a unit time. It is usually denoted by the symbol q and expressed in cubic metres per second (m^3/s). The definition of discharge is the product of the wetted cross-sectional area and the mean velocity vector perpendicular to it.

5.1.2 The measurement methods may either determine the bulk quantity discharge q directly, by measuring the time taken to fill a tank of known volume, or the methods may be indirect and require calculation of the discharge from measured flow velocities in all points of the wet cross-section. The latter are generally referred to as "velocity-area methods". In practice it is not possible to measure velocities at all points, and so the velocity-area methods deal with only a limited number of measuring points.

The transit-time method is a velocity-area method using flow velocities which have been determined by the equipment, and which are averaged along one or more lines which are usually, but not necessarily, horizontal.

5.2 Calculation of discharge from the transit-time measurement

5.2.1 Flow measurement by the ultrasonic transit-time technique is analogous to flow measurement by current meters. However, while the most commonly used current-metering method is based on the estimation of mean velocity at a series of verticals dispersed across the gauged cross-section, in the transit-time method the velocity samples are horizontally orientated (and vertically distributed). In principle, flow can be computed by exactly the same methods applied to a current meter gauging (see ISO 748). However, in practice, the different graphical methods available do not lend themselves easily to automatic computation, and only the arithmetic methods are useable.

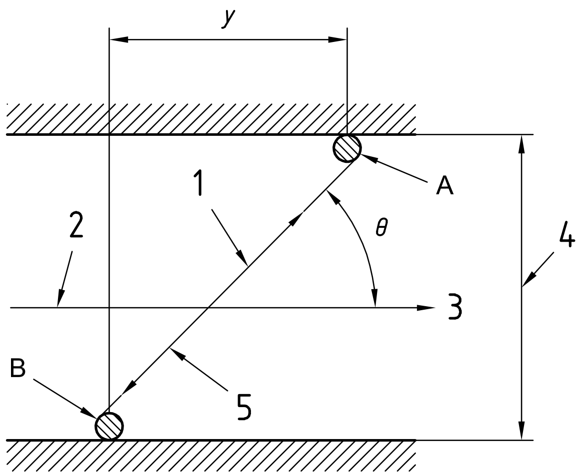
5.2.2 Discharge can be computed, provided that a relation can be established between the estimated (horizontally averaged) flow velocity and the mean cross-sectional velocity. If the measured velocity at a single elevation is not sufficient to establish this relation, measurements at more elevations can be carried out. The resulting samples of flow velocity can be vertically integrated to provide an estimate of mean cross-sectional velocity.

5.2.3 Discharge calculation also requires the cross-sectional area of the water to be known. An ultrasonic transit-time system will, therefore, normally be capable not only of making sample measurements of velocity, but also of determining (or accepting a signal from some other device determining) water depth, and of storing details of the relation between water depth and cross-sectional area. It will also normally be capable of executing the mathematical functions necessary to compute flow from the relevant stored and directly determined data.

6 Flow velocity determination by the ultrasonic (transit time) method

6.1 Principle

6.1.1 An ultrasonic pulse travels in a downstream direction faster than a similar pulse travels upstream. The speed of a pulse of sound travelling diagonally across the flow in a downstream direction will be increased by the velocity component of the water. Conversely, the speed of a sound pulse moving in the opposite direction will be decreased. The difference in the transit time in the two directions can be used to resolve both the velocity of sound in water as well as the component of the velocity along the path taken by the ultrasonic pulses.



Key

1 v_{path} component of water velocity along the path

2 v_{line} component of water velocity in the direction of the flow

3 direction of flow

4 channel width

5 ultrasonic path

A, B transducers

θ angle between the path and the direction of flow

y downstream distance between transducers

Figure 1 — Schematic illustrating the general principle

6.1.2 For the path between transducers A and B in Figure 1, the transit time for the ultrasonic pulses are:

$$t_{AB} = L/(c - v \cos\theta) \text{ and } t_{BA} = L/(c + v \cos\theta) \qquad (1)$$

where

t_{AB} is the transit time from transducer A to B, in seconds;

t_{BA} is the transit time from transducer B to A, in seconds;

L is the path length (distance between transducer A and transducer B), in metres;

c is the speed of sound in water, in metres per second;

v_{line} is the line velocity or the average velocity of the water across the channel in the direction of flow, in metres per second;

θ is the angle between the path and direction of flow.

Resolving for line velocity:

$$v_{line} = L \times (t_{AB} - t_{BA}) / (t_{AB} \times t_{BA} \times 2 \cos\theta) \qquad (2)$$

6.1.3 The transit times in Equation (2) are for the water path only, and do not include the fixed delays due to the travel times through the faces of the transducers and cables, delays in the transmitter and receiver circuits, and delays in signal detection (which may be affected by signal distortion). These fixed delays do not affect the transit-time difference ($t_{AB} - t_{BA}$), but will affect the term ($t_{AB} \times t_{BA}$). This factor is of particular importance for small channels or where long cable runs to the transducers are required.

Typical delay times for the transducers and electronic circuits are between 4 μs and 20 μs.

The delay time for the cables is typically 1 μs per 200 m of cable, i.e. for 100 m each way, transmit and receive.

Taking the signal delays into account, Equation (2) for the computed water velocity becomes:

$$v = L \times (t_R - t_F) / [(t_R - \delta) \times (t_F - \delta) \times 2 \cos\theta] \quad (3)$$

where

t_R is the transit time from the electronic unit via transducer A to B and back to the unit, in seconds;

t_F is the transit time from the electronic unit via transducer B to A and back to the unit, in seconds;

δ is the signal delay.

For a channel of width 1 m, with path angle of 45° and total signal delay of 10 μs, an error of 2 % in the computed water velocity would be introduced if the delay effect were to be ignored.

For wider channels, the effect of the signal delay is reduced in proportion to the path length, and may be insignificant.

6.1.4 It should be noted that the calculation of water velocity is

— independent of the speed of sound in water,

— proportional to the difference in transit times,

— inversely proportional to the product of the transit times,

— critically dependent on the angle between the path and the direction of flow (see Table 1).

Table 1 — Systematic errors incurred if the assumed direction of flow is not parallel to the channel axis

Path angle θ degrees	**Velocity error for 1° difference between actual and assumed flow direction** %
30	1,0
45	1,7
60	3,0

6.1.5 In open-channel flow measurement, practical considerations will normally dictate that

a) the transducers at either end of an “ultrasonic path” are located on opposite banks of the watercourse;

b) the line joining them is at an angle to the mean direction of flow, which should be between 30° and 65°.

6.1.6 The following limitations are encountered in open-channel flow measurement.

a) At intersection angles greater than 65°, the time difference between sound pulses in opposite directions may become small and therefore subject to a relatively large uncertainty, especially at low velocities.

b) At an angle of 90°, there will be no time difference between forward and reverse pulses, and thus velocity cannot be determined.

c) With large angles, there is also an increase in the error in velocity computation that results from assumptions made in the assessment of the angle. This is due to the presence of the cosine function in the equation relating time difference to velocity (see 6.1.3). Table 1 demonstrates this effect.

d) At intersection angles less than 30°, the following problems can arise.

   1) The length of the channel occupied by the gauge can become excessive, and cease to be quasi-uniform.

   2) The direction of flow relative to the path may not be constant.

   3) There can be practical problems with site selection, due to the length of the channel which is required to be set aside for the flow gauge, and maintained free of debris and weeds.

   4) The excessive length of the paths can cause problems of signal strength and/or signal reflection from the channel bed or water surface, especially if vertical temperature gradients are present.

6.1.7 To calculate discharge, the flow gauge should contain a means of storing details of the relation between water depth and cross-sectional area, determine water depth or stage, determine water velocity for each path, and be capable of executing the mathematical functions necessary to calculate flow from the relevant stored and directly determined data (see Clause 7).

6.2 Sound propagation in water

6.2.1 General

Sound is a mechanical disturbance of the medium in which it propagates. It encompasses a wide range of frequencies. The audible range is from approximately 50 Hz to 15 000 Hz, and is generally referred to as “sonic”. Frequencies less than 50 Hz are usually termed “subsonic”, and those above 15 000 Hz “ultrasonic”. Transit-time systems operate in the ultrasonic range at frequencies typically between 100 kHz and 1 MHz.

The performance of transit-time systems depends heavily on the characteristics of sound propagation in water. These characteristics are briefly described here.

6.2.2 Speed of sound in water

The speed of sound in water is independent of frequency, but depends on the temperature, salinity and pressure of the water. In open channels, the effect of pressure is negligible. Over the normal ambient temperature range, the speed of sound in fresh water varies from about 1400 m/s to a little over 1 500 m/s (see Table 2).

Table 2 — Speed of sound in non-saline water at different temperatures

Temperature °C	**Speed of sound** (approximate) m/s
0	1 402
10	1 447
20	1 482
30	1 509
40	1 529

NOTE 1 The above figures apply to the water in most natural fresh-water rivers and foul sewers.

NOTE 2 In seawater the corresponding speeds are approximately 50 m/s higher.

The speed of sound c in water is given by [6]:

$$c = 1\,402{,}4 + 5{,}01T - 0{,}055\,1\,T^2 + 0{,}000\,22\,T^3 + 1{,}33S + 0{,}000\,13S^2 - 0{,}013\,T\,S + 0{,}000\,1\,T^2S + 0{,}016d \quad (4)$$

where

c is the speed of sound in water, in metres per second;

T is the water temperature, in degrees Celsius;

S is the salinity of the water, in grams salt per litre water;

d is the depth of water, in metres.

6.2.3 Propagation losses

Only a portion of the acoustic energy transmitted reaches the target. The loss in signal strength is called propagation loss, and consists of spreading loss and attenuation loss.

Spreading loss is the reduction in acoustic intensity due to the increase in area over which the given acoustic energy is distributed. Losses due to this cause depend upon the relation between the path length, the diameter of the ultrasonic transducer and its characteristic frequency. Spreading occurs in accordance with the inverse square law, which applies in general to all forms of radiant energy. However, if signals are measured as voltages, where energy is proportional to the square of the voltage, then the spreading loss follows an inverse law. This effect can only be observed over short path lengths, up to about 20 m, in clean water. Above this value, attenuation losses due to absorption and scattering start to take effect.

Absorption is the process by which acoustic energy is converted into heat by friction between the water molecules, as the sound wave is subjected to repeated compressions and expansions of the medium. In general, this loss is a function of frequency squared.

Scattering is the modification of the direction in which acoustic energy is propagated, caused by reflections from the innumerable inhomogeneities in the water, for example microscopic air bubbles and suspended particulate matter. These inhomogeneities result in changes in specific acoustic impedance, causing the signal to reflect and scatter. The effect is greater at higher transducer frequencies.

Losses due to absorption and scattering increase exponentially with increasing path length. This means that if the suspended solids loading in sewer water were such as to cause a loss of half the signal energy when the signal propagates through a metre of water, then that signal would be halved again after passing through another metre of water. For a path length of 20 m, the signal would be reduced to one millionth of the value expected for clean water.

For a 5 m path length in a foul sewer, a signal reduction of a factor of 30 (a factor of about 5,5 in voltage) would be tolerable, but for a 20 m path length it is unlikely that any signal would be observable.

For these reasons, transducers of lower frequency are used for the longer paths. The range of values of transducer frequency f for a given path length L is illustrated in Figure 2.

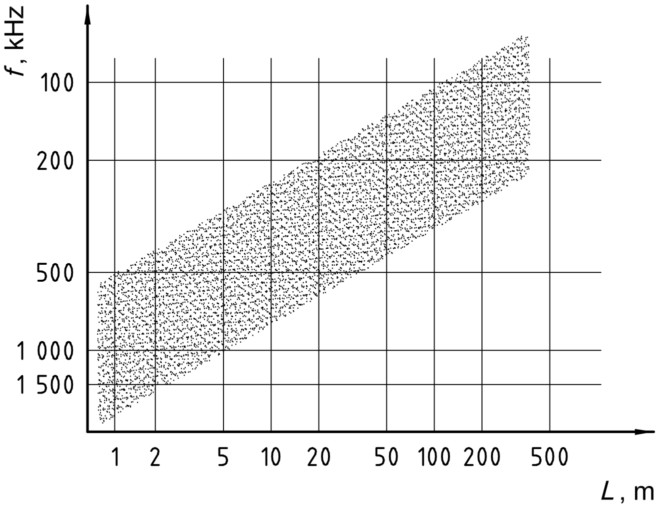


Figure 2 — Commonly used transducer frequencies for various path lengths

6.2.4 Signal path bending

6.2.4.1 The path taken by an acoustic pulse is bent if the water through which it is propagating varies significantly in either temperature or salinity. In slow-moving rivers, with poor vertical mixing, the effect of the sun upon the surface produces a vertically distributed temperature gradient. This causes the acoustic path to bend towards the river bed.

The acoustic wave propagates across the channel as a cone. If a vertical temperature gradient exists, only that ray which starts in a certain upward direction will arrive at the other end of the path. With a temperature gradient of 0,5 °C per metre of depth, over a path length of 50 m the vertical deflection D_r (as defined in Figure 3) will be about 0,5 m. In contrast, the effect of vertical density gradients (such as may be associated with salt water intrusion into the gauged reach) is to bend the path towards the surface.

Similar effects can be produced by horizontally distributed temperature or density gradients, as is the case with partial shading of the water surface from insolation such as found at the confluence where a tributary with waters of contrasting characteristics joins.

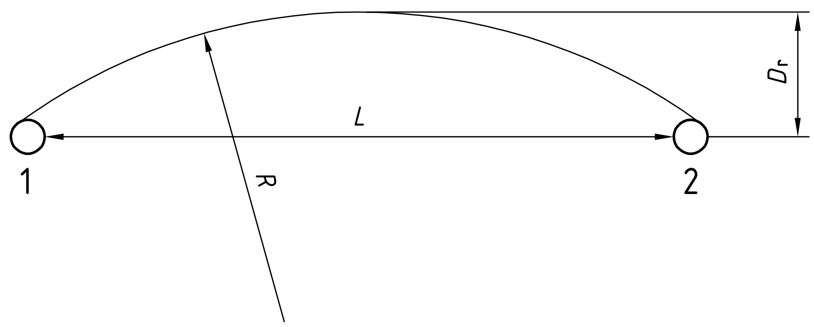
6.2.4.2 The approximate degree to which the signal path is bent is given by:

$$R = c_1 (d_2 - d_1) / (c_1 - c_2) \quad (5)$$

where

R is the radius of curvature of the ultrasonic path, in metres (see Figure 3);

c_1, c_2 is the speed of sound at depths d_1 and d_2 respectively, in metres per second [which can be calculated using Equation (4)].



Key

1 transducer

2 transducer

D_r deflection of the ultrasonic path

L path length

R radius of curvature of the ultrasonic path

Figure 3 — Signal bending as a result of a vertical temperature gradient

The deflection D_r of the ultrasonic path from a straight line is given by

$$D_r = R - \sqrt{\left(R^2 - 0{,}25L^2\right)} \quad (6)$$

where L is the path length, in metres.

6.2.5 Reflection

6.2.5.1 Sound is reflected from the water surface and, to a lesser extent, from the channel bed. The bed is usually a net absorber of sound. As the acoustic wave propagates across a channel (generally as a cone of around 5° width), some part of it will intersect with the water surface and be reflected, suffering a 180° phase change in the process. The secondary wave will proceed across the channel and arrive at the opposite bank. Its arrival will be sensed by the target transducer later than the direct wave, and the difference in arrival time will be a function of the difference in the respective lengths of the direct and indirect paths.

Errors in signal timing will occur if the secondary signal interferes with the first cycle of the direct signal. To avoid this effect, the difference in the two paths should exceed one acoustic wavelength (speed of sound/frequency). This will be achieved if the depth of water above the acoustic path exceeds that given by Equation (7):

$$D_{min} = 27\sqrt{\frac{L}{f}} \quad (7)$$

where

D_{min} is the minimum depth of water above the path and also the minimum clearance between the bed and the path, in metres;

L is the path length, in metres;

f is the transducer frequency, in hertz.