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ULTRASONIC FLOWMETERS

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ULTRASONIC FLOWMETERS

The term "ultrasonic flowmeter" covers a variety of different methods and meters because ultrasound may be used in a number of ways to extract information from a flow-process [1]. Here I will only deal with single phase fluids.
A division into three main groups, based upon principles of operation might be as follows:

- Reflection type or Doppler type meters.
- Transmittance type meters
  (including time-difference, phase-difference and frequency-difference/sing around-meters)
- cross-correlation meters.

The latter emphasise cross-correlation rather than ultrasonics.

Common to all these is the use of ultrasonic sensor devices and also the advantage of nonintrusiveness. Apart from that they utilize totally different principles to measure the velocity of flowing fluid and should thus be regarded as different types of instruments.

I will now look at each one in particular to point out

- what they are measuring
- indicate how they do it
- how well they perform on the base of the principle used.

For the sake of completeness we should first repeat what is going on inside the pipe and what to measure.

In practice, most flows are turbulent and the instant picture could be somewhat like Figure 1a. Eddies are generated and move along the pipe forming a rather complicated flowpattern. If particles, bubbles etc. are contained they will be moved correspondingly. The time-average velocity in each particular position of the cross-section, however, describes a continuous distribution

(velocity profile) across the pipe, Figure 1b.
This profile is subject to change by Reynolds number, changes in wall-roughness, upstream bends and fittings causing swirl and non-symmetric profiles. The quantity to be measured is the exact integral of the velocity profile or its exact mean value.

Reflection type or Doppler flowmeter [2], [3], [4]

These meters utilize the effect of a shift in frequency when a sound wave is reflected from a moving object, Figure 2.
The shift is proportional to the velocity component of the reflecting source in the direction of the ultrasonic wave. Thus a Doppler meter is in fact measuring the velocity of bubbles, particles etc. moving along with the fluid. Due to turbulence as mentioned this is bound to be an averaged value, but also because reflections will occur from various locations in the flow dependent on distribution of reflecting sources.

This measuring principle implies the following features and problems:

- The sensor could be clamped or bonded to the exterior of the pipe without any cutting or drilling of holes. This may be the most outstanding and attractive feature of this type of meter.
- Unlike most other meters, the Doppler meter operates only if there are particles, suspended solids, fluid interfaces or gasbubbles in the process fluid. It will not work with very clean fluids.
- The meter is profile dependent, like most other meters. The measured volume is normally 10-20 mm inside the pipe-wall and thus a real mean pipe-velocity measurement is not performed. In small pipes (< 2" diameter) you will probably read high, in larger pipes (> 6"), low. To correct for profile variations is thus difficult [3].
- The meter depends on distribution of reflecting sources. Gas in liquids tends to be concentrated near the wall, nonhomogeneous mixtures may give strange results and the larger the

reflecting sources the less likely it is that they will move with the same velocity as the surrounding fluid [3].

- The external mounting does not relax the need to know the pipe cross-section area which should be determined according to required and achievable accuracy.
- The meter provides a much better repeatability than accuracy which means that if in situ calibrations can be made, the accuracy in certain applications can be greatly improved.

Thus the Doppler flowmeter should be regarded as a meter of

- low accuracy (± 2% F.S.D. or more)
- high repeatability (< ± 1% F.S.D.)
- low initial purchase price (10.000 NOK)
- low installation and maintenance cost
- and requiring in situ calibration to achieve best accuracy.

Transmittance type

These meters utilize in slightly different ways the fact that an ultrasonic wave travelling downstream will go faster than one travelling in the opposite, upstream direction, Figure 3.
The difference in propagation velocity is proportional to the fluid velocity component in the direction of the ultrasonic beam. This component varies across the pipe due to the velocity profile of the flowing medium, but also because of turbulence. Thus what is achieved by measuring the difference in propagation velocity is the mean value or the integral of velocity along the acoustic path.

The different methods achieve this in the following way (Fig. 4):

- The transit time difference method measures difference in time of arrival of two pulses transmitted simultaneously but in opposite directions along the same path. This is the most used method and also regarded as most accurate. Time resolution is down to 0.1 ns (10^{-10}s) corresponding to 1 mm/s in a 4" pipe. Sampling rate depends on transit time which is approximately 0.1 ms per inch of pipe-diameter for a gas-meter [4], [5], [6].

- The differential phase method uses the phase difference between two waves continuously transmitted in opposite directions across the pipe. This is essentially the same measurement as the time difference above but uses other techniques in detection electronics, and produces an average over several wavelengths of the acoustic signal.
  High quality state-of-the-art electronics technology is required to achieve high accuracy [5], [6].
- The frequency difference method or sing-around technique transmits several pulses in both directions across the pipe. Each new pulse is transmitted at the arrival of the previous one. The frequency difference between the pulse-train transmitted downstream and that upstream is the averaged value of the mean velocity along the path. To achieve high resolution this implies averaging over say seconds, increasing as pipe-diameter increases.

As shown, the various methods all measure the same basic quantity. The difference is in the electronics and shows up mainly in response time and to some extent also in accuracy [5], [6].

As already indicated the transit time difference seems to be the most preferable method and is most the one used in instruments claiming high accuracy.

Of the various configurations of transducers in the meter section, the single path is most common (Figure 5). The path is located along the pipe diameter.

Transducers could be mounted withdrawn from the pipe wall or slightly intruding as shown (Figure 6).

The measuring principle and practical configurations of single path meters imply:

- none or negligible obstructions of flow-profile.
- relatively clean fluids required.

  Particles, bubbles etc. will introduce scatter and increase acoustic damping and thus making it more difficult to get signals through to the receiver. Large objects may even block the signals completely. Signal processing rejecting "bad measurements" will to some extent overcome these problems, depending on size and density of the disturbing elements.
- profile dependency exists.

  The measured mean velocity is not the mean pipe-velocity, but the mean of a narrow path along the diameter. A meter factor in the range 1.08 to 1.04 is thus required for Reynolds number from 10^4 to 10^7 [7]. This corresponds to a change of 1% for each magnitude of 10 in Reynolds number.

  Additional changes of profile caused by roughness and upstream disturbances resulting in swirl and non-symmetrical profiles could introduce even more serious errors. Errors of 3-4% 6 diameters downstream of a 90° elbow have for example been reported [8].
- Transducers could be mounted in existing pipe-works, but to achieve high accuracy meters should be installed as a separate section.
- Cross sectional area should be known. This will be the case when a separate pipe section is delivered.
- When electronics are properly designed meters will show very high repeatability.
- Calibration is unaffected by temperature, pressure, viscosity, and composition of fluid. As a physical property of non-flowing fluid which will depend on these factors, sound velocity is continuously measured and accurately compensated for. Thus the requirement is only to get the signal through to the receiver.

To summarize: The single-beam ultrasonic flowmeter is a meter of

- medium accuracy (± 1% F.S.D. or more)
- high repeatability (± 0.1% F.S.D. claimed)
- initial purchase price relatively independent of pipe size

Transducer + electronics	35.000 NOK
4" pipe section	1.500 NOK
48"	11.000 NOK

- maintenance costs are relatively low because of the absence of moving parts and simple mechanical design.
- relatively low calibration cost.

<u>Multipath meters</u> [2]

The main limitation of a single path meter is its flow profile dependence. The logical solution to this is to apply multiple paths at different locations in pipe cross-section. Each path results in a mean value through a defined part of the velocity profile (Figure 7). Combining these multipath measurements in proper ways will give the flowrate of the pipe.

Various computional schemes have been proposed, based on numerical integration formulas and knowledge of the extreme limits of profile-variations, and integration errors in the region of 0.1% are achievable for Reynoldsnumber ranging from 10^4 and upwards [10], [11], [12]. Errors less than 1% are reported even when measuring only 4 diameters downstream of a 90^0 elbow [13].

The multipath ultrasonic flowmeter thus possesses the same properties as the single beam meter considering non-intrusiveness, high repeatability, necessity for relatively clean fluids and independence of pressure, temperature, viscosity etc.

The meter section and transducer mountings should be precisely machined to acchieve high accuracy. Mounting of transducers in existing pipe is not therefore recommended.

However, the multipath ultrasonic flow-meter is supposed to be the most accurate available for medium to large pipes [14].

It should be regarded as a meter of

- very high accuracy (± 0.5%)
- very high repeatability (± 0.1% F.S.D. claimed)
- high purchase cost although relatively independent of size (> 100.000 NOK! This I think is closely related to low production volume and partly to expensive electronics.
- relatively low maintenance costs.

The cross-correlation flowmeter

This meter is based upon a comparison of "state" between two cross-sections of pipe located close to each other. The "state" defined as particles, bubbles, eddies etc. present at a given instant. The "state" of each cross section can be detected by an ultrasonic path sensing acoustic damping or velocity along the diameter. Like fingerprints in received signal the various state-pattern will be sensed in the two cross-sections with a time difference corresponding to the velocity of eddies, particles, bubbles etc. (Figure 8) [15], [16].

The flow-measurement is done through cross correlation of the two signals/states and thus the classification "ultrasonic" is secondary, as other types of sensor can be used instead.

The measuring principle implies

- external mounting of transducers
- clean or dirty liquids. Able to handle very difficult process fluids, such as corrosive fluids, slurries, vapour etc.
- profile dependence although more difficult to predict than for single-path meters.
- slow response due to cross-correlation calculations.

The meter is a new device on the market and the following characteristics could be suggested:

- low/moderate accuracy (supposed better than Doppler-meters)
- high purchase cost, but independent of pipe-size
- low installation and maintenance cost.

Applicability

So far, I have not distinguished between gas and liquid meters. The Doppler meter is for several reasons not commercially available for gas-metering but for multiphase measurements it could very well be used.

Transmittance types and cross-correlation meters will in principle work both in gas and liquid. In practice, however, the problem of making efficient transducers for gaseous media has to be overcome. This seems to be in the process of being solved now. A few single beam meters are on the market. At CMI we have been building gas-transducers for some years and recently the techniques have been applied in a 4" gas-meter with 3 paths. The meter is still in an experimental stage but accuracies better than 1% are indicated [17]. The meter will even work down to atmospheric pressure. This in fact is often a problem for this sort of instrument.

For crude oil multipath meter is used in the Alaska pipe-line for leak-detection where differences between meters are reported better than 0.1% [11].

The transit time difference meters combine high resolution and high bandwidth thus enabling measurement of transients and oscillations as for example reported by Dordain, ONERA in [18], and as has been mentioned, velocities down to a few mm/s may be measured.

The "clamp on" property of Doppler meters and cross-correlation meters make them very suitable for metering difficult fluids at extreme temperatures, corrosive fluids etc.
Use of temperature, chemical etc. protected transducers in meters of the transmittance type will also provide accurate instruments for these applications.

When referring to their properties I will suggest ultrasonic flowmeters to find an increased use

- where flare gases and exhaust fumes should be monitored, conditions requireing high dynamic range, non-intrusive meters and tough operational conditions.
- where large quantities of valuable fluids have to be metered to the highest level of accuracy over a long period.

Future trends

The ultrasonic meter is already a highly sophisticated electronic instrument and as such will surely benefit from the continuous improvement in technology. This implies

- higher accuracy
- accuracy will be relatively less expensive
- more extensive use of μ-processors to perform
  - corrections for flow-profile variations
  - self-testing and diagnostics
  - self-calibration and self-adjustment
- multipath meters could be made less expensive providing a high accuracy meter at comparable prices. High prices are closely related to electronics and low production volume
- more integrated meters where additional sensors could be added to compute mass flow and composition.

As the multipath meter will be able to provide increased accuracy and perhaps even more: to give accurate readings when distorted flow profiles exist, I think these meters will be paid increasing attention by both producers and users.

To conclude:

The ultrasonic sensortechnique offers a varity of flowmetering methods from the Doppler flowmeter at the low accuracy end to the very accurate multipath meter. As a result of their many advantages these should become even more used in flowmetering both for gases and liquids. As multipath meters will reach reasonable price levels, non-intrusive meters of very high accuracy and repeatability will become available.

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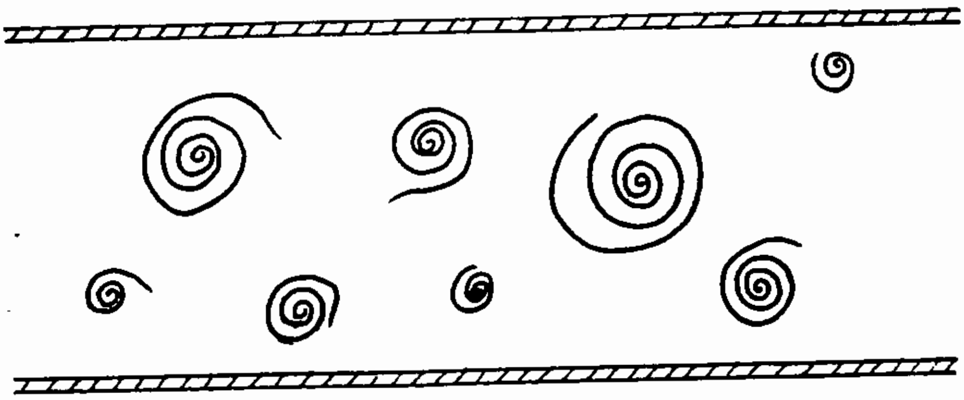
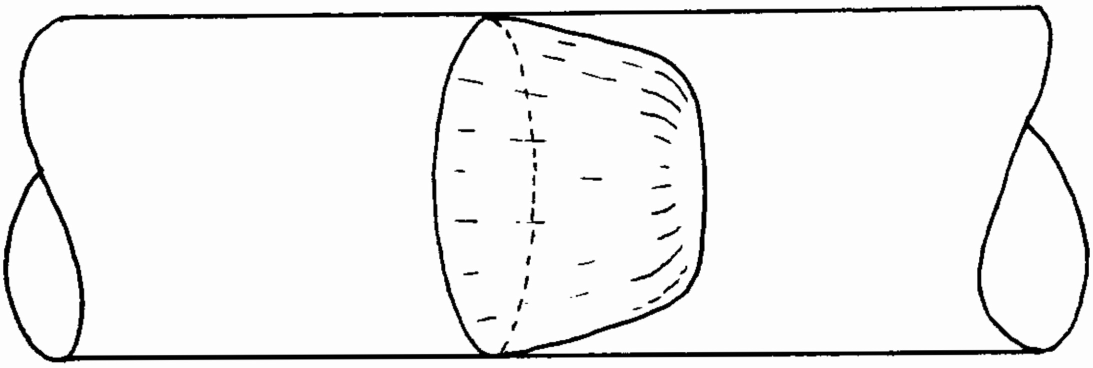


a) Turbulent flow. Instant picture.



b) Turbulent flowprofile. Time average.

Figure 1. Pipe flow.

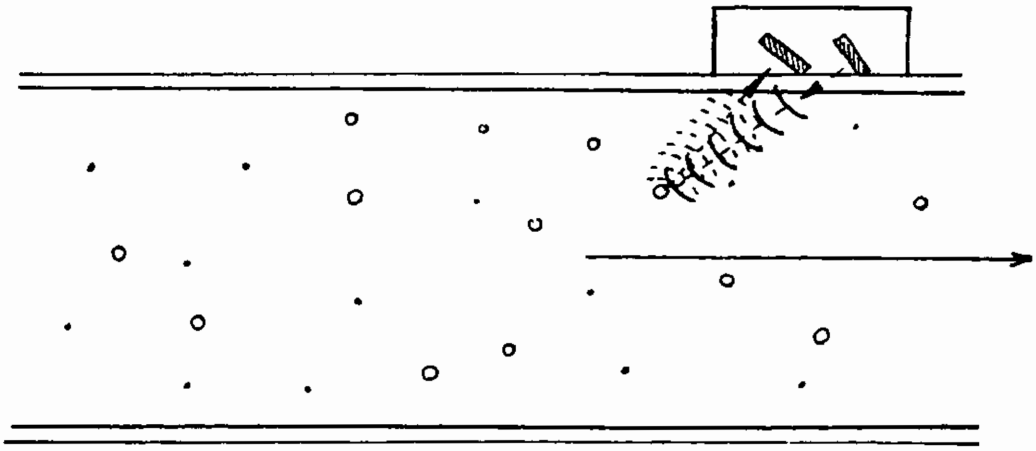


Figure 2. Doppler flow-measurement.

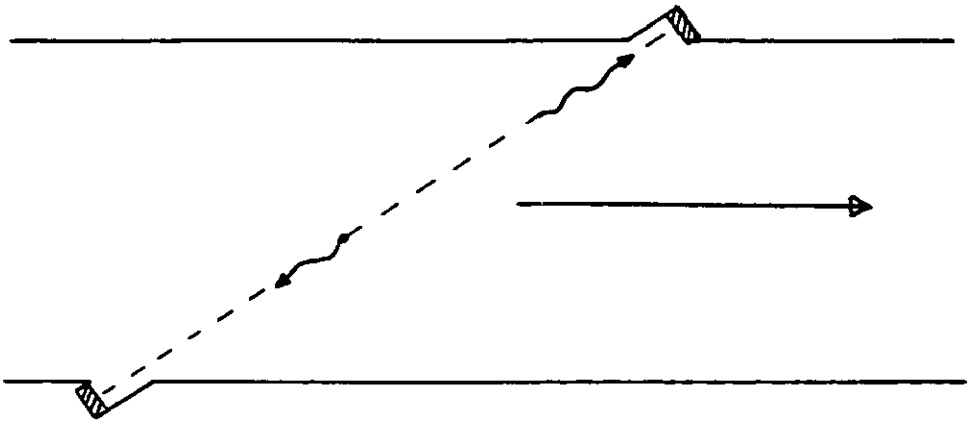
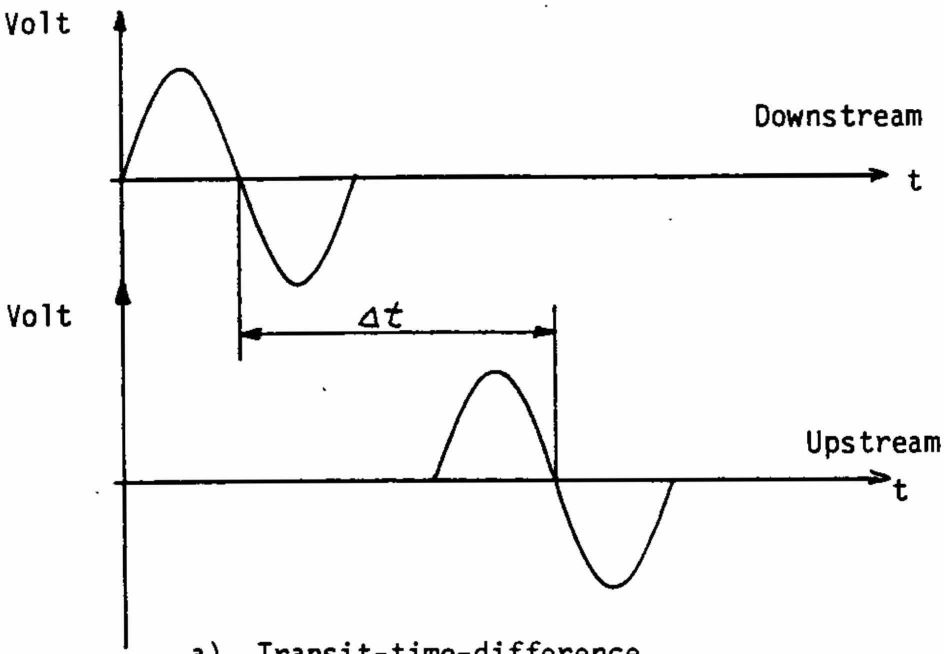
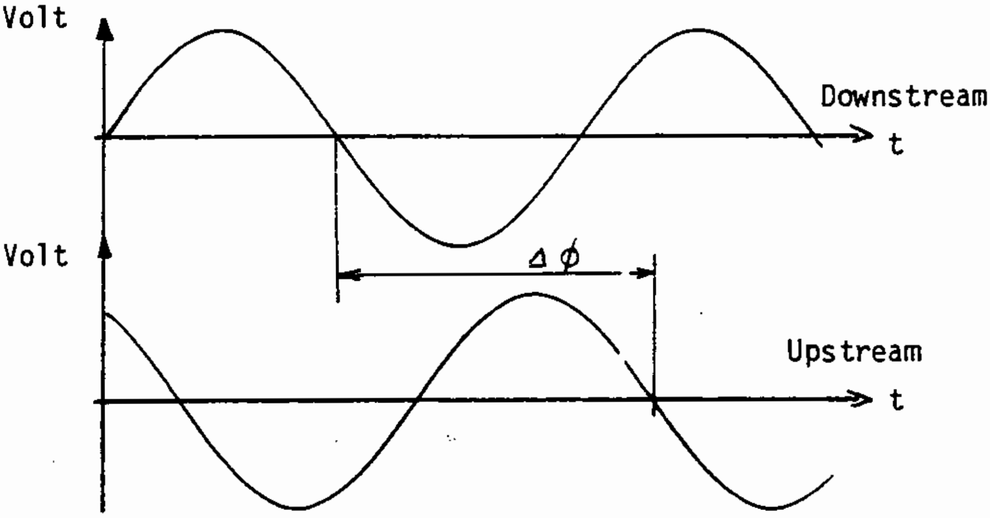


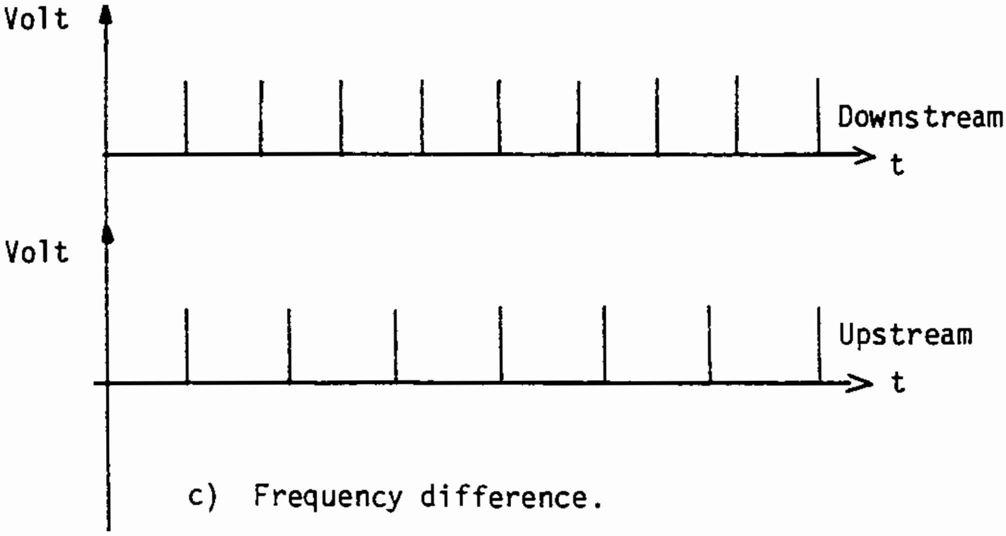
Figure 3. Transmittance type flow-measurement.



a) Transit-time-difference.



b) Phase difference.



c) Frequency difference.

Figure 4. Transmittance type principles.

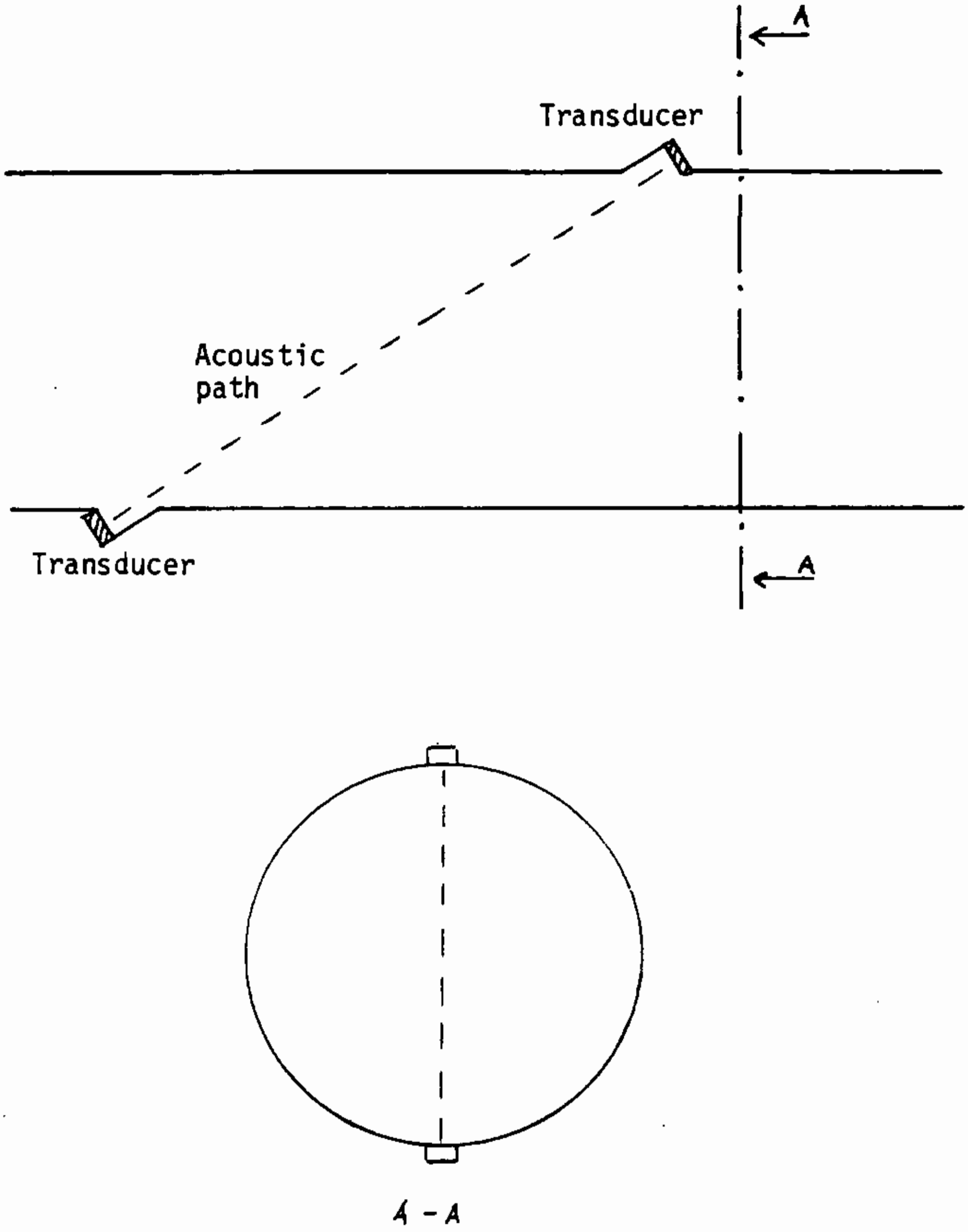


Figure 5. Singlebeam ultrasonic flowmeter.

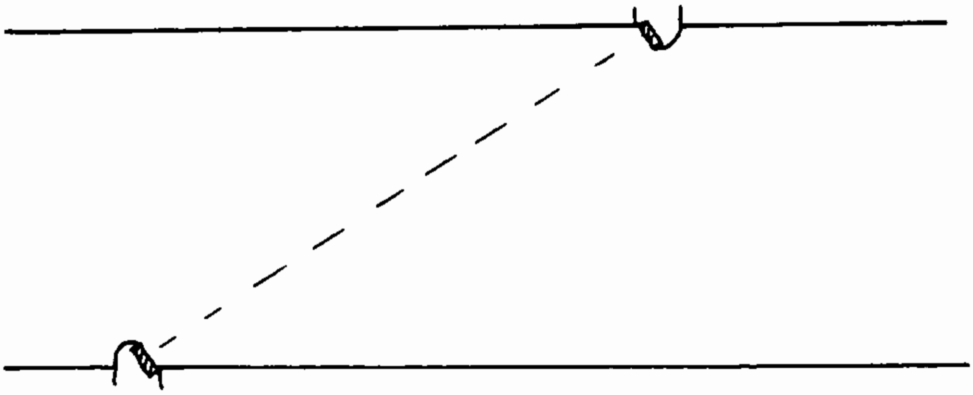


Figure 6. Singlebeam ultrasonic flowmeter.
Transducers slightly intrused.

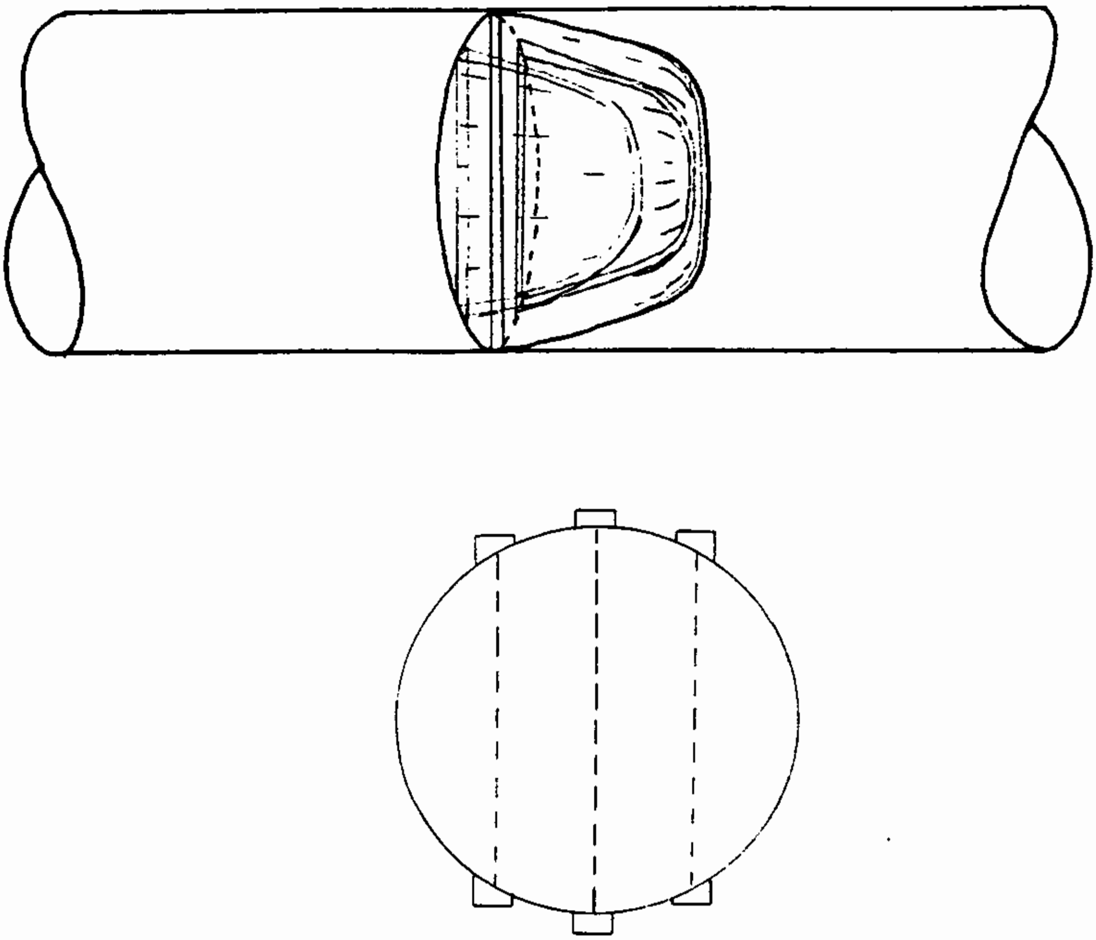


Figure 7. Multipath ultrasonic flowmeter.

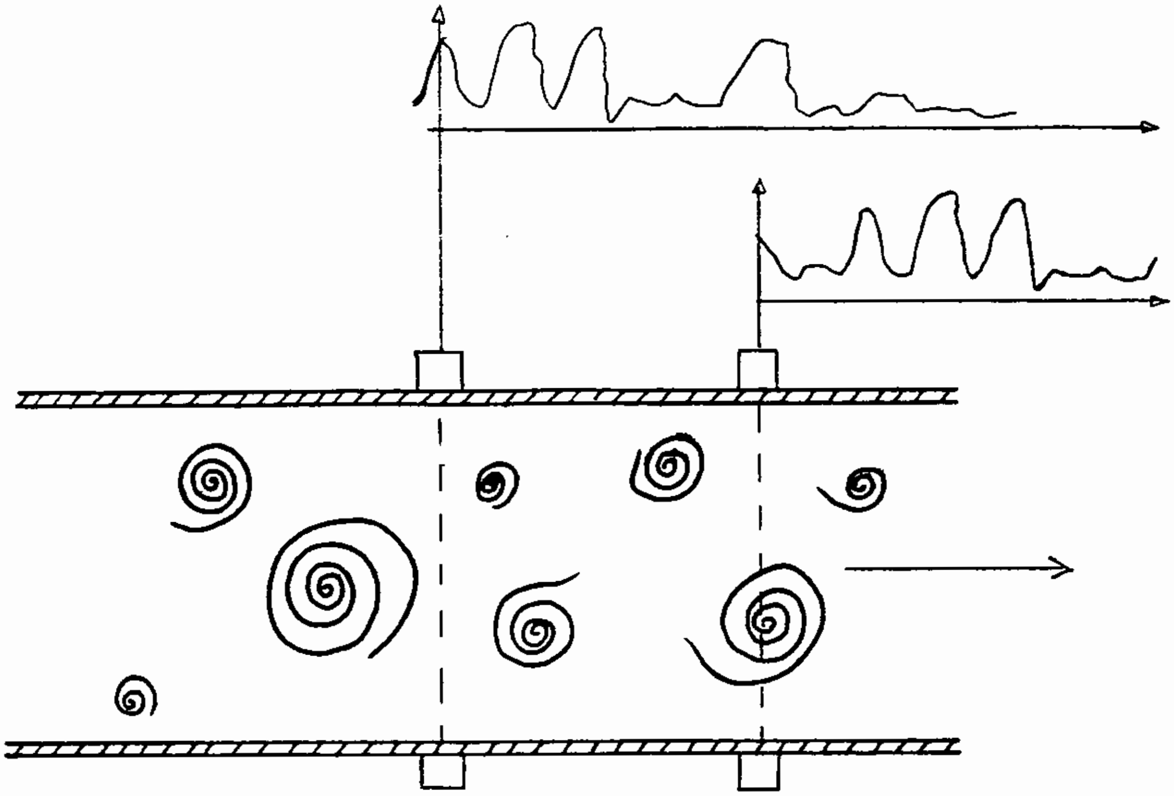


Figure 8. Ultrasonic crosscorrelation flowmeter.