Measurement

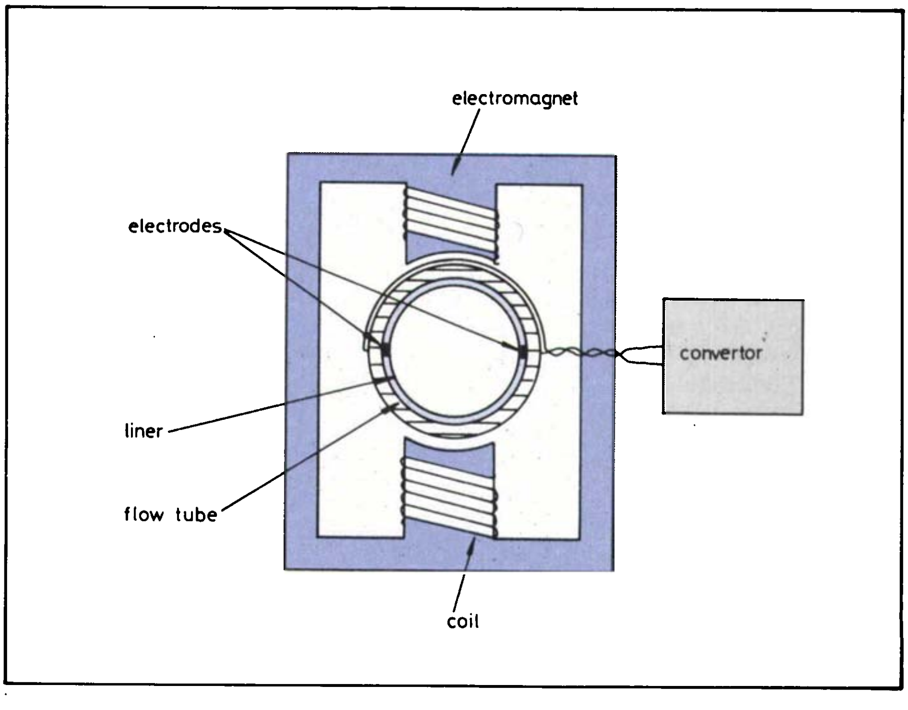
Electromagnetic and ultrasonic flowmeters: their present states and future possibilities

Traditional flowmeter methods, which involve physical contact with the fluid, can act as obstructions to the very flow they are trying to measure. Electromagnetic and ultrasonic flowmeters avoid this problem but create new ones. This article shows how the problems are overcome to make these meters truly reliable

by M.L. Sanderson

Electromagnetic flow measurement, based on Faraday's law of electromagnetic induction, has been available for industrial flow measurement for over 20 years, and is a widely used and accepted technique. A recent survey by one major manufacturer estimated that magnetic flowmeters represent approximately 10% of flowmeter sales by volume with a demand increasing at 10% per year. Ultrasonic flowmeters, on the other hand, represent newer technologies, having been available only in the last ten years, and at the present time have less than 1% of the flowmeter market with an estimated growth in demand of 5% per year. Both types of flowmeter offer a considerable advantage over other flowmeters such as orifice plates or turbines in that they offer no obstruction to the flow. The ultrasonic technologies also hold the possibility of a totally noninvasive measurement employing sensors clamped on to the outside of the pipe. Such a possibility offers considerable cost savings, as in many situations the installation costs of the flowmeter can be comparable with the cost of the flowmeter itself. From a theoretical point of view, electromagnetic flowmeter concepts are now well developed, but at the present time the theoretical basis for industrial ultrasonic flowmeters has not yet been developed. This article reviews the present state of the two flowmeters and indicates possible future developments.

The basic elements of the electromagnetic flowmeter are shown in Fig.1. The magnetic field, which is usually alternating to enable the flow-generated signal to be distinguished from the electrochemical, thermoelectric and electromotive potentials which are also present between the electrodes, is produced by the electromagnet. The electrodes (typical materials for which are 316 stainless steel, platinum/iridium, Hastelloy, titanium, tantalum) between which the EMF is developed are usually button electrodes flush with, or slightly protruding from, the walls of the flow



1 Electromagnetic flowmeter

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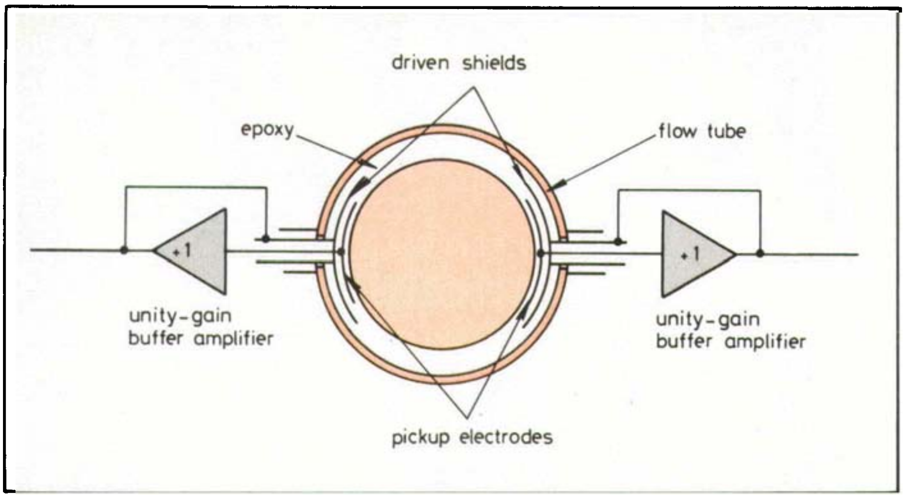
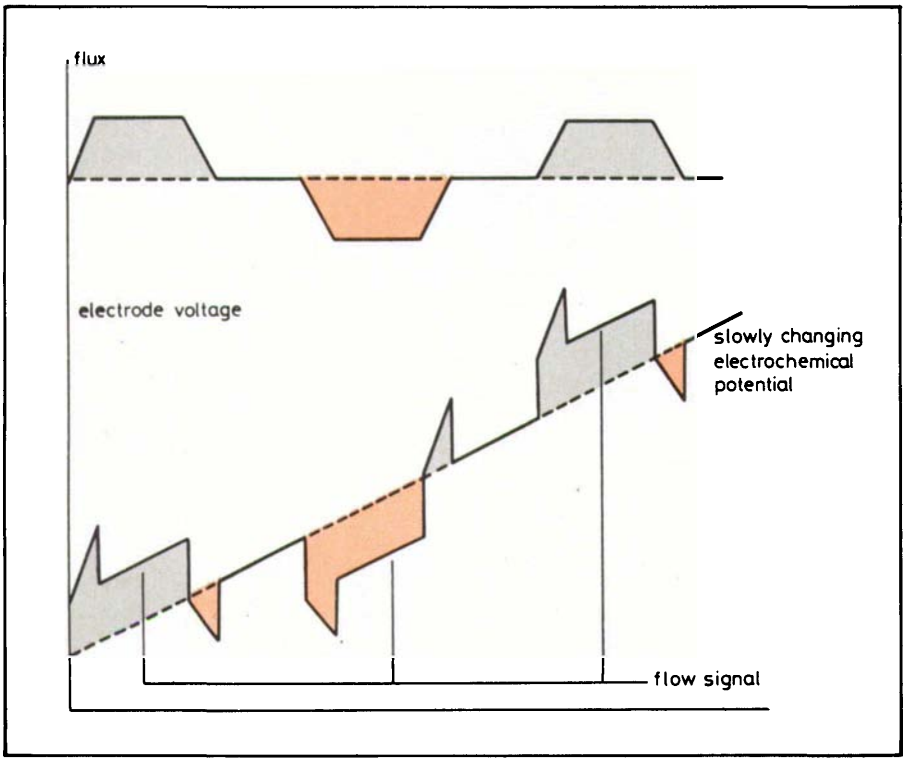


2 Capacitively coupled electromagnetic flowmeter



3 Nonsinusoidal excitation

tube, which is lined with an insulating material such as Meoprene, polytetrafluoroethylene (PTFE) or polyurethane. The convertor operates on the low-level flow voltage generated between the electrodes, rejects other artefacts additionally present between the electrodes, and provides a voltage, current, or pulse output suitable for display, control, transmission or totalisation.

The magnitude of the flow-generated EMF can be estimated by assuming that all the liquid is moving with the same velocity v. If the magnetic field is of infinite extent and uniform with a flux density B, then the output voltage U is given by $U = Bdv$, where d is the diameter of the tube. For a flow profile which has axial symmetry and with a uniform magnetic field of infinite extent the output is still proportional to the mean flow. Typically, for most flow-tube sizes, the output is 1 mV at 1 m/s and is independent of the conductivity of the fluid, although as this varies the output impedance associated with the EMF varies. At a minimum conductivity of 100 μS/m a magnetic flowmeter with button electrodes 1 cm in diameter will have an output impedance of 1 MΩ.

Velocity-profile effects

It has been observed that, when an electromagnetic flowmeter is placed downstream of a bend or obstruction, its calibration is altered as a consequence of the disturbance of the velocity profile. This usually results in the manufacturer specifying a certain number of diameters of straight run upstream and downstream of the flowmeter to ensure that the flowmeter is within specification. Difficulties may be experienced in producing these straight runs for large-diameter flowmeters. The question arises as to the exact output of the flowmeter under these circumstances. The answer to the question has been elegantly developed by Bevir[1] who showed that the output from the flowmeter could be written as an integral equation:

$$U = \int \mathbf{v}.\mathbf{W} d\tau$$

where U is the voltage developed between the electrodes; $\mathbf{v}$ is the velocity vector; and $\mathbf{W}$ is the weight function.

The integration is performed over the entire volume of the flowmeter and the weight function $\mathbf{W}$ is given by:

$$\mathbf{W} = \mathbf{B} \times \mathbf{j}$$

where $\mathbf{B}$ is the flux-density vector; and $\mathbf{j}$ is the virtual current density vector.

The virtual current-density vector is that current-density vector which would be obtained with zero magnetic field if unit current were passed in at one electrode and out at the other. Bevir also answered the important question as to what condition it was necessary to impose on $\mathbf{W}$ for the flowmeter to be ideal, i.e. so that it would respond only to the mean flow and would be independent of the velocity profile. He showed that the necessary and sufficient condition for the flowmeter to be ideal is that curl $\mathbf{W} = 0$.

Large-area-electrode flowmeters

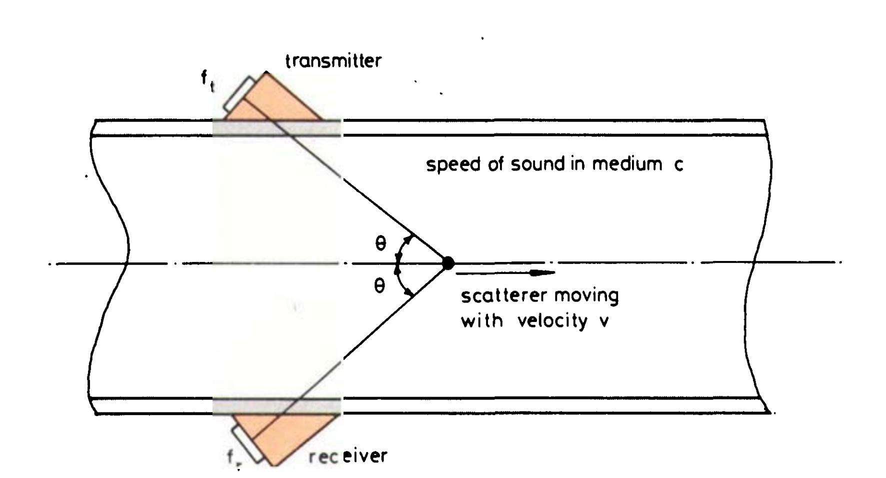
The weight function is related to both the magnetic field and the electrode structure and can be used to determine field and electrode configuration such that the flowmeter approximates more closely to the ideal. It can be shown that a flowmeter with point electrodes cannot be ideal, since it will always show higher sensitivity to flows near the electrodes. Large-area-electrode flowmeters show very much less velocity-profile sensitivity. However, large exposed electrodes are subject to fouling, which affects both the baseline stability and the weight-function distribution, and hence the sensitivity of the flowmeter. This fouling can be overcome by the use of an electrical burnoff technique, but a more satisfactory solution to the fouling problem is to use large-area electrodes which are capacitively coupled to the fluid through a thin layer of insulating material, as shown in Fig.2.

At least one commercial flowmeter is available which uses this technique. By varying the thickness of the insulating material between the electrode and the liquid over the face of the electrode, further modification of the weight function of the flowmeter can be obtained and flowmeters with performances closely approximating to the ideal can be achieved. The electronic problems associated with such flowmeters are somewhat more severe than those of the conventional flowmeter, since the source impedance of the flowmeter is somewhat higher and capacitive. This requires the use of driven-shield techniques and screening to prevent external interference. Microphonic effects can also be troublesome in such flowmeters.

Excitation techniques

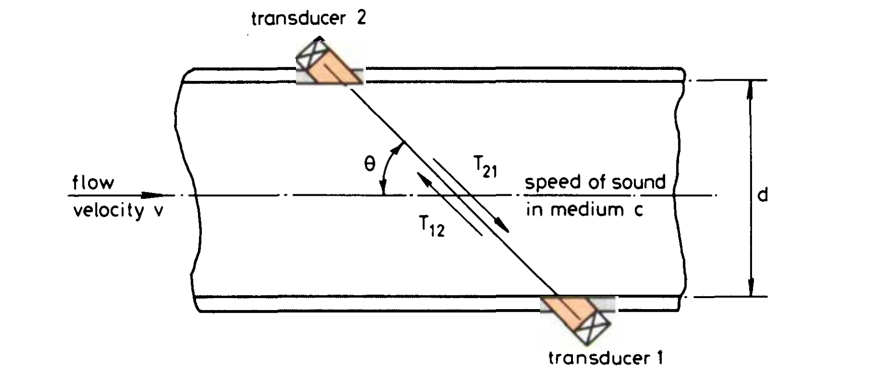
Until recently, most industrial magnetic flowmeters used sinusoidal excitation, with the electromagnet usually being driven directly from the mains. The sinusoidal excitation was employed to overcome the problems presented by the spurious voltages present on the electrodes in addition to the flow-generated voltage. The flow-generated voltage is thus an amplitude-modulated signal, but, additionally, a transformer-generated EMF is developed due to flux linkages in a loop consisting of the pickup leads and paths in the liquid. As this EMF is a rate-generated EMF it is orthogonal to the flow-generated EMF and can therefore be rejected by means of phase-sensitive detection techniques. The baseline stability of such systems is limited by the phase stability of this transformer-generated signal, which can be phase shifted by eddy currents in the tube wall and by electrochemical effects on the electrodes.

Nonsinusoidal excitation has recently become available for industrial magnetic flowmeters, the form of excitation being square wave (with unipolar or bipolar operation) or trapezoidal. The essence of these techniques is that in all of them there is a point in the measurement cycle when the field is stationary, and thus if flow measurements are made at this point the effect of the transformer-generated signal can be eliminated since $dB/dt = 0$. The addition of a measurement point in the cycle when there is zero magnetic field also allows for the measurement of and compensation for the spurious electrode voltages to be made. Fig.3 shows the waveforms for such a system. Initially, these systems operated with very low repetition frequencies, typically locked to the line frequency at 1/16th of line frequency. Recently, however, a second generation of such flowmeters has been developed with somewhat higher repetition frequencies. Nonsinusoidal excitation leads to flowmeters with significantly improved baseline stability, and therefore to flowmeters which can offer improved accuracy over a greater turndown ratio.



$$f_t - f_r = 2f_t \frac{v}{c} \cos\theta$$

4 Principle of the Doppler flowmeter



$$T_{12} = \frac{d}{\sin\theta\,(c - v\cos\theta)} \qquad T_{21} = \frac{d}{\sin\theta\,(c + v\cos\theta)}$$

$$T_{12} - T_{21} = \frac{2vd\cos\theta}{c^2} \qquad \text{since } c >> v\cos\theta$$

5 Transit-time ultrasonic flowmeter

Future developments

The weight-function concept is likely to be increasingly used in the design of magnetic flowmeters to produce flowmeters which exhibit significantly less velocity-profile sensitivity. This is most likely to be developed through the use of capacitively coupled electrodes. In addition, there is a trend in magnetic-flowmeter design to produce flowmeters having shorter axial lengths, and the weight function can be used here to produce flowmeters with minimum velocity-profile sensitivity consistent with the length of the flowmeter.

The weight function could also be applied to online calibration of magnetic flowmeters. A significant amount of effort in flowmeter production is spent in calibration, since it is difficult to predict accurately the sensitivity of the flowmeter. By performing auxiliary measurements to ascertain the field distribution and the virtual current distribution, and by operating on these measurements in a microprocessor online; calibration could be provided. This, together with self checking of the flow tube and electronics, and signal processing, could lead to a more efficient use of the microprocessor systems which are beginning to appear in electromagnetic flowmeters for drive-control purposes.

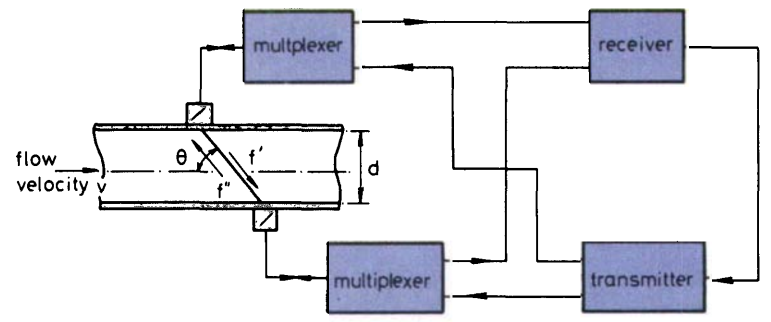
At the present time, the minimum conductivity for which an electromagnetic flowmeter can be used is typically 100 μS/m. This compares with a conductivity of deionised water of 5 μS/m, and excludes the use of such flowmeters with dielectric liquids such as petrol. The theory of the electromagnetic flowmeter as applied to dielectric liquids is now known,[2] and demonstrations have been made which indicate that it is possible to use electromagnetic techniques to measure the flow of such liquids. The major problem which is apparent at the present time is the static-charge problem, which severely limits the speed of response available from such devices. Considerable effort is likely to be expended in extending the range of liquids which can be monitored by electromagnetic techniques, as such extensions may enable the flowmeter to be applied in the petrochemical industry.

Ultrasonic flowmeters

Ultrasonic flowmeters employ two distinct technologies, and it is likely that much of the scepticism which is general in industry regarding ultrasonic flow-measurement techniques stems from a failure to recognise this fact. Bad experiences with one type of ultrasonic flowmeter have tended to make people way of all ultrasonic flowmeters.

Doppler flowmeters

Doppler flowmeters employ the well known Doppler shift and require scatterers in the flow such as solids or gas bubbles to provide the necessary frequency-shifted ultrasound used to estimate the velocity of the liquid (Fig.4). The electronics associated with such flowmeters is relatively straightforward RF technology, and therefore such flowmeters are available as cheap



$$f' - f'' = \frac{2v \sin\theta \cos\theta}{d}$$

6 Sing-around technique. The multiplexers allow the transducers to be used both as transmitters and receivers

clamp-on flowmeters. They represent the major proportion of ultrasonic flowmeters sold at the present time. It would, however, be more appropriate to class such devices as flow indicators rather than flowmeters. They give a reasonably high degree of repeatability in a given situation, but their accuracy depends on many factors such as the flow profile and the nature, number, size and spatial distribution of the scatterers, all of which vary from situation to situation and make precalibration difficult. Initially, such flowmeters were grossly oversold, and many plants have within them Doppler flowmeters which had been sold for situations in which they could never have worked. This overselling has now largely stopped, but it has made it much more difficult to introduce the second and complementary ultrasonic technology, the transit-time flowmeter, which is designed for use with clean liquids.

Transit-time ultrasonic flowmeters

This flowmeter is shown in Fig.5. The technique measures the difference between the transit times of ultrasonic beams passed upstream and downstream in the liquid, which occurs as a consequence of flow. The transit time for a beam at 45° to the pipe axis in water in a 100 mm pipe is 94 μs, and a flow of 1 m/s produces a transit time difference of 88 ns. The time differences are thus very small, and therefore high-precision electronics is required if an accuracy of 1% of reading is required. Three techniques are commonly employed for measuring the transit-time differences. These are leading-edge, phase-shift and sing-around techniques. As shown in Fig.5, the transit-time difference shows a dependence on the velocity of sound in the medium. Both leading-edge techniques, which measure the transit-time differences directly using ultrasonic pulses, and phase-shift techniques, which convert the time difference to a phase difference of a continuous or quasicontinuous ultrasonic signal, require velocity-of-sound compensation.

The sing-around technique, shown in Fig.6, does not require velocity-of-sound compensation since the time differences are converted into frequency differences. The sing-around frequencies in both directions are determined, the difference in these frequencies being proportional to flow and independent of the velocity of sound in the medium. In such a system it is necessary to allow for blockages in the form of air bubbles or solid material coming between the transmitter and the receiver, as these will upset the sing-around frequencies. Commercial systems are available employing a modified sing-around technique which claim only to require 2% of the transmitted pulses to be received to give a measurement within specification.

Velocity-profile effects

The beams employed in ultrasonic flowmeters tend to be narrow, and therefore they estimate the mean velocity in the tube by measurements made across a diameter. In fully developed flow of high Reynolds number the velocity profile is relatively flat, and the sensitivity of the flowmeter changes very little with flowrate (typically 1% per decade change in flow). In laminar flow, however, the estimate can be in error by up to 30%. Errors also occur in these flowmeters as a result of upstream disturbances. Velocity-profile effects in ultrasonic flowmeters can be reduced by the use of multibeam techniques, in which two or four beams are used and the mean velocity is estimated using a numerical integration technique. An alternative technique is the use of low-frequency broad-beam ultrasonic transducers to provide velocity averaging over the tube. At the present time there is no complete velocity-profile theory for the ultrasonic flowmeter. The equivalent theory to that of the weight function for the electromagnetic flowmeter is only just now emerging.

Future developments

One of the most important characteristics of the ultrasonic flowmeter is the ability to use it in a clamp-on mode as well as with wetted sensors. At the present time, however, the clamp-on flowmeters are required to be precalibrated for a given pipe size and liquid. Variations in parameters such as pipe-wall thickness or its internal diameter require recalibration of the flowmeter. It is conceivable that additional measurements of these parameters and their incorporation into the calculations performed within the ultrasonic flowmeter by means of a microprocessor could result in a much more versatile instrument. The microprocessor could additionally provide autozeroing and calibration of the transit-time measurement electronics for improved accuracy, as well as providing overall system control.

The understanding of ultrasonic flowmeters and the ability to design devices with improved velocity-profile immunity is dependent on having an adequate theory of such flowmeters. The development of electromagnetic-flowmeter theory has occurred mainly in the past ten or so years. It will be interesting to see whether in ten years time the theory of ultrasonic flowmeters has developed, and whether their present potential has been developed as shown by a significant increase in their share of the market.

Further reading

More extensive reviews of the state of the art in electromagnetic and ultrasonic flowmeters can be found in References 3 and 4.

References

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