Title: ULTRASONIC FLOW METER AND A METHOD FOR MEASURING FLOW

Abstract: The invention relates to a meter for the flow-rate in a medium, based on an ultrasonic transit-time delay. The meter consists of a body (2), an ultrasonic transmitter (5) and an ultrasonic receiver (6) connected to the body (2), the transmission and correspondingly receiver surfaces are essentially parallel, and means for determining (20-25) the flow rate of the medium, on the basis of the transit-time delay of the ultrasound between the transmitter (5) and the receiver (6). According to the invention, both the transmitter (5) and the receiver (6) are located on an essentially flat surface (2) in its immediate vicinity, and at least part of the beams of the transmitter (5) and the receiver (6) overlap each other, so that the measurement can be carried out without a reflecting surface.
Ultrasound Flow Meter and a Method for Metering Flow

The present invention relates to an ultrasonic flow meter, according to the preamble of Claim 1, for a gas or a liquid.

The invention also relates to a method for measuring a flow in a medium.

The invention also relates to a method for using an ultrasonic meter to measure surface level.

In many process-control systems and especially in anemometers, it is essential to determine the rate of flow of gases and liquids. Flow meters based on the use of ultrasound mainly apply transit-time measurement. The rate of flow of the medium can be ascertained using several different calculation algorithms.

US patent 5,343,744 discloses a wind-speed measurement method based on ultrasound. In such a system, there are typically three ultrasonic transceivers, the direction and force of the wind being determined on the basis of the transit times between the ultrasonic transceivers. Depending on the number of the pairs of ultrasonic transceivers, the flow field can be defined in one, two, or three dimensions.

A drawback of the state of the art is that the sensors are located at the ends of very long arms, or on other protruding structures, which increases the size of the measuring device and also makes it easily breakable. The location of the sensors at the ends of long arms and the tilted position of the sensor elements relative to each other, i.e. at an angle to the flow being measured, creates surfaces that disturb the flow in the actual measurement area. This causes errors in measurement. In addition, the protruding structures are mechanically complex and are thus difficult and expensive to manufacture. Such structures also collect ice and snow very easily.

The present invention is based on locating the ultrasonic sensors on an essentially flat or curved surface and on the transmitter and receiver beams being at least partly
overlapping. It is typical of the invention that the ultrasonic sensors are arranged as a sensor matrix, which allows the adjustment of the directional patterns of the sensor matrix by adjusting the delay between the individual sensor elements and thus allows the ultrasound signal to be directed from the transmitter to the receiver.

More specifically, the ultrasonic anemometer and flow meter according to the invention are characterized by what is stated in the characterizing portion of Claim 1.

The method according to the invention for measuring the rate of flow of a medium is characterized by what is stated in the characterizing portion of Claim 12.

The method according to the invention for using the ultrasonic meter for measuring surface level is, in turn, characterized by what is stated in the characterizing portion of Claim 16.

Considerable advantages are gained with the aid of the invention. A reflector construction can be avoided by using overlapping alignments of the transmitter and receiver beams. An anemometer according to the invention can be made very small. As the sensors do not essentially protrude from the attachment surface, the construction is mechanically rugged. The essentially smooth surface reduces flow disturbances, thus giving a reliable and accurate measurement. The sensor surfaces of the measuring device can also be set in such a way that water and snow do not collect on top of the sensors, but run off. The measuring device can be constructed for a one-, two-, or three-dimensional flow field. By using a combination of a cylindrical measuring device and a dense sensor matrix, wind can be measured in three dimensions, with no significant increase in cost.

In the following, the invention is examined with the aid of examples and with reference to the accompanying drawings.

Figure 1 shows the flow and ultrasound field on top of a flat surface.
Figure 2 shows a one-dimensional measurement arrangement according to the invention.

Figure 3 shows a sensor matrix according to the invention.

Figure 4 shows a simulated direction pattern as a function of angle.

Figure 5 shows graphically a received measured test signal as a function of time.

Figure 6 shows the shift in a measured ultrasound signal according to the flow field.

Figure 7 shows a block diagram of the electronics of the measuring device according to the invention.

Figure 8 shows a two-dimensional measuring arrangement according to the invention.

Figure 9 shows a three-dimensional measuring arrangement according to the invention.

Figure 10 shows a block diagram of an alternative configuration of the electronics according to the invention.

Figure 1 shows the flow profile 1 of a schematic flowing gas or liquid on top of a flat surface 2. Due to friction, the surface 2 slows down the flow u, so that the flow rate right on the surface is zero. The flow u increases with the distance from the surface, until the free flow rate is reached. The thickness of this boundary layer depends on, among other things, the properties of the flowing medium, the rate of flow, and the location. The boundary layer forms as a result of several physical phenomena. In terms of the present invention, the significant fact is that the layer thickness is typically between some tens of microns and a few millimetres thick.

Figure 1 further shows an ultrasound field 3 advancing on top of the surface. This ultrasound field can be implemented to travel both down 3 and up-stream 4, and also at a desired angle relative to the flow. In practice, the ultrasound travelling on top of the
surface advances both in the thin boundary layer and in the free flow. Because the ultrasound field advances on top of the surface tangentially to it, the ultrasound energy cannot penetrate into the actual surface 2, due to the acoustic discontinuity. The advance of the ultrasound is then limited to a semi-space, which is even more advantageous in terms of the signal-to-noise ratio of the measurement.

Figure 2 shows a cross-section of a one-dimensional measurement arrangement according to the invention. An ultrasonic transmitter 5 and an ultrasonic receiver 6, which have transmission/reception surfaces that are essentially parallel to each other, are embedded in the measuring device. Despite the embedded ultrasonic transmitter/receiver pair, the measurement surface 2 remains essentially flat, so that the flow on top of the surface is not disturbed. The directional patterns 7 and 8 of the sensors 5 and 6 are implemented in such a way that the acoustic signal of the ultrasonic transmitter 5 can be received by the ultrasonic receiver 6.

To optimize the signal-to-noise ratio, the directional patterns of the ultrasonic sensors 5 and 6 should be directed towards each other, so that the beams at least partly overlap. This can be realized in several different ways. The major or minor beams of the sensors can be exploited. A simple way to exploit the minor beams of the sensors is to suitably dimension the ultrasound wavelength and the sensor diameter that are used, according to the basic textbooks, with the aid of Bessel functions or their derivatives [Kinsler L. E., et al. *Fundamentals of Acoustics*. Wiley. New York. 4th ed. (2000)]. The beams of the sensors can also suitably-shaped by using methods known from radar technology and medical imaging devices [Drabowitch S. et al. *Modern Antennas*. Chapman. London (1998)]. In these, the alignment of the beam is based on dividing the sensor into elements, which are run and amplified exploiting transit times. The dimensioning of the transit times depends on factors such as the frequency used and the distance between the sensor elements.

Figure 3 shows a perspective view of an evenly spaced one-dimensional sensor matrix. The sensor matrix in question can act as both a transmitter and a receiver. For example, the sensor matrix elements' width, distance between, length, medium frequency, and
bandwidth are application-dependent optimization parameters. In the solution of Figure 3, the matrices 5 and 6 are formed from elements 9, the electrical signal fed into which causes the surface of the element to vibrate at the ultrasound frequency. The desired directional pattern is created by arranging a short delay between the individual elements, for example, with the aid of resistive or conductive components.

Figure 4 shows correspondingly the directional pattern of an equally spaced one-dimensional sensor matrix, as a function of angle. As the curve shows, the sensor’s major beam is turned from a direction normal to the radiating surface of the sensor, to a direction tangential to the radiating surface of the sensor. Most of the ultrasonic power radiated by the sensor is directed to the receiver of the measuring device, thus further increasing the signal-to-noise ratio of the acoustic signal travelling through the air.

Figure 5 shows the test signal of the receiver of a test arrangement. The transmitted signal is shown by a burst 10 and correspondingly the signal received by the receiver by a burst 11. Electrical cross talk from the received test signal can be detected as a pulse practically simultaneous with the burst 10. As the pulse representing the electrical cross talk would lie practically on top of the pulse 10, it is not shown in the figure. In time, the next to be detected is the acoustic pulse 11 that advances in air and which travels directly from the transmitter to the receiver. Last of all, a pulse 13, which travels through a possible reflector, is detected. A reflector was used in the test situation to define the journey/time compared to the direct journey. In an actual flow meter, a reflector is unnecessary. Pulses that travel through the body of the measuring device may also appear, but they arrive at the receiver much earlier than a pulse travelling through the air. Thus, a suitable time window can be used to concentrate the measurement on the actual acoustic signal 11 that travels straight through the air, the transit time of which is a function of the flow of the medium.

Figure 6 shows the shift of the measured pulse of ultrasound, due to the effect of the flow. The reference is the pulse 11 that arrived when the medium was at rest. When the medium moves in the same direction as the advancing ultrasound field, an ultrasound pulse that travels directly through the air on the top of the surface will be detected before
one in the zero-flow field, as a pulse 11'. When the medium travels against the
advancing ultrasound pulses, an ultrasound pulse that travels directly through the air on
the top of the surface will be detected later than one in the zero-flow field, as a pulse
11".

Several portions are required in the measuring device, in order to implement the totality
[Hietanen J. Capacitive Ultrasonic Transducers: Their Parameters and Testing.
University of Helsinki. (1996)]. Figure 7 shows the electronics of one measuring device
implementation at the block diagram level. Direct current is fed from a power supply 20
to a capacitive transmitter 5 and receiver sensors 6. The desired transmission pulse is
connected from a signal generator 24 to the direct current of the transmitter, with the aid
of a connection and protection circuit 21. Correspondingly, a connection and protection
circuit 22 is used to separate the detected measuring signal, which is amplified 23 and
filtered for further processing 25, from on top of the direct current of the receiver 22.
The measuring signal is processed both analogically and digitally, to provide flow data
(1990)].

The sensors and their related electronics should be implemented in such a way as to
permit the two-way operation of the ultrasonic transmitter-receiver pair. In other words,
each sensor can act as both a transmitter and a receiver. The measuring device can be
implemented using several different sensor technologies. These sensor technologies
require to some extent different kinds of driving-and-amplifier circuits connected to the
sensors, but in principle there are no great differences between them. Examples of
possible sensor technologies include a capacitive ultrasonic sensor, a PZT-based piezo-
ceramic composite-construction, flexible PVDF sensor, and other electromechanical
plastics, and even ferromagnetic sensors.

In a typical macroscopic measuring device implementation, the transmitter and receiver
sensors have a surface area of a few square centimetres. The distance between them is
centimetres. The sensors are integrated at essentially the surface level. When a sensor is
divided into sensor elements, they are line and point sources, optimized in terms of the
totality. Such an element has a width of about 1 mm. Though the distance between the centres of the elements depends on the desired beam direction pattern, their order of magnitude is one or more millimetres. A typical microscopic implementation has sensors with a surface area of a few square millimetres or less. The distance between the sensors is then, in turn, millimetres or less. If sensors built from different elements are used, their diameters and distances are in the order of millimetres. Intermediate forms between and combinations of microscopic and macroscopic constructions can also be used.

The sensor matrix can be easily increased from one dimension to two. Figure 8 shows several transmitter-receiver pairs 5 and 6, and 5' and 6' on a single surface, in which case it is easy to achieve two-dimensional measurement of a flow field. The flow measurement can be implemented equally well on top of, or beneath the plate. Setting the measurement plate downwards will stop water, snow, and ice from collecting on the sensor surface of the measuring device. Figure 9 shows a measurement arrangement, which can be used to measure flow in all three dimensions. The use of a cylindrical surface 31 allows both the horizontal and vertical components to be measured with the aid of additional meter pairs 30. It is further possible to develop a spherical measuring head (not shown). The measurement geometries are not restricted to only flat and convex surfaces - concave surfaces too, such as tubes and similar can also be utilized. Thus, according to Figure 9, a curved surface, such as a cylindrical surface 31, can be regarded as essentially a flat surface, according to the invention. According to the invention, the installation surface of the sensors 5, 6, and 30 should be flat, so that the flow being measured will conform to it. The sensors 5; 6; and 30 should also not be far enough from the installation surface to disturb the flow substantially. The sensors should also not be so far from the installation surface that their measurement area lies outside the flow defined by the surface 31.

According to Figure 10, the measuring system of Figure 7 can be altered so that it permits pulses to be simultaneously transmitted from and received on the sensors 5 and 6. The measurement is then two-way, with the signals travelling in opposite directions in the measurement area during measurement. In practice, measurement is permitted with the aid of switches 40, so that the signal of the signal generator 24 is sent simultaneously
to sensors 5 and 6. After transmission, the sensors 4 and 5 are changed by means of the switches 40 to become receivers and the transit-time difference of the signals is defined in the block 41. The use of this measurement arrangement makes the processing electronics very simple. The application is particularly suitable, for example, for flow rate measurements of air-conditioning equipment.

The measuring device has a very low acoustic power requirement. Little power is required compared to the other operational components needed in the device, such as microprocessors, pre-amplifiers, calculators, or bus amplifiers. The power required by the equipment unit as a totality is in the order of 10 mW.

If the measuring device is implemented so that the measurement plate faces downwards and the space below the measurement plate is free of supporting structures, not only is the collection of water, snow, and ice prevented, but it is also possible to advantageously implement a measuring device that can be used to investigate the surface level of water or snow beneath it. One practicable solution is, for instance, Figure 9, in which the sensors 5 - 6 are located on the under surface 50 of the measuring cylinder. In practice, the signal of the measuring device is the same as that shown in Figure 5. Suitable algorithms can be used to determine the surface level, as well as the flow field.

Other measuring devices (not shown) can also be combined with the aforesaid measuring heads, in which case the advantage of a flow and anemometer with a simple shape will be achieved.

The following summarizes the central features of the invention.

Unlike the prior art, a solution according to the invention directly exploits an acoustic signal advancing through the air on top of a surface. The sensors are integrated as part of the measuring apparatus, so that their effect on the flow field above the plate is minimized. In a solution according to the invention, ultrasound can be used to measure the flow rate on top of the surface, above the thermic boundary layer. The invention is suitable for measuring the flow rate of both liquids and gases.
The straight or curved surface used in a solution according to the invention stabilizes the flow. The sensors according to the invention can be located either on a level surface or alternatively on a curved surface, such as a cylindrical or spherical surface. Naturally, the location surface of the sensors can also be a part of a spherical or cylindrical surface.

The sensor structure is typically formed in such a way that the minor beam of the sensor is exploited, so that the transmission of power is maximized, or the direction of the major beam is exploited, or even both of them. The sensors can also be processed into the same body, for example, a semiconductor or other substrate.

The electronics are formed typically using traditional electronics. Phasing can be implemented passively using an RC or similar circuit, which will provide constant phasing and constant directional patterns in the sensors. Phasing can be implemented actively using a digital signal processor (DSP). Possible interfering signals can be eliminated by using a suitable measurement time window. The calculation algorithms for the received signals are similar to those in known solutions.

In the case of matrix transmitters and receivers, the receiver elements can be located in connection with the transmitter elements, so that the same unit can be used to transmit and receive simultaneously. For example, modulation can be used to separate from each other signals relating to different measurements.

The invention is not restricted to only the embodiment presented above, but can be adapted within the scope of the accompanying Claims.
Claims:

1. A meter for the flow-rate in a medium, based on an ultrasonic transit-time delay, which comprises
   - a body (2),
   - an ultrasonic transmitter (5) and an ultrasonic receiver (6) connected to the body (2), the transmission and correspondingly receiver surfaces are essentially parallel, and
   - means for determining (20 - 25) the flow rate of the medium, on the basis of the transit-time delay of the ultrasound between the transmitter (5) and the receiver (6),
   characterized in that
   - both the transmitter (5) and the receiver (6) are located on an essentially flat surface (2) in its immediate vicinity, and
   - at least part of the beams of the transmitter (5) and the receiver (6) overlap each other, so that the measurement can be carried out without a reflecting surface.

2. A flow rate meter according to Claim 1, characterized in that the major beams of the transmitter (5) and the receiver (6) overlap each other.

3. A flow rate meter according to Claim 1 or 2, characterized in that the minor beams of the transmitter (5) and the receiver (6) overlap each other.

4. A flow rate meter according to Claim 1, characterized in that the transmitter (5) and the receiver (6) are located on the level of the surface (2) of the body.

5. A flow rate meter according to any of the above Claims, characterized in that the transmitter (5) and/or the receiver (6) are formed from several transmitter/receiver elements.
6. A flow rate meter according to any of the above Claims, characterized in that the transmitter (5) and/or the receiver (6) are formed form a comb-like, one or two-dimensional sensor matrix.

7. A flow rate meter according to any of the above Claims, characterized in that the transmitter (5) and the receiver (6) are equipped with connecting devices (40), in order to implement simultaneous measurement in two or more directions.

8. A flow rate meter according to any of the above Claims, characterized in that the transmitter-receiver pairs (30) are arranged to measure the flow in several different directions.

9. A flow rate meter according to any of the above Claims, characterized in that the body (2) is arranged as a cylindrical surface (31).

10. A flow rate meter according to any of the above Claims, characterized in that the body (2) is arranged as a spherical surface.

11. A flow rate meter according to any of the above Claims, characterized in that the measurement sensors (5, 6, 30) are arranged on the bottom surface (50) of the measuring device.

12. A method for measuring a flow rate on the basis of the transit-time delay of ultrasound, in which method

- an ultrasonic transmitter (5) is used to form an ultrasound field and an ultrasonic receiver (6) is used to receive the signal sent by the transmitter (5), and
- the rate of flow of a medium is determined on the basis of the transit-time delay of ultrasound between the transmitter (5) and the receiver (6), characterized in that
- both the transmitter (5) and the receiver (6) are located on an essentially flat surface (2), in its immediate vicinity, and

- at least part of the beams of the transmitter (5) and the receiver (6) are positioned to overlap each other, so that the flow of the medium on top of the flat surface (2) in the vicinity of the surface is measured using the generated advancing ultrasound field, so that the measurement can be made without a reflecting surface.

13. A method according to Claim 12, characterized in that the major beams of the transmitter (5) and the receiver (6) are positioned to overlap each other.

14. A method according to Claim 12 or 13, characterized in that the minor beams of the transmitter (5) and the receiver (6) are positioned to overlap each other.

15. A method according to Claim 12, characterized in that the transmitter (5) and the receiver (6) are located on level of the surface (2) of the body.

16. A surface-level measuring method combined in an anemometer, characterized in that the surface level is measured using an anemometer of the above Claims, the transmitter (5) and receiver (6) of which are located on an essentially level surface (2) in its immediate vicinity and that the measurement sensors (5, 6; 30) are arranged on the under surface (50) of the measuring device.

17. A distance measuring method combined in an anemometer, characterized in that the distance is measured using an anemometer of the above Claims, the transmitter (5) and receiver (6) of which are located on an essentially flat surface (2) in its immediate vicinity and that the measurement sensors (5, 6, 30) are used to scan the desired measurement object.
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC7: G01F 1/66, G01P 5/24
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
SE, DK, FI, NO classes as above

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Further documents are listed in the continuation of Box C. See patent family annex.

Date of the actual completion of the international search: 15 May 2003
Date of mailing of the international search report: 23-05-2003

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