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Scarpa

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[45] **June 24, 1975**

[54] **PIEZOELECTRICALLY DRIVEN ULTRASONIC GENERATOR**

[75] Inventor: **Thomas J. Scarpa**, Edison, N.J.

[73] Assignee: **Scarpa Laboratories, Inc.**, Metuchen, N.J.

[22] Filed: **Sept. 4, 1973**

[21] Appl. No.: **394,407**

[52] **U.S. Cl.** ..... **310/8.2**; 73/194 E; 73/71.5 US; 116/137 A; 116/DIG. 19; 310/8.3; 310/8.7; 310/9.1; 340/8 MM; 310/9.7; 310/26

[51] **Int. Cl.** **H04r 17/00**

[58] **Field of Search** ..... 310/26, 8.2, 8.3, 8.7, 310/9.1, 9.4; 73/67.5 R, 67.6, 67.8, 69, 71.5 (U.S. only), 194 A, 194 B, 194 E; 340/8 MM; 259/1; 116/137 A, DIG. 19; 181/.5 J, .5 AG; 51/59 SS

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Primary Examiner—Mark O. Budd
Attorney, Agent, or Firm—Martha G. Pugh, Esq.

[57] **ABSTRACT**

Ultrasonic system for measuring fluid flow by comparing the responses from pulsed beams transmitted obliquely in opposite directions through fluid flowing in a pipe section. The transducer assembly includes a driving element comprising a piezoelectric generator in the form of a disk with a high mass backing element bonded to one face and an acoustic wave transformer bonded to the other face. The wave transformer element varies in cross-section in an axial direction, comprising disks of maximum dimension at the generator face and at the radiating face, which are separated by a connecting portion of minimum dimension. In preferred form, the wave transformer is shaped like a barbell. An advantage of this configuration is that the beam pattern is a function of frequency, having a dominant central lobe at about 45 kilocycles per second which becomes relatively depressed with respect to increasing side lobes as the frequency is increased. Although the invention has been described in general terms, the primary uses of the system and components as disclosed herein are for the measurement of the flow of gases.

8 Claims, 15 Drawing Figures

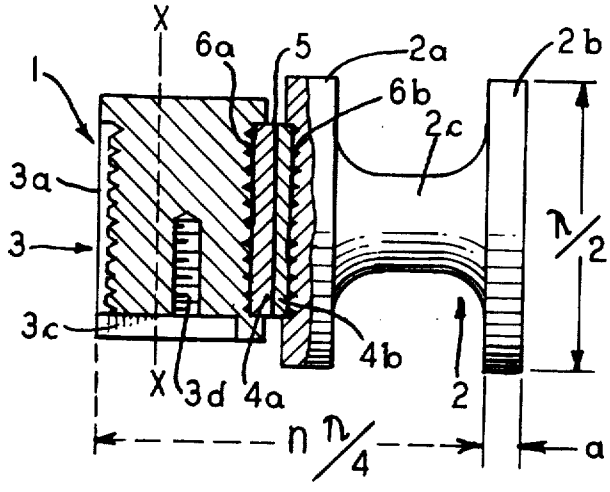


FIG. 1

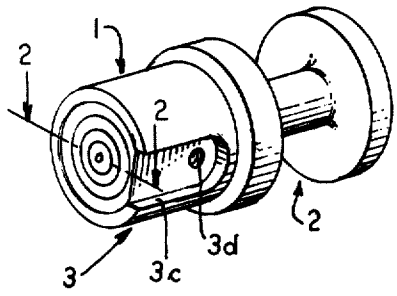


FIG. 3A

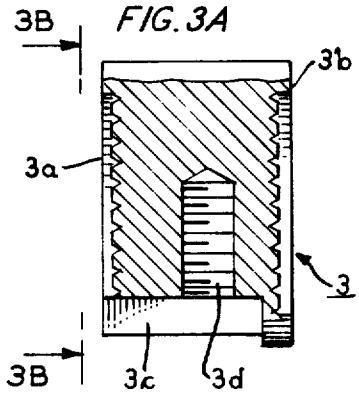


FIG. 2A

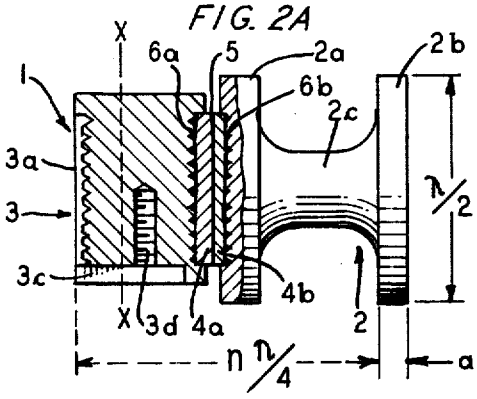


FIG. 3B

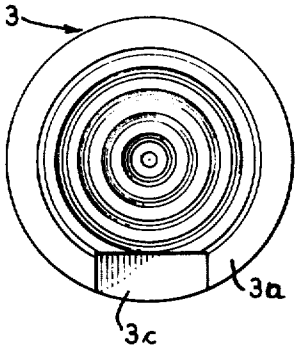
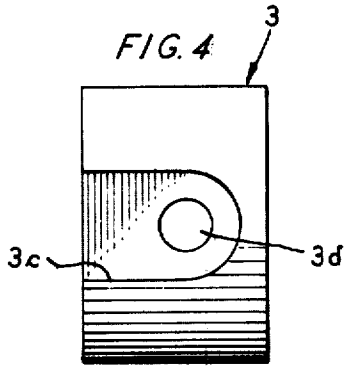


FIG. 4



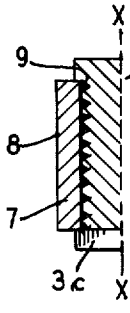


FIG. 2B

FIG. 5B

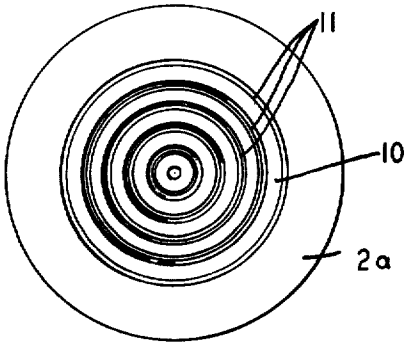


FIG. 5A

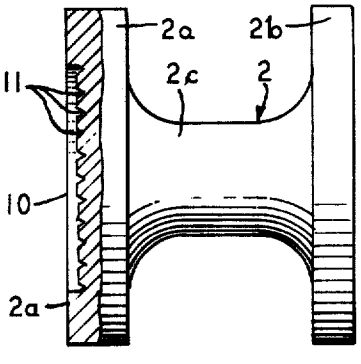


FIG. 6

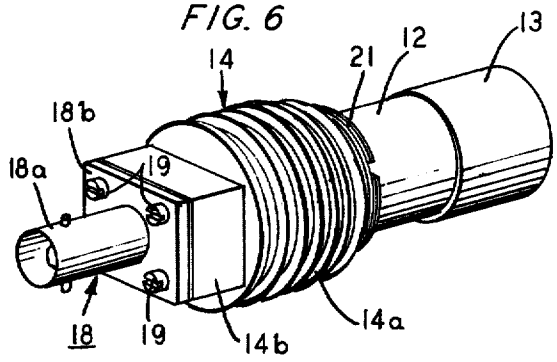


FIG. 7

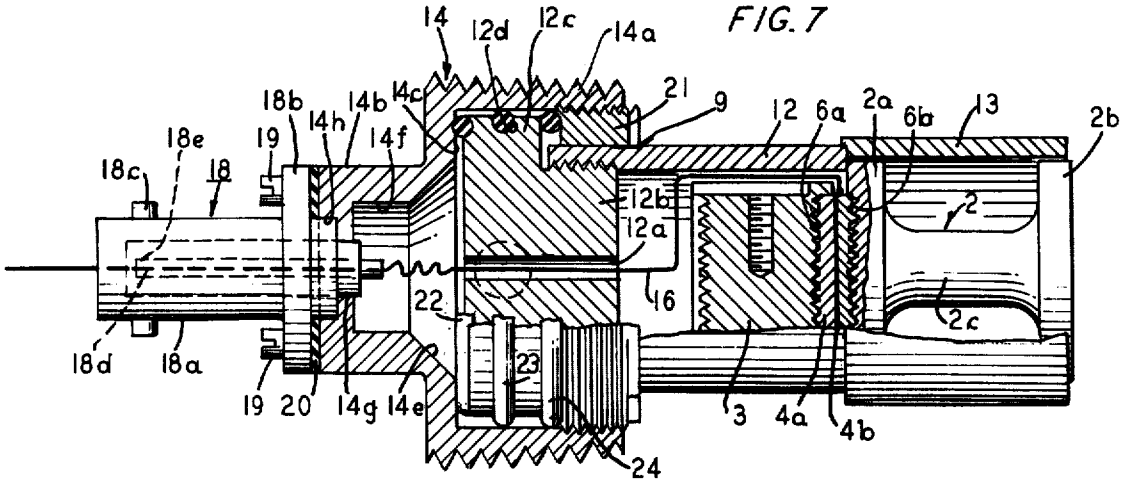


FIG. 8

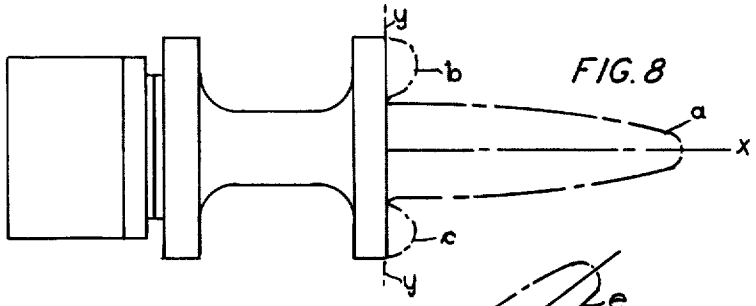


FIG. 9

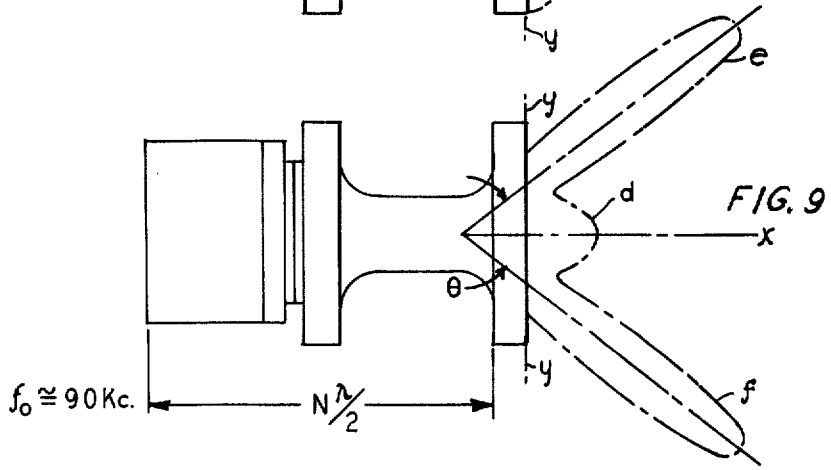


FIG. 10

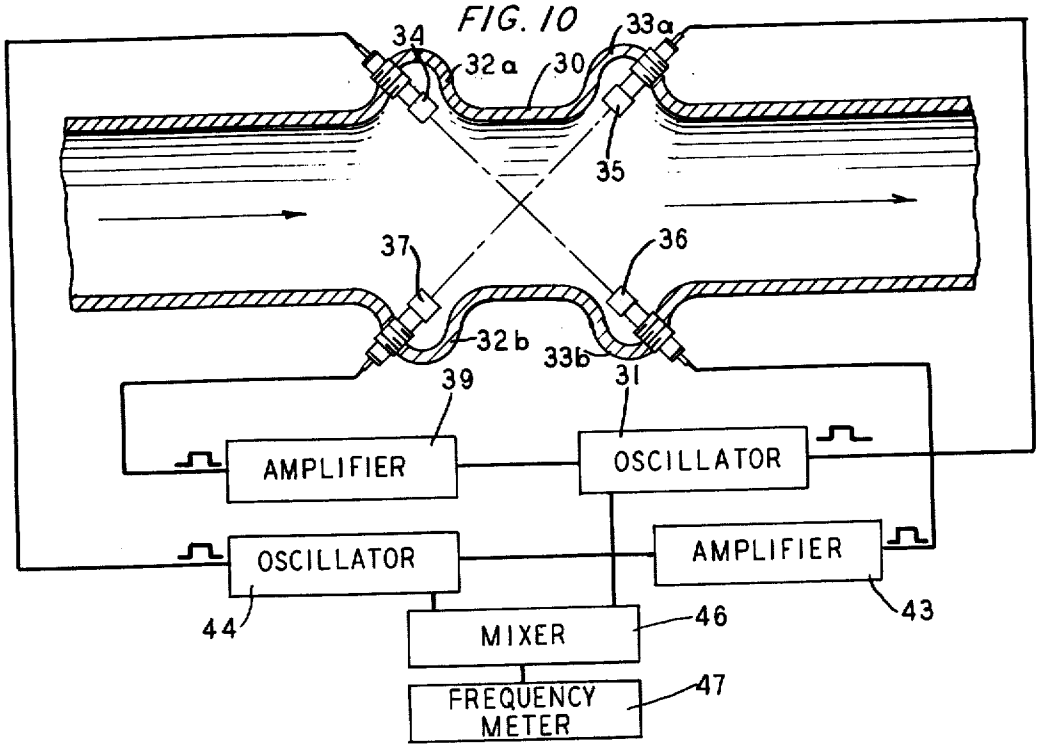


FIG. 11

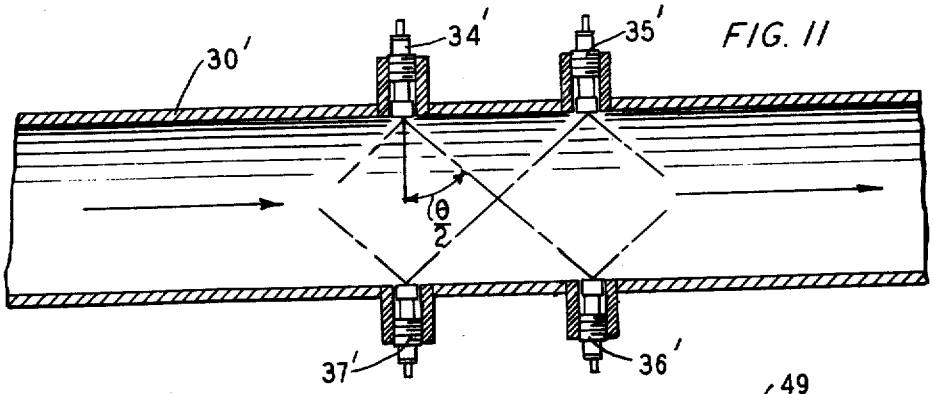
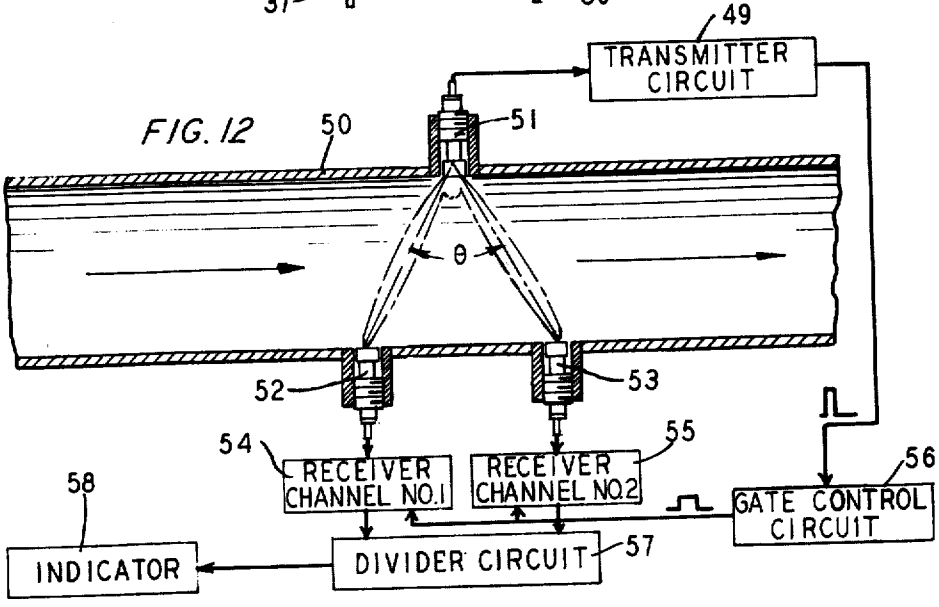


FIG. 12



PIEZOELECTRICALLY DRIVEN ULTRASONIC GENERATOR

BACKGROUND OF THE INVENTION

This relates in general to ultrasonic flowmeter systems and, more specifically, to the transducer assemblies employed in such systems, particularly for measurement of the flow of gas.

In ultrasonic flowmeter systems of a type disclosed in the prior art, the velocity of fluid flowing in a test pipe section is measured by transmitting a pulsed ultrasonic beam obliquely across the pipe section from a transmitting transducer interposed at one point in the pipe to a receiving transducer interposed at a second position in the pipe, spaced up or downstream from the first. When an ultrasonic wave is transmitted through the test fluid, the time required for such transmission is dependent on the velocity of the ultrasound in the fluid, the length of the path over which the beam is transmitted and the velocity at which the fluid is flowing. The velocity of fluid flow either adds to or subtracts from the transmission time, depending on whether the beam is transmitted against or in the direction of the stream of flow. Thus, a feedback circuit produces a signal having a frequency of repetition which varies in accordance with the time required for the ultrasound waves to travel over a predetermined path in the fluid.

Such ultrasonic systems are well-known in the art, as disclosed, for example in U.S. Pat. No. 2,669,121 to R. L. Garman et al., issued Feb. 16, 1954, and by others.

In accordance with prior art practice, the transducers used for transmitting and/or receiving the ultrasonic beam in such a system were so constructed that the maximum lobe of the emitted beam was directed in substantially a normal direction from the face of the transducer. Thus, in order to provide a beam capable of crossing the stream of fluid flowing in the pipe at an oblique angle, it was necessary to build a shoulder or supporting nipple onto the surface of the pipe. This obviously requires precise modifications in the pipes to which such a system is applied. Moreover, it creates a series of recesses in the inner pipe wall, associated with the obliquely positioned transducers which tend to cause interruptions or turbulence in the fluid flow being measured.

In addition, particularly in measurement of the flow rates of gases or low density liquids, problems arise in impedance matching the radiating member of the transducer assembly to the fluid in such a way as to avoid unwanted reflections and thereby energy loss.

SUMMARY OF THE INVENTION

Accordingly, it is a principal object of the present invention to provide an ultrasonic system for measuring fluid flow in pipe systems which is substantially more sensitive, more efficient and more economically constructed than the systems of the prior art.

A particular object of the present invention is to provide an ultrasonic system for measuring fluid flow in pipes transporting gases and low density fluids in which the ultrasonic transducing assemblies are impedance matched to the measured fluid.

Another object of the invention is to provide a system in which alterations in the test pipe surface for installing transducers are minimized.

A further object of the invention is to provide a system in which turbulence and other distortions in the flow of the test fluid are minimized.

Another object of the invention is to provide an ultrasonic system including transducer assemblies which are constructed to radiate narrow, high velocity beams.

Another object of the present invention is to provide an ultrasonic system including a transducer assembly in which the principal beam direction with reference to the radiating face may be controlled as a function of frequency.

These and other objects, features and advantages will be apparent to those skilled in the art as set forth in the invention hereinafter.

The present invention relates to ultrasonic systems for measuring fluid flow in a pipe in which one or more pulsed beams is transmitted obliquely through the fluid from a transmitting transducer interposed through the pipe wall in one position to a receiving transducer interposed through the pipe wall in another position, the effect of the fluid flow velocity on the pulse transmission time being computed electronically.

In order to facilitate the operation of such a system, the present invention contemplates a novel type of transducer assembly which includes a driving element comprising a longitudinal thickness-mode piezoelectric generator in the form of a disk having a backing element of relatively high mass bonded to one face and an acoustic wave transformer bonded to the other face. The whole assembly is preferably an integral number of quarter-wavelengths along the principal axis in the vibrating frequency of the system. The transformer diminishes in cross-section from a maximum at the bond with the driving element to a relatively small cross-sectional dimension along its axis at a parallel plane remote from the bond. The small cross-sectional dimension is broadened out at the radiating end to form a center driven radiating disk of relatively small mass. The diameter of the radiating disk is preferably a half-wavelength in the operating frequency; and, it is disposed parallel to the face of the piezoelectric generator and normal to the axis of the transformer. The mass ratio between the backing element, which may comprise a metal cylinder, and the transforming element lie anywhere within the range 2:1 to 30:1, thereby producing a particle velocity transformation of from 2:1 to 100:1 between the face of the piezoelectric generator and the radiating disk. The transformer, including the disk, functions to step down the impedance by increasing the area of contact at the radiating surface, which moves in small arc vibrations at high velocity. Thus, the low impedance at the face of the radiating disk is substantially equal to that of air, or any other low density fluid. This has the advantage of greatly increasing the efficiency of the transducer assembly by reducing the energy losses from distortions and reflections at the interface. A tight beam of small angular divergence is radiated by transducer assemblies designed in accordance with the present invention. This permits the ultrasonic beams so radiated to be transmitted and received over greater distances than with the same expenditure of energy using prior art structures.

In accordance with a preferred form of the invention disclosed herein, the solid energy transforming member may assume a shape somewhat like a barbell with disks of equal diameter on the two ends connected by a cylindrical axial portion having a diameter about one-

third that of the end disks. In the disclosed embodiment, the left-hand disk which is bonded to the face of the piezoelectric generator is substantially thicker than the radiating disk.

In accordance with a variation, the cross-sectional dimension of the transforming member decreases exponentially until it reaches a minimum cross section of, say, one-tenth the diameter bonded to the piezoelectric element. The minimum cross-sectional plane is then bonded or otherwise integrally connected in driving relation to the center of a thin disk about the same diameter as the piezoelectric generating element. There are numerous other suitable shapes for the transforming element of the present invention, the only requirement being that the cross-sectional dimension decrease in a manner symmetrical about the longitudinal axis from a maximum at the area of contact with the piezoelectric generator surface to a minimum along the axis at a plane removed from the generator surface; and, that the minimum cross-sectional area function as the central driving means for an expanded radiating surface comprising a relatively thin disk normal to the axis. Such a transformer configuration bonded to one face of a piezoelectric generator, to the other face of which is bonded a backing element of relatively higher mass, constitutes a transducer assembly with numerous advantages. It produces a highly efficient narrow ultrasonic beam impedance matched to gas and low density liquids.

As a further feature of the present invention, the transducer assembly described in the foregoing paragraphs is supported in a coaxial acoustically isolating housing for providing electrical connections between the energizing circuit and the piezoelectrically active transducer, which may comprise a sandwich transducer of the bimorph type.

A particular advantage of the structure of the present invention is that the beam pattern has been found to be a function of frequency. Whereas at a frequency of about 45 kilocycles per second, the beam has a dominant central lobe and relatively suppressed side lobes, I have found that by increasing the operating frequency to about 90 kilocycles per second, the central lobe is depressed and the side lobes become dominant.

When transducers of the type disclosed herein are incorporated in an ultrasonic flowmeter of the general circuit arrangement disclosed by Garman et al., supra, substantial advantages ensue in that such a flowmeter is especially adapted to measure the flow rates of gas and other low density fluids with high efficiency. Moreover, assuming the transducer assemblies are operated in a frequency range producing dominant side lobes, it becomes unnecessary to build shoulders or nipples into the pipe wall for respectively supporting the individual transducer assemblies in an oblique direction with reference to the axis of the pipe. Instead, the transmitting and/or receiving transducer assemblies may be interposed into the test pipe section in directions respectively normal to the pipe surface. In this type of operation the pulsed side lobe beams are transmitted and/or received obliquely in the pipe from two or more identically operated transducers positioned in obliquely spaced-apart positions so that while one transducer assembly transmits an obliquely directed beam, another transmitter assembly is positioned to receive the obliquely transmitted beam, and vice versa.

Other objects, features and advantages will be understood from a detailed study of the specification hereinafter with reference to the drawings of which the following is a short description.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an overall perspective showing of the narrow beam transducer assembly of the present invention;

FIG. 2A is a longitudinal section through the plane indicated by the arrows 2—2 of FIG. 1;

FIG. 2B is a modification of a section of the left of the plane x—x in FIG. 2A, including a feedback crystal;

FIG. 3A is an enlarged sectional showing of the backing element 3 of FIGS. 1 and 2;

FIG. 3B is an end elevation showing the face 3b;

FIG. 4 is an enlarged side elevational showing of the backing element 3 of FIG. 1, showing the recessed area for the screw hole 3d;

FIG. 5A is an enlarged side elevational showing of the acoustical transformer 2 of FIG. 1;

FIG. 5B is an end elevational showing of the left-hand end face 2*a* of the acoustic transformer 2 of FIG. 5A;

FIG. 6 is a showing in perspective of the transducer assembly in one form of housing for incorporation into a test pipe system;

FIG. 7 is a longitudinal section of the assemblage of FIG. 6;

FIG. 8 is a schematic cross-sectional showing of the transducer assembly disclosed in FIGS. 1 and 2, indicating the general outline of the ultrasonic beam radiated at an operating frequency of about 45 kilocycles per second, comprising an enlarged central lobe and minimal side lobes;

FIG. 9 is a schematic cross-sectional showing of the transducer assembly disclosed in FIGS. 1 and 2, indicating the general outline of the ultrasonic beam radiated at an operating frequency of about 90 kilocycles per second, comprising enlarged side lobes, the central lobe being substantially suppressed;

FIG. 10 is a schematic circuit showing of an ultrasonic flowmeter of the pulsed beam type employing a rectangular array of four transducer assemblies of a type shown in FIG. 8, driven at about 45 kilocycles per second, and each characterized by a beam having a prominent central lobe;

FIG. 11 is a schematic circuit showing of an ultrasonic flowmeter of the pulsed beam type employing a rectangular array of four transducer assemblies of a type shown in FIG. 9, driven at about 90 kilocycles per second, and each characterized by a beam having a pair of enlarged side lobes and a suppressed central lobe; and

FIG. 12 is a schematic circuit showing of an ultrasonic flowmeter of an alternative from to that indicated in FIG. 11 employing a triangular array of three transducer assemblies of a type shown in FIG. 9, driven at about 90 kilocycles per second, and each characterized by a beam having a pair of enlarged side lobes and a suppressed central lobe. Detailed Description

Reference will now be made to FIGS. 1 and 2A of the drawings which show a preferred from of the transducer assembly of the present invention.

The radiating face 2*b* of the transducer assembly may be considered to be a center driven thin plate, vibrating in a flexural mode. The driving force is a longitudinal or compressional wave that is converted by the geome-

try into a flexural, radial wave in the disk. In such a transition, the phenomenon of velocity dispersion occurs which makes the resonant frequency of the disk difficult to mathematically predict and is usually arrived at by empirical experimentation.

The velocity constant c_f for the flexural wave in the disk **2***b* may coarsely be computed from an equation that is derived from a fourth order differential equation given by P. M. Morse, *Vibration and Sound*, second edition, McGraw Hill, New York, 1948, pp. 154 and 209. For a plate whose width $> a$: $c_f = [Y_o K^2/\rho(1 - 6^2)]\ ¼\ (2\ \pi f)^{1/2}$

where:

c_f = Flexural velocity
Yo = Youngs Modulus
a = Plate thickness, of 2*b* as indicated in FIG. 2
K = Radius of gyration (for a plate = $a/\sqrt{12}$
ρ = Density of the plate
6 = Poisson's Ratio
f = Frequency of vibrations.

The combination **1**, disclosed in FIG. **1**, in perspective, has two visible elements, namely, the acoustic wave radiator **2** and the backing element **3**. As shown in the sectional view of FIG. **2A**, a composite piezoelectric driving unit of the bimorph type comprising elements **4***a*,**4***b* is mounted contiguously with the circular inner faces of the backing element **3** and the acoustic wave radiator **2**, or transforming element.

The active elements **4***a*,**4***b* may be any piezoelectric crystalline body known in the art, formed or polarized to vibrate principally in a resonant-thickness mode of vibration. For the purposes of the present invention, elements **4***a*,**4***b* are preferably disk-shaped wafers of lead-zirconate-titanate dimensioned in accordance with the desired frequency. In the present illustrative embodiment, they are 0.500 inch in diameter and, say, 0.078 inch thick; and are constructed to vibrate in a longitudinal-thickness mode of a resonant frequency of about one megahertz. It will be understood that the wafers **4***a*,**4***b* are thicker or thinner, depending on the desired resonant frequency of the principal mode. Disks of lead-zirconate, titanate, of a type and dimension suitable for the uses of the present invention, may be obtained commercially in various diameters and in thicknesses of 0.5 inch or less.

As a step in their preparation, the piezoelectric wafers **4***a*,**4***b* are polarized in accordance with well-known prior art practice by the application of a polarizing voltage in a thickness direction substantially normal to the major faces of the wafer, while the temperature is lowered through the Curie temperature. Moreover, the elements **4***a*,**4***b* are aged to give them stable electroacoustic characteristics, poling and aging having been carried out by the suppliers in a manner taught, for example, in a bulletin entitled "Aging of Ferroelectrics," New Jersey Ceramic Research Station, Rutgers University, New Brunswick, Technical Report No.1, Rt. 1, TR-59-128 (July 1, 1959) (AD-227-737-1004).

An important step in the process of preparing these piezoelectric elements is the careful cleansing and preparation of the contacting surfaces prior to assemblage into any of the combinations disclosed hereinafter. For example, the wafers **4***a*,**4***b* when obtained commercially, or after prepolarizing treatment, may have permanent electrode coatings on their major parallel surfaces. For some embodiments of the present invention these are carefully removed by lapping to a depth of 0.005 inch with any of the lapping compounds known in the art, such as, for example, aluminum oxide and water.

After the foregoing treatment the surfaces of the ceramic wafers **4***a*,**4***b* are further cleaned by exposing the elements to ultrasonic cleaning action in a container of, for example, an isoprophyl alcohol or acetone, or any similar solvent which is characterized by rapid evaporation, and which is not readily absorbed by the ceramic. The ultrasonic vibrations are generated in the cleansing liquid by means of, for example, a 100 to 200 watt generator operation at a frequency of, say, 40 kilocycles per second, for about 10 minutes.

In addition to the use of lead-zirconate-titanate, which is the piezoelectric disclosed in the present illustrative example, any other ceramic or piezoelectric crystalline materials may be employed for the purposes of the present invention which are capable of producing an element which vibrates in the longitudinal-thickness mode, such as, for example, barium titanate, x-cut quartz, etc.

As pointed out hereinbefore, the crystal elements **4***a*,**4***b* are sandwiched together with an electrode coating, preferably an acoustic conducting epoxy characterized by an electrical resistivity of at least about 0.01 ohm-centimeter at 25° C., providing a coating which forms the inner electrode **5**. A suitable conductive cement for this purpose can be obtained from the Hysol company as No. 4238, which is cured with Hysol hardener No. 3469, or a similar combination. The external electrodes **6***a*,**6***b* comprises similar coating applied to the external surfaces of elements **4***a*,**4***b*. As previously stated, the piezoelectric sandwich **4***a*,**4***b* is interposed between the cylindrical backing element **3** and the acoustical transforming element **2**, which will now be described.

Although the piezoelectric element **4***a*,**4***b* is disclosed herewith as a bimorph, it will be understood that a single crystal wafer can be used. Moreover, although elements **4***a*,**4***b* are disclosed as being cylindrical in the present illustrative example, it will be understood that they can be other shapes, such as rectangular.

Referring to the FIGS. **3A**, **3B** and **4**, it will be seen that in the present example the backing element **3** comprises a substantially cylindrical metal element of stainless steel having an outer diameter of 0.625 inch and an axial length of 0.410 inch. The right- and left-hand faces **3***a* and **3***b* each have circular recesses symmetrical about the axis which are 0.02 inch deep and have a diameter of 0.500 inch. The inside faces of each of these recesses are respectively grooved with a series of annular grooves 0.010 inch deep and spaced apart 0.050 inch. The recess of right-hand face **3***b* serves to accommodate the face of the piezoelectric element **4***a*, together with the cementing epoxy mixed with conducting coating which is forced into the indentations to provide a better bond. Adjacent the left-hand face is a lengthwise indentation **3***c* about 0.250 inch wide and 0.360 inch deep which is rounded at the inner end to accommodate a screw hole **3***d* which is 4/40 inches in diameter with a tap one-fourth inch deep. This serves for mounting the backing element **3** when the transducer has been assembled. It will be understood that in addition to stainless steel, as disclosed for the present illustrative example, backing element **3** may alternatively be formed of any high density element, such as high carbon steel, monel metal, or even ceramic material having sufficient density to serve as a loading ele-

ment. Although the backing element 3 is disclosed herein as being cylindrical, it will be understood it is not limited to that shape.

In addition to the piezoelectric elements 4*a*,4*b*, a modificaton of the invention shown in FIG. 2B includes an auxiliary piezoelectric element 7 for feedback purposes, which may be of any thickness between, for example, 0.15 inch and 0.78 inch. This is bonded into the recess of the left-handed surface of the backing element 3 in the same manner that the composite element 4*a*,4*b* is bonded to the right-hand recess. Similarly, electrode coatings 8 and 9 are included which may also comprise conducting epoxy of the type previously described.

The unique element of the combination disclosed is the energy transforming and acoustic wave radiating element 2. This combination is preferably formed of a metal such as aluminum, titanium, monel or stainless steel.

In accordance with the present invention, the element 2 has substantially smaller mass than the element 3. However, the ratio of the mass of the backing element 3 to the acoustic wave tranforming-radiating element 2 may lie anywhere within the range 1:1 up to 30:1 or 40:1 or higher.

The function of the impedance member 2 is two-fold. One function is to provide a substantial increase of the particle velocity from its driving end 2*a* to its driven and 2*b*. Another function is to provide a driven end having an impedance substantially matched to air or gas impedance, which is center-driven and has a large radiating surface constructed to withstand high temperatures and pressures, and substantially resistant to corrosion, This is accomplished by providing an element shaped, for example, as shown in FIG. 5A, in which the left-hand, or driven, portion comprises a disk-like end 2*a* which has a diameter 0.750 inch and is cylindrical having a thickness in an axial direction of 0.135 inch. As explained with reference to the element 3, the left-hand face of the disk-like end 2*a* has a recess 10 matching the recess in the right-hand end of the cylindrical element 3 for mounting the face 4*b* of the piezoelectric sandwich element 4*a*,4*b*. As described with reference to the backing element 3, the recessed portion of the left-hand face 2*a* is provided with a series of annular grooves 11 which are 0.010 inch deep and spaced apart 0.050 inch for receiving the conducting epoxy coating on the contacting face of the piezoelectric sandwich element 4*b*. In the present embodiment, the transforming member 2 is 0.625±0.005 inch long, in an axial direction, tapering conically to a diameter at mid-section of about 0.250 inch. The right-hand end is expanded in cross section to a diameter of 0.750 inch, forming a plate-like radiating member 2*b* 0.090 inch thick, the radiating face being made parallel within ±0.002 inch to the face of the driven end 2*a* which is in contact with the electrode coating on the face of piezoelectric active element 4*b*. The diameter of the radiating element 2*b* preferably approximates a half-wavelength in the vibrating frequency of the transducer; altough it will be apparent that this is only approximate, as the system is designed to operate over a range of frequencies. In order to have a pronounced main lobe the diameter of the disk should be limited to under one wavelength. However, the smaller the diameer, the less is the impedance match. If the diameter exceeds one wavelength, the vibration of the disk breaks up into multiple modes and produces a suppressed main lobe and pronounced side lobes, generally two main lobes with a multiplicity of minor lobes. The axial length of the combination, as shown in FIG. 2A, from the center of the radiating end 2*b* to the left-hand face of the backing element 3, preferably approximate an integral number of quarter-wavelengths in the vibrating frequency.

It will be understood that although a specific embodiment of the transforming element 2 is disclosed herein by way of illustative example, the transforming element can take other forms within the teaching of the present invention, in which the driving means applied at the center of the right-hand radiating element 2*b* serves to step-up the particle velocity anywhere within the range 2:1 to 100:1; and, the disk element 2*b*, which is disposed at the high velocity end of the transformer, serves to substantially step-down the impedance between the transforming element and the contacting medium by substantially increasing the area of contact.

It will be apparent that the manner in which the cross section of the transforming means 2 is reduced between the elements 2*a*,2*b* may assume the form of any one of a number of cross-sectional curves well-known in the art, such as cone, parabola, catenary, etc., as long as the cross-sectional dimension is tapered from a large diameter at the driving end to a substantially small diameter at the plane at which the radiating member 2*b* is applied, so as to provide a velocity step-up.

Referring now to FIGS. 6 and 7 of the drawings, there is shown a preferred type of housing including a pipe fitting for a transducer assembly of the type described with reference to FIGS. 1 through 5B of the drawings.

FIG. 6 is an external perspective showing of the transforming assembly in the housing; whereas, FIG. 7 shows the complete assembly in longitudinal section.

The transducer assembly comprising the active piezoelectric sandwich element 4*a*,4*b*, backed by cylinder 3 and disposed in driving relation to a solid acoustic transformer 2, is enclosed in the stainless steel tubular housings 12 and 13. The latter are fitted together in longitudinal relation with the right-hand end of tube 12 bonded into a slight recess in the left-hand end of tube 13. The latter is 0.895 inches in outer diameter and 0.748 inches in inner diametr, being slightly recessed at the left-hand end, as indicated. Tube 13 is fitted coaxially around the solid transformer element 2 so that the right-hand face 2*b* of the latter protrudes about 0.015 inches from the end of the tube in an axial direction. Tubular housing 12 is 0.850 inch in outer diameters, 0.748 inches in inner diameter and 1.187 inches in axial length. Screwed onto the left-hand end of the tubular housing 12 is an end plug 12*b* having an annular flange 12*c* which is one-fourth inch thick, 1.020 inch in outer diameter. At its right-hand end, plug 12*b* is reduced in diameter to form a screw-threaded nipple about 0.733 inch in outer diameter which protrudes one-fourth inch coaxially for internal engagement with a matching screw-threaded recess in the inner end of the tube 12. An axial bore 12*a* which is 0.078 inch in diameter, for accommodating lead wire 16, extends through the flange 12*b* and the nipple.

Flange 12*c* provides an annular shoulder extending outwardly about 0.075 inches in a radial direction from the screw-threaded surface of the nipple. The flange 12*c* includes an annular notch 12*d* which is 0.068 inches wide and 0.035 inch deep, symmetrically disposed between the opposite faces of the flange. The

left-hand face of the plug **12***b* also includes an annular o-ring groove having a means diameter 0.95 inch, which is 0.04 inch wide and 0.015 inch deep. An annular collar **21** which is 0.065 inch in inner diameter and 0.0884 inch in outer diameter one-fourth inch in axial length, and externally screw-threaded, is fitted near the left-hand end of tube **12**, providing an annular clearance 0.05 inch wide with the shoulder of flange **12***c*. The aforesaid three annular notches are constructed to retain three o-rings **22**, **23** and **24**, which serve to acoustically isolated the inner transducer assembly and its housing from tubular brass enclosure **14**, in a manner which will now be described.

The tubular enclosure **14** comprises an enlarged open right-hand end **14***a*, externally screw-threaded at 11½ turns per inch. It is 1⅜inch in maximum outer diameter, 0.680 inch in overall length and slightly tapered from left to right in accordance with the National Plumbing code taper for one-inch pipe. The open end of enclosure **14** forms a cavity 1.041 inch in diameter and 0.567 inch along the axis, terminating at its left-hand end in an annular inner shoulder **14***c* which is about one-fourth wide in a radial direction. The cavity is internally screw-threaded at its open right-hand end at a pitch of 32 turns per inch.

At its left-hand end, tubular enclosure **14** has a square tubular extension **14***b*, symmetrical about the axis, the outer dimension of which is 0.70 inch on a side, and which extends externally three-eighth inch to the left of the flanged screw-threaded portion **14***a*. The diameter of the cylindrical inner cavity of enclosure **14** drops off from the inner shoulder **14***c* for an axial length of about 0.113 inch, to form a smaller cylindrical inner cavity **14***f* which is one-half inch in diameter and 0.4 inch along the axis. This is partly closed at the left-hand end, except for an axial opening **14***g* which is 0.209 inch in diameter to accommodate an "Amphenol" BNC-type connector, as will be described. In the present example, the axial depth of opening **14***g* is 0.055 inch; and, it leads into an annular recess **14***h* which is 0.351 inch in diameter and 0.045 inch deep at the center of the rectangular left-hand face of the extension **14***b*. The latter is constructed to mate with an Amphenol-type plug assembly **18**, which will now be described.

The "Amphenol" coaxial-type connector is of particularly the general form indicated in J. V. Malek et al., U.S. Pat. No. 3,054,981, issued Sept. 18, 1962, or C. W. Concelman U.S. Pat. No. 3,103,548, issued Sept. 10, 1963. It comprises a tubular outer conductor **18***a* of silver, or other conducting material, three-eighth inch in outer diameter, one-third inch thick, which extends five-eighth inch in axial length, terminating at the center of a rectangular plate **18***b*, eleven-sixteenth inch by eleven-sixteenth inch and three-sixteenth inch thick. This has screw holes to accommodate the screws **19** at its four corners, so that it mates adjacent the left-hand face of the rectangular extension **14***b* of the outer housing **14**, in contact with gasket **20**, about one thirty seconds inch thick, comprising rubber, "Neoprene" or another similar elastomer. A pair of diametrically opposite protuberances **18***c* provide means for locking shell **18***a* in electrical connection with an external coaxial lead. It will be apparent to those skilled in the art that the specific dimensions of pipe **14***b* and pipe plug **18***b* will vary so that each Amphenol type connector **18** is fitted to the pipe plug securely. Before the connector is put in place, a quantity of silicone rubber is internally into the opening **14***g* to secure the connector. After the connector is in place, the silicone is allowed to cure 24 hours, after which a test is made to determine that there is no air leakage around the connector.

Amphenol connector **18** has a cental conductor **18***d*, about one-sixteenth inch in diameter, embedded in an annular insulating member **18***e*, three-sixteenth inch in diameter. This combination is embedded internally in a solid conducting sheath **14***g* which makes solid integral contact with the inside of shell **18***a*, which extends from a position about five-eighth inch inside the left-hand end and continuing through to the right-hand face of the rectangular connecting plate **18***b*, where it protrudes about one-sixteenth inch beyond the surface of the plate, surrounding the insulating portion **18***e*, which protrudes an additional one-sixteenth inch, surrounding the axial conductor **16** which is connected to the high potential electrode coating **5** of piezoelectric elements **4***a*,**4***b* to which it is soldered or otherwise electrically connected.

The flanged end **12***c* of tubular housing **12** fits into the cavity in the screw-threaded outer connector **14***a* so the left-hand face rests against the o-ring **22**, one inch in outer diameter and one-sixteenth inch in thickness, resting against internal shoulder **14***c*. The o-ring **22** is preferably rubber or a rubber substitute, such as Neoprene or any other insulating material having a similar coefficient of elasticity. The second similar o-ring **23** is interposed in the annular notch **12***d*; and, the third similar o-ring **24** rests against the shoulder formed by the right-hand face of the flange **12***c*. As previously mentioned, the function of these three gaskets is to acoustically isolate the external housing from the transducer assembly. The combination, including o-ring **22**, 23 and **24**, is held in place by the annular collar **21**, the rings being screw-fitted into the internal threads of the outer tubular housing **14***a*. The left-hand end of collar **21** contains two or three peripheral notches which are one-eighth inch wide and 0.09 inch deep. These are symmetrically spaced around the circumference of the collar.

Assuming the acoustically isolating o-ring **22**, **23** and **24** to be nonconducting or insulating material, a conducting tab **9**, about one-fourth inch wide and one-half inch long, is force-fit between the external surface of the cylindrical shell **12** and the internal surface of the screw-threaded collar **21**, so as to make electrical contact between the two, providing a conducting path for the electrode coatings **6***a*,**6***b* which are connected together to make electrical contact with the transformer face **2***a*, and hence, internal surface of the shell **12**.

As an alternative to using the conducting tab **9**, the elastomer o-rings **20**, **22**, **23** and **24** are formed of a mixture of elastomeric material with metallic powder, having a resistivity of at least 0.01 ohm-centimeter at 25° c. For example, a suitable conductive epoxy cement can be obtained from the Hysol Company as No. 4238, which is cured with Hysol hardener No. 3469 or a similar combination.

Referring to FIG. **8** of the drawings, let us assume that a transducer assembly of the type previously described is connected to a conventional high frequency oscillator operating at a frequency of the order of 45 kilocycles per second. The ultrasonic radiation pattern of the plate **2***b*, indicated in FIGS. **1** and **2A**, includes

a centrally directed ultrasonic beam having a major central lobe which is substantially symmetrical about the *x* axis. Laboratory measurements show that at a distance of one foot from the center of the plate **2***a*, along the x axis, the beam intensity varies in a relative manner as illustrated.

If a receiving meter is moved in a plane perpendicular to the face of the radiator through a series of points of identical ultrasonic intensity, a plotting of these points indicates a pronounced central lobe *a*, flanked by a pair of substantially symmetrically disposed side lobes *b* and *c*, considerably weaker intensity. These patterns assume measurements made in air or another gas.

If, however, the frequency of the oscillator, operating at the same voltage and power, is increased to about 95 kilocycles per second, the radiation pattern changes to the general form indicated in FIG. **9.** Measurements at the same level of ultrasonic intensity in a plane perpendicular to the face of the radiator produce a series of readings which, when plotted, indicate a radiation pattern of the form shown in FIG. **9** of the drawings. As indicated, the central lobe *d* is now suppressed, and a relatively larger amount of energy is contained in the side lobes. It is apparent that the operation of the transducer assembly at the 95 kilocycles per second frequency, in such a manner that it includes the prominent side lobes as shown, has many applications not hitherto shown in the art. Two of these will be described with reference to FIGS. **11** and **12** of the drawings.

First, however, a gas flowmeter circuit of FIG. **10** will be described wherein are employed four transducer assemblies of the type indicated in FIGS. **1** and **2A**, which are operated at a pulse modulated frequency of the order of **45** kilocycles per second to produce in each case a beam pattern having a single prominent lobe of the type indicated in FIG. **8** of the drawings. The operation of the circuit shown in FIG. **10** is substantially similar to that described in U.S. Pat. No. 2,669,121 issued to R. L. Garman et al. on Feb. 16, 1954, entitled Supersonic Flowmeter. The ultrasonic flowmeter shown schematically in FIG. **10** is designed so that the velocity of fluid in a pipe section is determined directly, the indication obtained being independent of the velocity of sound in the fluid. Different fluids transmit sound at different velocities, the velocity of travel through any particular fluid varying with temperature. By providing a device whose measured output is independent of such a variable, the necessity for recalibration and the allowance for temperature errors and other variables are avoided.

When an ultrasonic wave is transmitted through a fluid, the time required for such transmission is dependent on the velocity of sound in the fluid, the length of the path over which the ultrasonic wave is transmitted and the velocity of the fluid itself, the latter either adding to or subtracting from the transmission time depending on whether the ultrasonic wave is transmitted against or with the stream of flow.

In the flowmeter shown in FIG. **10,** the time required for transmission of the ultrasonic waves over a predetermined path in the measured fluid is determined by the use of a feedback circuit which produces a pulsed signal whose repetition frequency is a function of the transmission time. This leaves two variables: namely, the velocity of the fluid to be determined and the velocity of sound through the fluid. In order to eliminate the velocity of the sound by cancelling it out from the final indicating instrumentality, two feedback circuits, driven from a common source of power, are utilized. One circuit includes amplifier **42** and pulse modulated, high frequency alternating current oscillator **44** which energizes transmitting transducer assembly **34** to transmit an ultrasonic beam to receiving transducer assembly **36,** so that the beam obliquely intersects the fluid path. The other, which includes amplifier **39** and pulse modulated, high frequency alternating current oscillator **31,** energizes transmitting transducer assembly **33** to transmit an ultrasonic beam to receiving transducer assembly **37,** so that the beam obliquely intersects the fluid path in the opposite direction. Each of the transducer assemblies **34, 35, 36** and **37** is so operated that it directs a principal ultrasonic beam substantially normally to the radiating surface. Hence, the axes of transducer assemblies **34** and **35** are respectively mounted in nipples **32***a* and **33***a* which are disposed obliquely in the wall of pipe section **30.** Transducer assemblies **36** and **37** are similarly mounted in obliquely disposed pipe nipples **33***b* and **32***b*. In such an arrangement, each separate path will generate a signal of a different repetition frequency. The frequency of the signal in one path, namely from transducer assemblies **34** to **36,** will be greater than the means by an amount which is proportional to the velocity of the fuid; and, the frequency of the signal in the other path, from transducer assemblies **35** to **37,** will be less than the means by a like amount. Signals are derived from both paths and are impressed in opposing relation on the mixer circuit **46.** The difference signal from mixer circuit **46,** varying only as the velocity of the fluid, is used to provide an indication in meter **47,** which is a function of the velocity of fluid flow in the pipe.

The foregoing will be more clearly understood by reference to the description in the aforementioned U.S. Pat. No. 2,669,121 to Garman et al., supra, which describes in detail the manner of operation of the circuit of FIG. **10,** with the exception of the transducer assemblies **34, 35, 36** and **37,** which are specifically of the form described in FIGS. **1, 2A,** et seq. of this application, operated to radiate a beam having a dominant central lobe, in the manner of FIG. **8.**

Assume for further example that transducer assemblies **34, 35, 36** and **37** are replaced with transducer assemblies **34′, 35′, 36′** and **37′** which are operated in the manner indicated in FIG. **9** of the drawings, at a frequency of the order of 95 kilocycles per second; and further, assume that the circuit to which they are connected is substantially of the configuration and operation shown and described hereinbefore with reference to FIG. **10.**

Because of suppressed central lobe and the angular spread of approximately thirty degrees between the side lobes *e* and *f* (FIG. **9**), it is no longer necessary to modify the surface of the pipe section to provide special nipples **32***a*, **32***b*, **33***a* and **33***b* in which to mount the transducer assemblies as indicated in FIG. **10.** Instead, pipe section **30′**, as shown in FIG. **11,** is substantially unmodified, except for the drilling of an opening in a direction normal to the pipe wall for the positioning of each of transducer assemblies **34′, 35′, 36′** and **37′** in their respective housings. The latter are screwed, or otherwise closely fitted, to protrude in a normal direction through the wall of pipe section **30′**, so that the radiating face **2***b* of each of the transducer assemblies is substantially flush with the inner surface of the pipe.

Referring to FIG. 9, it will be seen that each of the aforementioned transducer assemblies, when driven at a frequency of about 95 kilocycles per second, generates a pair of dominant ultrasonic side lobes for transmitting and/or receiving, which are directed obliquely, each at an angle $\theta/2$ relative to the direction of fluid flow in the pipe, where θ is the angle between the dominant side lobes. At the radiating face of each transducer assembly, one lobe is directed upstream, and the other downstream. Thus, with this modification, the system shown in FIG. 11 has its transducer assemblies 34', 35', 36' and 37' connected in substantially the same manner as the corresponding transducer assemblies of FIG. 10, in a pulse transmission and receiving system constructed and operated in a substantially similar manner thereto.

It will be appreciated that alternative arrangements of the flowmeter systems of FIGS. 10 and 11 can be made using, for example, two transducer assemblies positioned as indicated by 34' and 36', instead for four, with the circuit modified so that the direction of wave transmission is reversed at alternate intervals by alternately switching each transducer between the transmitting and receiving circuit.

Another alternative flowmeter system, making use of side beam transducer assemblies operated as indicated in FIG. 9, is shown in FIG. 12 of the drawings. This includes a conventional pipe section 50 in which there are drilled three openings in a triangular arrangement into which are interposed three transducer assemblies 51, 52 and 53, of the form shown and described in FIGS. 1 and 2 of the drawings, and operated as shown in FIG. 9. These are interposed in a direction normal to the pipe wall so that the radiating surface 2*b* of each of the transducer assemblies is substantially flush with the inner surface of pipe 50. Transducer assembly 51, which is located at the apex of the triangle, is connected to the output of the pulse transmitting circuit 49. The two transducer assemblies 52 and 53, which are located at the base angles of the triangle, are respectively connected to the input terminals of receivers 54 and 55, the latter being respectively tuned to two different high frequency channels designated as No. 1 and No. 2. The outputs of these two receiver channels are modulated with gating pulses derived from the gate control circuit 56 which, in turn, is synchronized with the operation of the transmitter circuit 49. The two output channels from receivers 54 and 55 are imposed on the divider circuit 57 to provide a difference signal which actuates the flowmeter indicator 58. Details of the operation of this circuit may be better understood from a study of U.S. Pat. No. 3,204,456, issued Sept. 7, 1965, to W. Welkowitz, entitled Ultrasonic Flowmeter.

It will be seen that the side beam transducer assembly 51 which simultaneously directs two beam with an angle of θ between them from the radiating surface thereof to the receiving surfaces of transducer assemblies 52 and 53, provides a novel and advantageous system of operation.

Although the patterns disclosed in FIGS. 8 through 12 have been described in general terms, it will be understood that these specific patterns, as shown, are based on measurements made with air as the fluid medium.

It will be understood that the invention is not limited to the specific forms of transducer assemblies shown and described herein by way of example; or to the specific flowmeter circuit arrangements herein shown and described, but is limited only by the scope of the claims hereinafter set forth.

What is claimed is:

1. A transducer assembly comprising in combination:
an ultrasonic generator which includes a pair of piezoelectric ceramic wafers having substantially parallel opposite major surfaces comprising electrode means interposed between the internal major surfaces of said wafers and on the two external surfaces thereof, said generator designed to vibrate in the direction of the longitudinal axis of said transducer assembly in a principal resonant-thickness mode of vibration.
a cylindrical backing element having a pair of substantially flat end surfaces,
means interposed between one said end surface of said cylindrical backing element and one of the opposite surfaces of said generator for bonding said backing element to said one face,
a solid transforming member formed to include at its opposite ends a pair of substantially circular parallel disks coaxial with said ultrasonic generator each having a diameter slightly exceeding the diameter of said generator, said disks spaced apart along the axis thereof by a connecting portion symmetrical about the said axis and declining therebetween to a minimum diameter not exceeding about one-third the diameter of said disks,
one of said disks being bonded in acoustical transfer relation to the other face of said generator, and the other said disk being free to function as an ultrasonic radiator.

2. The combination in accordance with claim 1 wherein the flat major surfaces of said cylindrical backing element and of said solid transforming member each have engraved thereon a series of concentric grooves,
and said bonding means includes an epoxy cement interposed between said grooves in the one face of said backing element and one of the outer surface of said piezoelectric generator,
and means including an epoxy cement interposed between said grooves in the major face of said transforming member and the outer surface of said piezoelectric generator.

3. The combination in accordance with claim 2 wherein said electrode means interposed between the major surfaces of said generator wafers and on the external surfaces thereof comprises electrically conducting epoxy.

4. The combination in accordance with claim 2 wherein the axial length of said transducer assembly from a plane bisecting the thickness of said radiator plate to the other end surface of said backing element approximates an integral number of quarter-wavelengths in the principal vibrating frequency of said transducer, and wherein the diameter of said disks approximates a half-wavelength in said vibrating frequency.

5. The combination in accordance with claim 2 wherein the ratio between the mass of said backing element and the mass of said transforming member including said radiator plate is at least about 1:1.

6. The combination in accordance with claim 1 wherein said transducer assembly is enclosed in a tubu-

lar inner housing, the end of the cavity of said housing containing the backing element of said asembly being partially closed by a plug having a central bore for accommodating a pair of energizing leads connected across terminals on the electrode means of said ultrasonic generator,

said end plug terminating in an annular flange,

an externally screw-threaded hollow cylindrical outer housing having an enlarged cylindrical inner chamber constructed to accommodate the flanged end of said tubular inner housing,

means comprising a series of o-rings of elastomer material constructed to fit between said tubular inner housing and the inner chamber of said outer housing for acoustically isolating said innner housing from said outer housing,

said outer housing having a coaxially disposed extension,

an electrical coaxial connector containing a solid insulating shell between a pair of conductors comprising a central conductor and an outer coaxial shell accommodated in the extension of said housing, said outer shell being in electrical contact with the said external housing,

means for connecting one of the electrode terminals of said ultrasonic generator to the said central conductor,

and means for providing an electrical conducting path between the other electrode terminal of said ultrasonic generator and said external housing.

7. the combination in accordance with claim **6** wherein said means for providing an electrical conducting path between the other electrode terminal of said ultrasonic generator and said external housing comprises a conducting strap interposed therebetween.

8. The combination in accordance with claim **6** wherein said means for providing an electrical conducting path between the other electrode terminal of said ultrasonic generator and said external housing includes conducting material interposed into said o-rings.

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