

Oct. 16, 1962

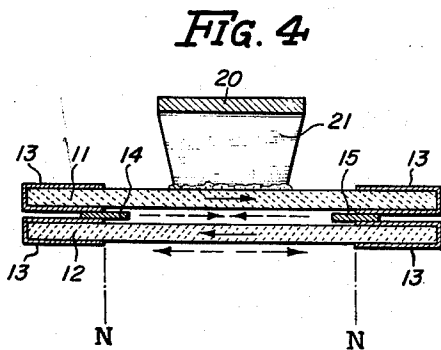
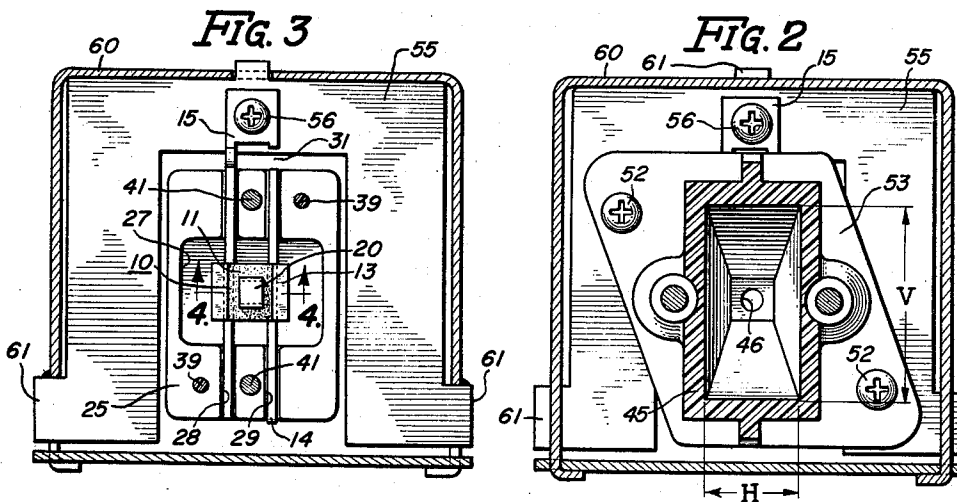
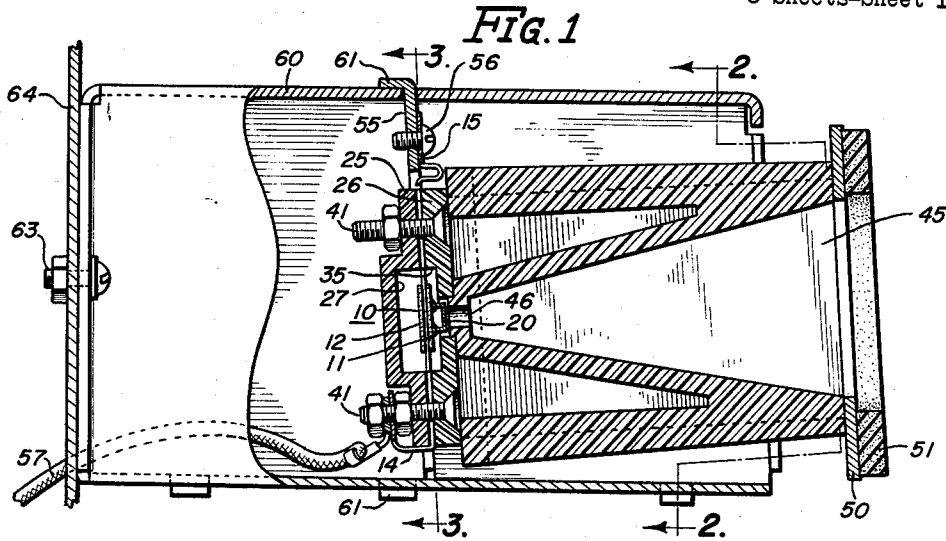
R. ADLER

3,058,539

TRANSDUCER WITH IMPEDANCE-MATCHING BRIDGE

Filed May 15, 1958

3 Sheets-Sheet 1



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TRANSDUCER WITH IMPEDANCE-MATCHING BRIDGE

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3 Sheets-Sheet 3

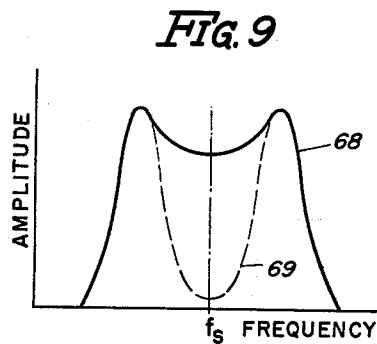
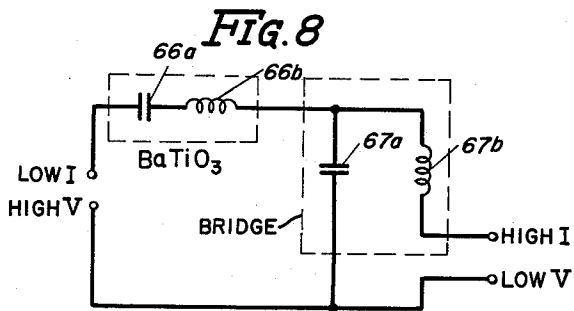


FIG. 11a

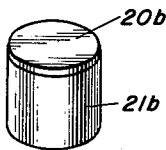


FIG. 12a

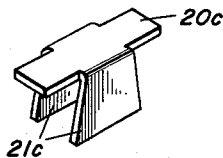


FIG. 13a

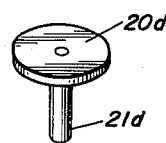


FIG. 11b

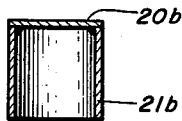


FIG. 12b

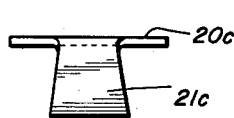


FIG. 13b

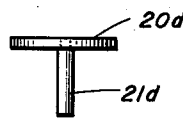
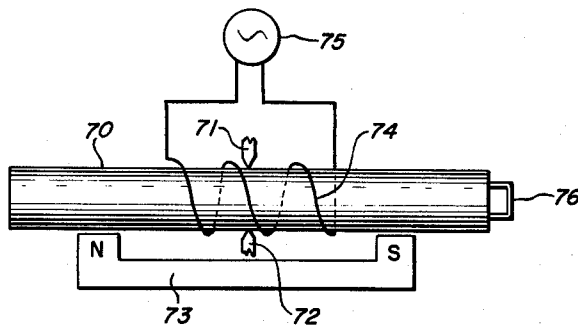


FIG. 14



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3,058,539

TRANSDUCER WITH IMPEDANCE-MATCHING BRIDGE

Robert Adler, Northfield, Ill., assignor to Zenith Radio Corporation, a corporation of Delaware
Filed May 15, 1958, Ser. No. 735,548
18 Claims. (Cl. 181—5)

This invention relates to electromechanical transducers in general and is particularly concerned with the construction of an improved transducer arrangement for effecting energy transfer to or from a wave-propagating medium which exhibits a materially different impedance at a given signal frequency than the mechanical impedance of the transducer itself.

Transducers of the type under consideration are frequently employed for the purpose of transferring signal energy from air or other wave-propagating medium to a wave signal receiver, but because of the reciprocal properties of wave signal reception and transmission, the teachings hereof may be advantageously applied to transmitting as well as to receiving systems. The invention is especially suited for use in remote control systems wherein a controlled or satellite station executes any of several controlled functions depending upon the frequency of command signals transmitted by a controlling station and, for convenience of illustration, the ensuing detailed description will be directed to a microphone and transmitter for that application.

A very successful remote control system featuring the use of a multiplicity of command signals, distinguished from one another by the frequency of the transmitted energy, is the subject of U.S. Letters Patent 2,817,025, issued on December 17, 1957 in the name of Robert Adler and assigned to the same assignee as the present invention. As there described, the controlled device is a television receiver in which the functions of on-off switching, channel selection and sound muting are accomplished through remote control. Channel selection is achieved by appropriate energization of a bi-directional motor which drives a turret-type tuner in either clockwise or counter-clockwise direction. That arrangement requires four different command signals, two to permit control of the tuning motor in both directions and one each for the on-off and sound muting. These commands take the form of bursts or pulses of acoustical energy transmitted upon the actuation of ultrasonic radiators contained within a compact, lightweight and portable transmitting unit. Each sonic radiator is a longitudinal-mode passive vibrator, for example, an aluminum rod supported at a centrally located nodal point and a striker for impinging against the free end of the rod. Since four signals are required, the transmitter includes four such rods and the length of each, in combination with the velocity of signal propagation therein, determines the signal frequency.

It is necessary that the controlled receiver be as insensitive to false actuation as practicable or, expressed in other words, it must be relatively free from actuation in response to interference and spurious signals that may be encountered in the vicinity of the controlled receiver. To that end, the controlled station has a narrow acceptance band and is thus able to reject, on the basis of frequency discrimination, interfering signals which do not fall within its acceptance band. By way of illustration, the command signals may be included in the frequency range from 38 to 42 kilocycles and the controlled device only responds to this small band of frequencies.

In the Adler patent, further frequency selectivity within this restricted band is achieved by the use of frequency-discriminator circuits to which command signals are applied by a sonic receiver, specifically, a microphone of

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the electrostatic type. An electrostatic microphone of improved construction particularly valuable for use as a sonic receiver in such a system is described and claimed in a copending application of Robert Adler, Serial No. 661,348 filed May 24, 1957 now Patent No. 2,908,772 and likewise assigned to the same assignee as the present invention. It is distinguished from commercially available electrostatic microphones by its high sensitivity in the above-mentioned frequency range in the vicinity of 40 kilocycles and it has a bandwidth of 8 kilocycles; however, it would be desirable to employ a piezoelectric microphone as the sonic receiver because of its potentially greater sensitivity, because its bandwidth may be conveniently confined to narrow limits and because it lends itself more conveniently to utilization with transistor amplifiers to which the sonic receiver may be coupled.

Prior attempts to adapt piezoelectric microphones to this application have not attained adequate efficiency nor have they realized the potential of that type microphone, primarily because of the difficulty of effecting a satisfactory impedance-matching relation between air and the piezoelectric device, which has a very high mechanical impedance relative to that of air. By "mechanical impedance" is meant the quotient of force divided by velocity in a vibratory system, in complete analogy with the definition of electrical impedance as the quotient of voltage divided by current in an electrical circuit. It has been proposed, for example, that a piezoelectric element made from a material such as barium titanate be polarized transversely in two adjacent semi-circular portions which are connected in series. Such a microphone, if used without a tuning inductance to tune out the capacitance which is represents, has a sharp frequency response, exhibiting high sensitivity at the frequency of mechanical resonance but having a rapidly decreasing sensitivity at all other frequencies. If the capacitance of the microphone is tuned out by means of a tuning inductance, a response characteristic results which is of the double-peaked or saddle-shaped variety associated with a coupled pair of tuned circuits having the same frequency of resonance. That characteristic may be shaped and made fairly flat through the expedient of electrical damping. This approach to the microphone problem has not proved out well; the inductance required for tuning is very large and costly and must be carefully shielded, which adds further to the cost. The sensitivity of this device is not sufficiently higher than that realized with an electrostatic microphone of the type described in the afore-identified application to warrant the increased expense.

Accordingly, it is an object of the present invention to provide an electromechanical transducer, such as a piezoelectric microphone, which avoids the disadvantages of prior structures and has enhanced sensitivity.

It is another object of the invention to provide an improved electromechanical transducer in which an auxiliary mechanical resonator, having an impedance intermediate that of the principal transducing device and the medium in respect of which signal energy is to be transferred, greatly enhances the signal-transferring properties of the arrangement.

It is a particular object of the invention to provide a piezoelectric microphone of greatly improved efficiency attained through improved mechanical impedance matching between the microphone and the medium, such as air, to which it is coupled.

It is a specific object of the invention to provide an improved structure for efficiently coupling or matching an electromechanical transducer to a wave-propagating medium having an impedance very much different than the mechanical impedance of the transducer itself.

Another specific object of the invention is to provide a microphone, including a piezoelectric element, suitable for convenient utilization with an amplifying stage employing either vacuum tube or transistor amplifying devices.

Still another specific object of the invention is to provide a piezoelectric ceramic microphone having greatly improved sensitivity throughout a well-defined pass band.

An electromechanical transducer arrangement, constructed in accordance with the invention, is especially suited for effecting transfer of energy with respect to a medium, such as air, which has a predetermined impedance at a given signal frequency. The arrangement comprises a transducer element having a frequency of mechanical resonance approximately equal to the signal frequency and having a mechanical impedance at that frequency which is high relative to the impedance of the aforesaid medium. The arrangement further includes a resonant, mechanical impedance-transformation device supported for vibration in a flexural mode for coupling the transducer to the medium. The mechanical device has an impedance at the signal frequency intermediate that of the transducer and the medium; it has a frequency of mechanical resonance corresponding to that of the transducer, and it is mechanically connected thereto to constitute therewith a mechanical impedance transformer which is the analogue of an electrical impedance transformer for converting between parallel and series resonant impedance relations in a resonant circuit.

The teachings of the invention have general application to transducer arrangements of the type in which the impedance of the transducer element is high in comparison with the impedance of air or other medium with respect to which a transfer of signal energy is desired. Accordingly, the inventive concept may be advantageously employed where the transducer is an electromagnetic or electrodynamic device, a piezoelectric element, a longitudinal-mode vibrator such as an aluminum rod or even a magnetostrictive device. All such transducers as normally constructed are too heavy, that is to say represent too high an impedance, to be matched efficiently to air except for particular frequency ranges which generally vary with the type transducer. The difficulty of bridging the dissimilar impedances of such devices and air is obviated through the present invention which contemplates the use of an auxiliary mechanical resonator as an impedance-matching device functioning in a manner analogous to an electrical resonant circuit which acts as a transformer converting between parallel and series resonant impedance relations. In the descriptive material to follow, detailed consideration is given to the application of this principle to a piezoelectric microphone and to a sonic transmitter of the magnetostrictive type.

In both these applications, it is convenient and effective to employ a bridge element as the auxiliary resonator. The bridge is formed of a thin strip of metal, such as aluminum, proportioned to have the same frequency of mechanical resonance as the transducing device which it is to couple to air. While this is a particularly satisfactory form of resonator to employ, a variety of other shapes of resonator devices is available and certain of them are also discussed in the detailed description and illustrated in the drawings.

The features of the present invention which are believed to be novel are set forth with particularity in the appended claims. The organization and manner of operation of the invention, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with the accompanying drawings, in the several figures of which like reference numerals identify like elements, and in which:

FIGURE 1 is a view, in vertical section, of a microphone assembly embodying the present invention;

FIGURES 2 and 3 are additional views taken as indicated by section lines 2—2 and 3—3 in FIGURE 1;

FIGURE 4 is an enlarged sectional view of the piezoelectric element taken as indicated by section line 4—4 in FIGURE 3;

FIGURE 5 is an exploded perspective view revealing component details of the microphone assembly;

FIGURE 6 is an enlarged fragmentary cross-sectional view of the central region of FIGURE 1;

FIGURE 7 is a view similar to FIGURE 6 but with a modification of one of the parts;

FIGURE 8 is a schematic circuit diagram of the electrical analogue of the microphone assembly;

FIGURE 9 illustrates the frequency response characteristic of the microphone;

FIGURE 10 represents a modification of the microphone structure;

FIGURES 11a—b, 12a—b and 13a—b are enlarged views of different shapes of auxiliary resonators that may be used for impedance matching; and

FIGURE 14 is a schematic representation of a magnetostrictive transducer embodying the invention.

Referring now more particularly to the drawings, especially FIGURE 1, the electromechanical transducing arrangement there represented is a device for effecting the transfer of energy with respect to a medium which propagates a signal wave of a given frequency and which exhibits a known impedance at that frequency. As indicated above, detailed consideration is to be given to a microphone for receiving ultrasonic energy radiated from a transmitter and propagated to the receiver through air. Air, as any wave signal propagating medium, has a characteristic impedance at sonic frequencies which may be defined as the quotient of the pressure by the particle velocity in the sound wave. Stated more fully, characteristic impedance is the ratio of force to velocity of volume flow in a distributed medium capable of propagating sound, particularly in air. By referring both force and velocity to a common unit of cross-sectional area, characteristic impedance may also be defined as the ratio of sound pressure to the amount of volume flowing through one unit of area per unit time. Since this latter amount is equal to the particle velocity, characteristic impedance is also equal to the quotient of the pressure divided by the particle velocity, as stated initially. The great difficulty encountered in achieving a piezoelectric ceramic microphone of high sensitivity is in effecting a good impedance match between the piezoelectric element and the air in spite of the fact that the mechanical impedance of the ceramic element is very much higher than the impedance of air at the signal frequency. Air is a very light medium, is easy to move and experiences a large displacement in response to a relatively small moving force, whereas a piezoelectric transducer is very hard to move and is a heavy device compared with air. It yields but little and experiences only a small displacement in response to the application of a relatively high moving force.

A salient feature of the invention is a structure which, in effect, bridges such dissimilar impedances to attain an efficient coupling therebetween. This is accomplished through the agency of an auxiliary mechanical device which is itself heavier than air and yet lighter than the piezoelectric element. The matching structure is further characterized by a frequency of mechanical resonance matching that of the piezoelectric element and it is connected to that element to define with it a mechanical structure which is the full equivalent of an electrical impedance transformation network converting between series and parallel impedance in a resonant circuit.

More specifically, the microphone structure of the embodiment of the invention under consideration comprises a dimorphic piezoelectric element 10.

A dimorphic piezoelectric device is one which has at least two piezoelectric wafers or components having such

relative polarization and electrical coupling through their electrode structures that the electrical signals developed, in response to bending, are additively related. As detailed in FIGURES 4 and 6, the dimorph is made up of two wafers 11, 12 of a material having a high electromechanical coupling factor in order to provide a high efficiency of energy transfer between the electrical and mechanical actions. The class of materials known as titanates is particularly suited for use in the wafers. Such compositions as barium titanate and barium strontium titanate are frequently employed. The wafers are rectangular in shape and have silvered surfaces 13, 13 extending along the upper and lower margins in the width dimension, these surfaces also preferably having an interconnecting portion extending in the thickness direction. The silver may be applied through a silkscreen process and fired in situ to bond it to the wafer. The silvered surfaces are the electrodes through which a unidirectional polarizing potential is applied to the wafer for the purpose of establishing a permanent polarization in a given direction, in the longitudinal mode for the structure shown in the drawing.

After the wafer pair have been polarized, they are assembled in the relative orientation shown in FIGURES 4 and 6, namely, with opposed directions of polarization indicated by the full-line arrows in FIGURE 4. Thin flexible electrode leads 14 and 15 are interposed at the approximate locations of the nodal axes assuming the dimorph to be supported for vibration in the lowest flexural mode. The locations of the nodes are designated by the broken construction lines N—N; they are spaced approximately 22½% of the full length of the wafers from the edges of the wafers. The leads are formed of coined silver and are bonded to the contiguous silvered surfaces through a conductive cement in a pressing operation which integrates the sandwich or dimorph assembly. It is not essential that there be conductive connections between leads 14, 15 and the adjacent silvered surfaces, but best efficiency results if such connections are established.

Leads 14, 15 serve to support the dimorph from a mounting structure to be described presently and have the advantage of relieving the requirement that the supports be precisely located at the nodal points. The dimorph has its least displacement or movement at the nodal points so that if it is supported at such points the support contributes the least amount of detuning and damping. Thin flexible support leads accommodate the bending forces encountered if the supports are not, in fact, precisely located with respect to the flexural nodes.

The active portion of the dimorph is that included between the silvered surfaces or between broken construction lines N—N and it is not necessary to polarize the remaining edge portions of the wafers. The assembled dimorph is dimensioned to have a frequency of fundamental flexural resonance equal to a reference signal frequency and adjustment as to frequency of mechanical resonance is achieved by grinding. In some constructions, opposed external broad surfaces are subjected to grinding in order to arrive at the desired frequency which, of course, removes the silvered coating 13. A more expedient adjustment as to frequency is obtained by edge grinding of the dimorph. This, too, tends to remove a portion of the silvering but only that which is on the edge of the wafers and this is not significant or important.

A mechanical impedance transformation device is employed for coupling the dimorph to air, that is to say, for effecting an efficient impedance match between the dimorph and air. It is an auxiliary resonator having an impedance at the signal frequency between that of dimorph 10 and air and may be constructed in any of a variety of shapes. In a preferred embodiment, the resonator is a bridge member formed of a thin strip of metal, such as aluminum, of U-shape shown in detail in FIGURES 4 and 6. It has a bight portion 20 and legs 21, 21 normal to portion 20. The legs, which are secured to the surface

of the dimorph as presently to be described, support portion 20 at each end permitting it to vibrate in a flexural mode and section 20 is proportioned to have a frequency of mechanical resonance corresponding to the frequency of mechanical resonance of the dimorph.

The bridge is mechanically connected to the dimorph in such a manner as to constitute therewith a mechanical impedance transformer which is an analogue of an electrical resonant circuit transforming between parallel and series impedance relations in a resonant circuit, as mentioned hereinabove. The mechanical connection is effected through legs 21, 21. If desired, terminal portions 21a of the legs may be bent to constitute supporting shoes for the bridge as indicated in FIGURE 7. Structures of this type have been employed with the connection to the dimorph established by cementing the shoes to the upper surface. It is found, however, that there is a tendency toward instability if the assembling process is not carefully carried out because cement may seep between the shoe and the dimorph. To avoid this possibility, the free ends of the legs are cemented to the dimorph in the manner of FIGURE 6.

It is preferred to orient the dimorph and the bridge to arrive at a mechanical structure which provides a high ratio of impedance transformation. Specifically, the loop or anti-node of the dimorph is parallel to the construction lines N—N of FIGURE 4 and the orientation of the bridge is chosen so that its loop or anti-node is normal or perpendicular to that of the dimorph. With reference to FIGURE 4, the anti-node of the bridge is in a plane parallel to the plane of the drawing. The anti-node of the dimorph is centered between nodal points N—N and therefore the lowest mechanical impedance is encountered if the bending force is applied thereto. Accordingly, the legs 21 of the bridge are affixed to the dimorph in this region. In theory, legs 21 of the bridge should be tapered to provide point contacts at the anti-node point but this would result in a mechanically-weak structure. On the other hand, a line contact between the legs of the bridge and the dimorph would tend to stiffen the dimorph in this region which is normally subject to maximum bending and it is preferred to avoid unnecessary stiffening. Consequently, legs 21 are tapered in the manner represented in FIGURE 4 to achieve a mechanically-strong union between the bridge and the dimorph consistent with minimum stiffening of the dimorph resulting from the mechanical junction. Preferably, the bridge structure is centered with respect to the anti-node, that is, with respect to the central region of maximum bending or displacement of the dimorph.

The dimorph and bridge assembly is housed within a mounting structure comprising a base 25 and a cap 26, both formed of an insulating material such as polystyrene. While the assembled mount appears in cross-section with FIGURE 1, the details of its principal components are more clearly revealed in FIGURE 5 wherein it appears that base 25 has a centrally-located recessed area 27. It also has a pair of parallel, longitudinally extending slots 28, 28 and 29, 29 leading from opposite sides of recess 27. These slots are dimensioned to receive the electrode leads.

The detail of FIGURE 5 shows that leads 14, 15 collectively define a generally rectangular frame to which the dimorph-bridge assembly is centrally affixed. Each side of this frame is cut as indicated at points 30, 31 so that the electrodes are not conductively connected to one another after the structure is assembled. Actually, a complete and continuous framework is provided by elements 14, 15 during the fabrication of the dimorph to facilitate precise assembly, but as soon as this is finished the frame is broken at points 30, 31.

Cap 26 has a central recess 35 which, in conjunction with recess 27 of base 25, defines a cavity for receiving the dimorph-bridge assembly with the bridge positioned within a close-fitting window 36 cut out of the center por-

tion of recess 35. A pair of ribs 37, 37 and 38, 38 project from the inner surface of cap 26 to be received within slots 28, 28 and 29, 29 of the base to complete a clamping engagement of electrode leads 14, 15. In this fashion, the dimorph and bridge assembly is mechanically supported for vibration in a flexural mode. Dowel pins 39, 39 project from the inner face of base 25 and are received in apertures 40, 40 of the cap to facilitate assembling the housing structure. A pair of screws 41, 41 feed through aligned apertures in both parts 25, 26 of the mounting structure and nuts 42, 42 drawn up on the screws lock the structure into an integrated assembly.

The bight portion 20 of the bridge has a smaller surface area than the parallel surface of the dimorph. More significantly, it is small compared with the wavelength in air at the signal frequency and is coupled to air through a tapered horn 45 shown in FIGURES 1, 2 and 5. The dimensions of the mouth of the horn are selected in accordance with the requirements of the signalling system in which the microphone is to be employed. It has been assumed that the microphone under consideration is intended for use in a remote control system of the type described in aforesaid Patent No. 2,817,025 for controlling certain operating conditions of a television receiver. The larger the mouth dimensions of the horn, the more signal energy it intercepts but, at the same time, the more directional it becomes. In the environment in which the microphone is to be employed, only a small directivity can be tolerated in a horizontal direction because the remote control transmitter should be effective over as wide an angle with respect to the mouth of the horn as possible. Much greater directivity can be accommodated in a vertical direction because there will be only a few instances in which the transmitter will have any considerable elevation with respect to the microphone. An acceptable compromise of directivity with respect to the quantity of energy intercepted is achieved by a dimension H of one wavelength in the horizontal direction and a dimension V of two wavelengths in the vertical direction, as represented in FIGURE 2. The throat dimensions of the horn are selected to fit closely about bridge 20. The length is chosen with relation to a limiting angle at which incident sound would be reflected out of the horn. The steepness of the horn is made less than the angle at which any such reflection is encountered. The horn is shown with a straight taper, but other types of taper such as an exponential taper may be used.

The throat of the horn communicates with bight 20 of the bridge through an acoustical impedance-matching section 46 which is a tubular space having a length of one-quarter wavelength at the signal frequency. FIGURE 6 includes an enlarged showing of quarter-wave section 46 which is seen to have a terminal portion projecting into window 36 of cap 26. The horn may also be formed of an insulating material such as polystyrene and its mechanical elements, aside from those which collectively define the horn and quarter-wave terminating section, are provided for the purpose of increasing the mechanical strength of the structure. A flange plate 50 mechanically secured to the mouth of the horn bears a cushion 51 of sponge rubber material serving as a bumper to protect the structure when in position on a control chassis with the mouth of the horn in juxtaposed relation to a sound opening through which sonic command signals make their way to the microphone.

The horn and flange assembly is integrated with the dimorph housing by a pair of machine screws 52, 52 extending through a pedestal 53 formed integrally with the horn. The mounting screws extend through holes 54, 54 located in flange projections of cap 26 and thread into tapped holes provided in a metallic supporting plate 55. Dowel pins 48, 48 extending from base plate 53 are received by apertures 49, 49 in cap 26, and facilitate assembling the horn to mounting structure 25, 26. Plate 55 constitutes an electrical ground plane and electrode lead

15 of the dimorph is grounded thereto by a machine screw 56. The other electrode lead 14 threads over machine screw 41 serving as a terminal post to which an output lead 57 connects, as illustrated in FIGURE 1. Obviously the pictorial view of FIGURE 5 has been selected to reveal the details of the structure and should not be taken to mean a curvilinear structure. Reference to the assembly view of FIGURE 1 makes clear the fact that this is a linear structure.

10 The entire assembly is enclosed within shield receptacle 60, mounting plate 55 being mechanically secured thereto by means of tabs 61 projecting from the plate and extending through slots in the casing. The tabs may be soldered to the casing or bent over to lock the confined assembly in position. A machine screw and nut assembly 63 extending through an end plate of receptacle 60 and receiver chassis 64 facilitates mounting the structure in operating position.

20 In the operation of the described microphone, an ultrasonic radiated signal reaching horn 45 is channeled through the quarter-wave impedance-matching section 46 to impinge upon bight portion 20 of the metal bridge. The received sonic signal constitutes a small force applied to the resonant section of the bridge to set it into flexural-mode vibration. The small force applied at the center of the bridge produces a displacement there of large amplitude and results in a much larger force appearing at the supports of the resonant section, namely, at legs 21, 21. The large force developed at support points 21, 21 is applied to the center of the dimorph and results in displacement or bending of the dimorph. This displacement is of much smaller amplitude than that experienced by the bridge in view of the high mechanical impedance of the dimorph but, nonetheless, establishes flexural-mode vibrations therein. The mechanical bending action, through piezoelectric conversion, results in electrical signals appearing on electrode leads 14, 15. While lead 15 is maintained at ground potential, the variations in potential of lead 14 represent the received signal and may be applied over conductor 57 to an amplifier.

30 The described mechanical impedance transformation from a condition of large amplitude displacement and low driving force acting upon bridge 20 to a condition of low amplitude displacement and high driving force acting upon the dimorph is analogous to the electrical transformation achieved with the electrical analogue represented in FIGURE 8. The electrical analogues of the resonant bridge and dimorph are indicated in broken-line boxes with the legends "Bridge" and "BaTiO₃." Dimorphy 10 has as its electrical equivalent the series combination of a capacitor 66a and an inductor 66b, and bridge 20 has as its electrical equivalent the parallel combination of a capacitor 67a and an inductor 67b. The entire equivalent network takes the form of the parallel combination of capacitor 67a and inductor 67b with the input terminals being in series with inductor 67b, that parallel combination being in turn paralleled by the series combination of capacitor 66a, inductor 66b and the output terminals. The indicated high current and low voltage at the input terminals with the reverse at the output terminals are the analogue of the mechanical relationships present in the apparatus herein disclosed, current corresponding to velocity and voltage to force.

40 Since the dimorph and the bridge have the same frequency of mechanical resonance, they establish for the transducer a frequency response curve 68 of the type represented in FIGURE 9. It is peaked at two frequencies equally spaced from the signal frequency f_s and is analogous to the double-peaked or saddle-shaped characteristic of two coupled electrical circuits resonant at the same signal frequency. Were the microphone operated in air at reduced pressure, the response characteristic in the region between the peak responses would be generally as indicated in broken-construction line 69. Specifically, the response would consist of two very

sharp peaks with little, if any, amplitude therebetween. That reduction in response would be occasioned by the fact that the structure has no inherent damping. However, the response may be shaped by loading either or both of the resonant bodies. It is possible, by means of mechanical and/or electrical loading, to, in effect, fill in the saddle or shape the characteristic to achieve a substantially flat response throughout the bandwidth of the microphone. More particularly, damping may be achieved by mechanically loading the bridge or by electrically loading the dimorph. In the arrangement specifically illustrated, air resistance effects mechanical loading of the bridge to attain a more nearly uniform response over the acceptance band of the microphone.

By way of summary, bridge 20 performs two important functions which contribute to the outstanding properties of the microphone: (1) it serves as an impedance transformer between the dimorph and air which have materially different mechanical impedances or, expressed in other words, it is a mechanism for efficiently coupling the dimorph to air; and (2) in conjunction with the mechanical resonant properties of the dimorph, it establishes a response characteristic which is the analogue of two coupled tuned circuits having a common resonance frequency. The band-pass of the device may be controlled by adjustment of the ratio of mass to stiffness of the two mechanically resonant bodies.

In one embodiment of the microphone constructed and successfully operated, the dimorph and bridge had the following dimensions and properties:

Piezoelectric elements 11 and 12...	wafers of longitudinally polarized barium titanate, .310 inch long by .250 inch wide and .010 inch thick.
Frequency of mechanical resonance	40 kilocycles.
Bridge 20	4 mils aluminum.
Bight portion	.100 by .119 inch.
Legs	70 mils high, width tapered from 100 to 70 mils.
Frequency of mechanical resonance	40 kilocycles.
Frequency separation of peaks of response curve	5.3 kilocycles.
Sensitivity between peaks	-44 to -45 decibels below 1 volt per dyne/cm. ² .

The microphone represented a capacitance of approximately 16 micromicrofarads and was employed to drive a pentode amplifier for which the input electrode capacitance and associated stray capacitance was approximately 15 micromicrofarads.

As suggested above, the dimorph may be loaded electrically to enhance the mechanical damping produced by the air. Where electrical loading is to be employed, the capacitance represented by the microphone is first tuned out by a tuning inductance or coil and then any suitable amount of resistance damping applied. Damping of this type is not necessary, and is not resorted to when coupling the microphone to a vacuum tube amplifier but it is employed when working the microphone into a transistor amplifier in view of the low input impedance of this type of amplifier. In arranging the microphone to drive a transistor amplifier, it is preferred to use transverse rather than longitudinal-mode polarization of the dimorph because this increases the capacitance represented by the microphone, reduces the amount of tuning inductance required and makes it easier to attain a suitable measure of electrical damping from the input resistance of the amplifier.

Another mode of polarization which may be used in certain constructions is the so-called reverse alternate mode described and claimed in patent Re. 23,813, reissued on April 20, 1954 in the name of Robert Adler and assigned to the same assignee as the present invention. Where that type of polarization is to be used, wafer 11 could, for example, be considered to have two sections, one being the portion of the wafer from the center line

to the silvered strip on the left-hand side and the other being the portion from the center line to the silvered surface on the opposite side. Polarization of those two sections would be toward one another, as indicated by the broken-construction arrows in FIGURE 4, and a silver strip along the center line would provide one terminal. The corresponding sections of wafer 12 are polarized oppositely or away from one another, also as indicated by broken-construction arrows in FIGURE 4, and its silvered surfaces 13, 13 would be interconnected to provide another terminal.

A modified form of microphone is represented in FIGURE 10, differing from that already described in the use of two bridges 20 and 20'. They may be individually constructed as the bridge arrangement of FIGURE 1 and are positioned side-by-side along the central region of maximum bending of the dimorph. This structure is useful to attain increased driving force for the dimorph and may be used for dimorphs made of certain compositions which result in stiffer and/or heavier piezoelectric elements than those made of barium titanate.

Other forms of matching resonators, simple in structure and comparatively inexpensive to fabricate but at the same time entirely suited for substitution in place of resonator 20, 21 are shown in FIGURES 11, 12 and 13. In each of these figures, the view having the subscript "a" is a perspective view and the view having the subscript "b" is an elevation. The resonator of FIGURE 11 is a hollow cylinder open at one end and closed at its opposite end by a flexible membrane 20b which may be made of sheet aluminum. In the use of this resonator, the open end of the cylinder is affixed to dimorph 11, 12 in the manner described with respect to the legs 21 of the bridge of FIGURE 1, cylinder wall 21b corresponding to legs 21 and membrane 20b corresponding to bight 20. The mounting arrangement would be essentially the same as that heretofore described, both as to mechanical affixation and space relation relative to the loop or anti-node of the dimorph.

The modification of FIGURE 12 is a T-shaped structure with a horizontal member 20c supported by a pair of tapered legs 21c. It is easily fabricated by punching a suitably shaped section from sheet metal and subsequently forming a T by bending. This resonator may also be directly substituted for the bridge of FIGURE 1 with member 20c corresponding to bight 20 and legs 21c corresponding to legs 21. It may be considered as two cantilevers having a common mounting point and, in use as a resonator, experiences vibration in a fundamental flexural mode. If one visualizes this structure bisected through the legs, each half constitutes an inverted L, or a resonator having a single cantilever. This, too, may be used in place of auxiliary resonator 20, 21 of FIGURE 1.

The resonator structure of FIGURE 13 is in the form of a disc 20d which is center clamped to a mounting element 21d through which the disc may be supported to a transducer. In this case, the resonator employs flexural-mode resonance of the disc 20d which corresponds to bight 20 with element 21d corresponding to legs 21.

It will be understood that each of the several forms of resonators represented in FIGURES 11-13, inclusive, has an impedance at the signal frequency which is intermediate that of the transducer and air. Further, each such resonator is constructed to have a frequency of mechanical resonance corresponding to that of the transducer and, therefore, each operates in generally the same way as bridge 20, 21 of FIGURE 1 in bridging the impedance dissimilarities of the dimorph and air to attain efficient coupling therebetween. The analogy of an electrical impedance transformer converting between series and parallel resonance relations, described in connection with FIGURE 1, is equally applicable to these several embodiments if they are mechanically connected to the dimorph in generally the same manner as bridge 20, 21.

All of the matching or auxiliary resonators described employ resonance of the flexural-type which, while not a necessary limitation of the structure, is adopted because resonators of the flexural type may be constructed to have lower impedance values than resonators of the longitudinal type. Additionally, flexural-mode devices are especially desirable where the dimensions of the transducer assembly are to be kept small.

As mentioned above, the concepts of this invention for achieving a greatly improved impedance match between a transducing device that has a much higher impedance than air, or whatever the wave-signal propagating medium may be to which it is to be coupled, are applicable to a variety of transducers, and the embodiment of FIGURE 14 represents schematically the application of a transducer of the magnetostrictive type.

The transducer of this embodiment comprises a longitudinal-mode resonator 70 in the form of an elongated rod of magnetostrictive material such as ferrite, nickel, or nickel/iron alloy having strong magnetostrictive properties. It is supported mechanically in the vicinity of its longitudinal center as indicated schematically at 71, 72. The resonant frequency of the rod is a function of its length and is selected to the end that the frequency of mechanical resonance is approximately equal to the desired signal frequency. The rod is subjected to a magnetic biasing field which may be established by an electromagnet or by a permanent magnet, a permanent magnet 73 being represented for convenience of illustration. An excitation coil 74 encircles the central region of the magnetostrictive rod to establish mechanical vibrations therein in response to an excitation signal supplied from a source 75.

Since rod 70 is a longitudinal-mode resonator, the auxiliary resonator, in the form of a bridge 76 similar to bridge 20, 21 in the embodiment of FIGURE 1, is affixed at a free end of the resonator for the purpose of improving its impedance match with air. The described arrangement lends itself particularly well to use as a sound transmitter, radiating a sonic signal corresponding to the mechanical resonant frequency of the rod. A signal of like frequency is applied to exciting coil 74 by generator 75 and the flux variations which it establishes are converted into mechanical stress waves which set the rod into longitudinal vibration. This results in the radiation of a sonic signal and the bridge 76 provides efficient coupling of the transmitter to air with a desired increase in the amount of radiated sound per milliwatt of electrical input.

Generally, such a magnetostrictive transmitter is highly selective in frequency but the auxiliary resonator 76 permits it to operate efficiently over a predetermined bandwidth, in addition to increasing its coupling efficiency to air. The device is effective over a band of frequencies for essentially the same reasons described in the discussion of the frequency characteristic of FIGURE 9 since the arrangement of FIGURE 14, instead of having a single resonant element characteristic of the usual magnetostrictive transmitter, has two resonant elements. One is the rod and the other is bridge 76. These structures have the same frequency of mechanical resonance and, being mutually coupled, introduce a saddle-type frequency response characteristic. The loading imposed on the bridge by the radiation resistance of air fills in the saddle, so to speak, and causes the transmitter to be effective over a band of frequencies. In other words, the structure may be likened to a properly terminated mechanical bandpass filter.

Electromechanical transducers embodying the invention, whether employed for purposes of reception as discussed in connection with the embodiment of FIGURE 1, or for transmission as with the arrangement of FIGURE 14, are exceedingly efficient devices as contrasted with predecessor arrangements. They exhibit unusually high sensitivity over a desirable band of frequencies and achieve

this result through the use of structures that are relatively simple. In particular, the auxiliary matching resonator increases the coupling efficiency of transducer elements which are otherwise difficult to couple to air because of their high impedance compared with the impedance of air. The resonator, in addition to providing a vast improvement in coupling efficiency, also imposes a desired frequency response, permitting even a longitudinal-mode vibrator, which is normally quite restricted in frequency response, to be effective over a band of frequencies. Moreover, and with particular reference to a transducer of the piezoelectric ceramic type, the auxiliary resonator enhances the flexibility in that the resulting structure is suited for driving either a vacuum tube or a transistor amplifier.

While particular embodiments of the invention have been shown and described, it will be obvious to those skilled in the art that changes and modifications may be made without departing from the invention in its broader aspects, and, therefore, the aim in the appended claims is to cover all such changes and modifications as fall within the true spirit and scope of the invention.

I claim:

1. An arrangement for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: an electromechanical transducer having a vibratory frequency of mechanical resonance approximately equal to said signal frequency and a mechanical impedance at said signal frequency which is high relative to the impedance of said medium; a mechanical impedance-transformation device coupling said transducer to said medium and comprising a flexural-mode mechanically-resonant vibrator element coupled to said medium and having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of flexural-mode mechanical resonance corresponding to that of said transducer; and means mechanically connecting said vibrator element only to said transducer to translate energy therebetween so that said device and said transducer constitute a mechanical impedance transformer which is the analogue of an electrical impedance transformer converting between parallel and series resonant impedance relationships.

2. An arrangement for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: an electromechanical transducer vibratory in a flexural mode with a frequency of mechanical resonance approximately equal to said signal frequency and a mechanical impedance at said signal frequency which is high relative to the impedance of said medium; a mechanical impedance-transformation device coupling said transducer to said medium and comprising a flexural-mode mechanically-resonant vibrator element coupled to said medium and having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of flexural-mode mechanical resonance corresponding to that of said transducer; and means mechanically connecting said vibrator element only to said transducer to translate energy therebetween so that said device and said transducer constitute a mechanical impedance transformer which is the analogue of an electrical impedance transformer for converting between parallel and series resonant impedance relationships.

3. An arrangement for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: an electromechanical transducer having a vibratory frequency of mechanical resonance approximately equal to said signal frequency and a mechanical impedance at said signal frequency which is high relative to the impedance of said medium; a mechanical impedance-transformation device comprising a U-shaped structure having a flexural-mode mechanically-resonant bight portion and legs normal thereto coupling said transducer to said medium, said

bight portion having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of flexural-mode mechanical resonance corresponding to that of said transducer; and means mechanically connecting the free ends of said legs to said transducer to translate energy therebetween.

4. An arrangement for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: an electromechanical transducer having a vibratory frequency of mechanical resonance approximately equal to said signal frequency with a mechanical impedance at said signal frequency which is high relative to the impedance of said medium and having a line of maximum vibrational displacement; a mechanical impedance-transformation device coupling said transducer to said medium and comprising a flexural-mode mechanically-resonant vibrator element coupled to said medium and having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of flexural-mode mechanical resonance corresponding to that of said transducer; and means mechanically connecting said vibrator element only to said transducer and on said line to translate energy therebetween so that said device and said transducer constitute a mechanical impedance transformer which is the analogue of an electrical impedance transformer for converting between parallel and series resonant impedance relationships.

5. An arrangement for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: an electromechanical transducer device having a vibratory frequency of mechanical resonance approximately equal to said signal frequency and a mechanical impedance at said signal frequency which is high relative to the impedance of said medium; a mechanical impedance-transformation device coupling said transducer to said medium and comprising a flexural-mode mechanically-resonant vibrator element coupled to said medium and having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of flexural-mode mechanical resonance corresponding to that of said transducer; means mechanically connecting said vibrator element only to said transducer to translate energy therebetween so that said device and transducer have maximum vibratory response at two frequencies spaced equidistantly above and below said signal frequency, the vibratory motion of at least one of said devices being damped to increase the vibratory response of said device and transducer intermediate said two frequencies relative to said maximum vibratory response thereat.

6. An arrangement for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: an electromechanical transducer having a vibratory frequency of mechanical resonance approximately equal to said signal frequency and a mechanical impedance at said signal frequency which is high relative to the impedance of said medium; a mechanical impedance-transformation device coupling said transducer to said medium and comprising a flexural-mode mechanically-resonant vibrator element coupled to said medium and having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of flexural-mode mechanical resonance corresponding to that of said transducer; means mechanically connecting said vibrator element only to said transducer to translate energy therebetween so that said device and transducer have maximum vibratory response at two frequencies spaced equidistantly above and below said signal frequency, said vibrator element being mechanically loaded by said medium to increase the vibratory response of said device and transducer intermediate said two frequencies relative to said maximum vibratory response thereat.

7. An electromechanical transducer for effecting trans-

fer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: an electromechanical transducer having a vibratory frequency of mechanical resonance approximately equal to said signal frequency with a mechanical impedance at said signal frequency which is high relative to the impedance of said medium and having a line of maximum vibratory displacement disposed in a given direction; a mechanical impedance-transformation device coupling said transducer to said medium and comprising a flexural-mode mechanically-resonant vibrator element coupled to said medium and having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of flexural-mode mechanical resonance corresponding to that of said transducer and having a line of maximum vibratory displacement; and means mechanically connecting said vibrator element only to said transducer to translate energy therebetween with said maximum vibratory displacement line of said element disposed in a direction normal to said maximum vibratory displacement line of said transducer.

8. An electromechanical transducer for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: a piezoelectric transducer vibratory in a flexural mode, having a frequency of vibratory mechanical resonance approximately equal to said signal frequency with a mechanical impedance at said signal frequency which is high relative to the impedance of said medium and having a central line of maximum vibratory displacement disposed in a given direction; a mechanical impedance transformation device coupling said transducer to said medium comprising a thin strip of material formed into a U-shaped structure having a flexural-mode mechanically resonant bight portion and legs normal thereto, said bight portion having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of flexural-mode mechanical resonance corresponding to that of said transducer and having a line of maximum vibratory displacement; and means mechanically connecting the free ends of said legs to said transducer on said central line thereof with said line of maximum vibratory displacement of said bight portion disposed in a direction normal thereto.

9. An arrangement for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: an electromechanical transducer vibratory in a flexural mode, having a frequency of flexural-mode mechanical resonance approximately equal to said signal frequency with a mechanical impedance at said signal frequency which is high relative to the impedance of said medium and having a central line of maximum vibratory displacement disposed in a given direction; a mechanical impedance-transformation device coupling said transducer to said medium comprising a thin strip of material formed into a U-shaped structure having a flexural-mode mechanically-resonant bight portion and convergently tapered legs normal thereto, said bight portion having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of mechanical resonance in a flexural mode corresponding to that of said transducer and having a line of maximum vibratory displacement; and means mechanically connecting the free ends of said legs to said transducer on said central line thereof with said line of maximum vibratory displacement of said bight portion disposed in a direction normal thereto.

10. An arrangement for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: an electromechanical transducer vibratory in a flexural mode, having a frequency of flexural-mode mechanical resonance approximately equal to said signal frequency with a mechanical impedance at said signal frequency which is

high relative to the impedance of said medium and having a central line of maximum vibratory displacement disposed in a given direction; a mechanical impedance-transformation device coupling said transducer to said medium comprising a thin strip of material formed into a U-shaped structure having a flexural-mode mechanically-resonant bight portion and legs normal thereto, said bight portion presenting a bending surface which is small relative to the bending surface of said transducer, having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of mechanical resonance in a flexural mode corresponding to that of said transducer and having a line of maximum vibratory displacement; a tapered horn, having throat dimensions of a size approximately matching said bight portion, coupling said U-shaped structure to said medium; and means mechanically connecting the free ends of said legs to said transducer on said central line thereof with said line of maximum vibratory displacement of said bight portion disposed in a direction normal thereto.

11. An arrangement for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: an electromechanical transducer vibratory in a flexural mode, having a frequency of flexural-mode mechanical resonance approximately equal to said signal frequency with a mechanical impedance at said signal frequency which is high relative to the impedance of said medium and having a central line of maximum vibratory displacement disposed in a given direction; a mechanical impedance-transformation device coupling said transducer to said medium comprising a thin strip of material formed into a U-shaped structure having a flexural-mode mechanically-resonant bight portion and legs normal thereto, said bight portion presenting a bending surface which is small relative to the bending surface of said transducer, having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of mechanical resonance in a flexural mode corresponding to that of said transducer and having a line of maximum vibratory displacement; a tapered horn, having throat dimensions of a size approximately matching said bight portion, coupling said U-shaped structure to said medium, the mouth of said horn having a width approximately equal to one wavelength in said medium at said signal frequency and having a length approximately twice said width; and means mechanically connecting the free ends of said legs to said transducer on said central line thereof with said line of maximum vibratory displacement of said bight portion disposed in a direction normal thereto.

12. An electromechanical transducer for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: a mounting structure; a piezoelectric transducer vibratory in a flexural mode, having a frequency of flexural-mode mechanical resonance approximately equal to said signal frequency with a mechanical impedance at said signal frequency which is high relative to the impedance of said medium and having a central line of maximum vibratory displacement disposed in a given direction; a pair of flexible, conductive electrodes secured to nodal sections of said transducer and mechanically affixed to said structure for supporting said transducer therefrom; a mechanical impedance-transformation device coupling said transducer to said medium comprising a thin strip of material formed into a U-shaped structure having a flexural-mode mechanically-resonant bight portion and legs normal thereto, said bight portion having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of flexural-mode mechanical resonance corresponding to that of said transducer and having a line of maximum vibratory displacement; and means mechanically connecting the free ends of said legs to said transducer on said central line thereof

with said line of maximum vibratory displacement of said bight portion disposed in a direction normal thereto.

13. An electromechanical transducer for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: an electromechanical transducer having a vibratory frequency of mechanical resonance approximately equal to said signal frequency with a mechanical impedance at said signal frequency which is high relative to the impedance of said medium and having a line of maximum vibratory displacement disposed in a given direction; a plurality of mechanical impedance-transformation devices coupling said transducer to said medium, each comprising a flexural-mode mechanically-resonant vibrator element coupled to said medium and having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of flexural-mode mechanical resonance corresponding to that of said transducer; and means mechanically connecting each of said vibrator elements only to said transducer with said elements disposed side-by-side along said line to translate energy between said elements and said transducer and so that each is an impedance transformer which is the analogue of an electrical impedance transformer for converting between series and parallel impedance relationships in a resonant circuit.

14. An arrangement for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: an electromechanical transducer having a vibratory frequency of mechanical resonance approximately equal to said signal frequency with a mechanical impedance at said signal frequency which is high relative to the impedance of said medium; a mechanical impedance-transformation device coupling said transducer to said medium comprising a cylinder closed at one end by a flexible membrane vibratory in a flexural mode, said membrane having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of flexural-mode mechanical resonance corresponding to that of said transducer; and means mechanically connecting the other end of said cylinder to said transducer.

15. An arrangement for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: an electromechanical transducer having a vibratory frequency of mechanical resonance approximately equal to said signal frequency with a mechanical impedance at said signal frequency which is high relative to the impedance of said medium; a mechanical impedance-transformation device coupling said transducer to said medium comprising a T-shaped structure defining two balanced cantilevers vibratory in a fundamental flexural mode, said cantilevers having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of flexural-mode mechanical resonance corresponding to that of said transducer; and means mechanically connecting the said T-shaped structure to said transducer.

16. An arrangement for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: an electromechanical transducer having a vibratory frequency of mechanical resonance approximately equal to said signal frequency with a mechanical impedance at said signal frequency which is high relative to the impedance of said medium; a mechanical impedance-transformation device coupling said transducer to said medium comprising a disc center-clamped to one end of a mounting element and vibratory in a flexural mode, said disc having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of flexural-mode mechanical resonance corresponding to said transducer; and means mechanically connecting the other end of said mounting element to said transducer.

17. An arrangement for effecting transfer of energy

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with respect to a medium having a predetermined impedance at a given signal frequency comprising: an elongated longitudinal-mode resonator having a vibratory frequency of longitudinal-mode mechanical resonance approximately equal to said signal frequency with a mechanical impedance at said signal frequency which is high relative to the impedance of said medium; a mechanical impedance-transformation device coupling said resonator to said medium and comprising a flexural-mode mechanically-resonant vibrator element coupled to said medium and having an impedance at said signal frequency intermediate that of said resonator and said medium and a frequency of flexural mode mechanical resonance corresponding to that of said resonator; and means mechanically connecting said element only to one end surface of said resonator.

18. An arrangement for effecting transfer of energy with respect to a medium having a predetermined impedance at a given signal frequency comprising: a magnetostrictive transducer including an elongated longitudinal-mode resonator having a longitudinal-mode vibratory frequency of mechanical resonance approximately equal to said signal frequency with a mechanical impedance at said signal frequency which is high relative to the impedance of said medium; a mechanical impedance-transformation device coupling said transducer to said medium and comprising a flexural-mode mechanically-resonant vibrator element coupled to said medium and having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of flexural-mode mechanical resonance corresponding to that of said transducer; and means mechanically connecting said vibrator element only to said transducer to translate energy therebetween so that said device and said transducer constitute a mechanical impedance transformer which is the analogue of an electrical impedance transformer converting between parallel and series resonant impedance relationships.

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ance of said medium; a mechanical impedance-transformation device coupling said transducer to said medium and comprising a flexural-mode mechanically-resonant vibrator element coupled to said medium and having an impedance at said signal frequency intermediate that of said transducer and said medium and a frequency of flexural-mode mechanical resonance corresponding to that of said transducer; and means mechanically connecting said vibrator element only to said transducer to translate energy therebetween so that said device and said transducer constitute a mechanical impedance transformer which is the analogue of an electrical impedance transformer converting between parallel and series resonant impedance relationships.

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