April 16, 1968 J. L. BUTLER 3,378,814

DIRECTIONAL TRANSDUCER

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FIG. 1

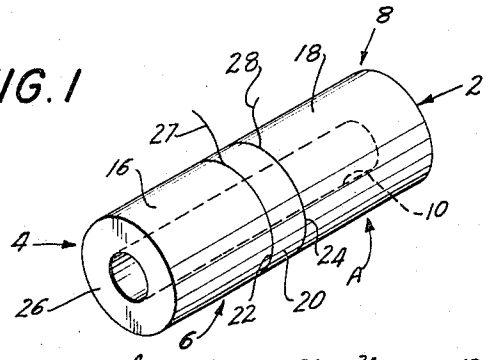


FIG. 2

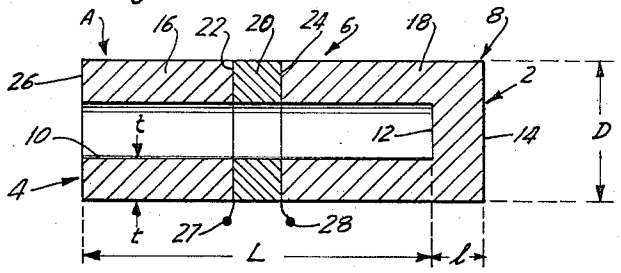
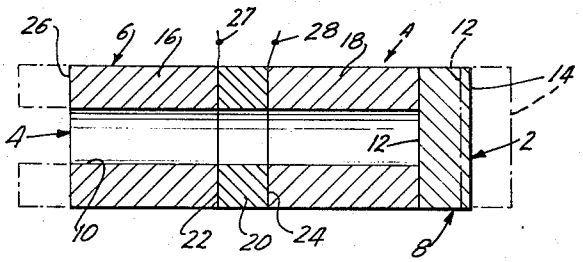


FIG. 3



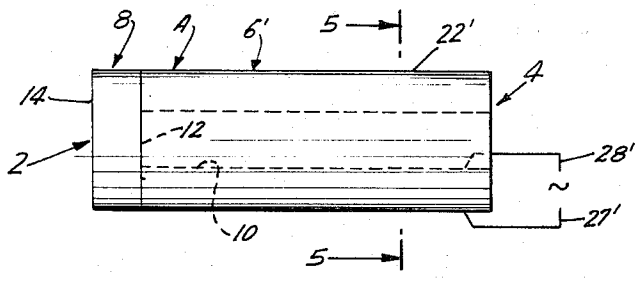


FIG. 4

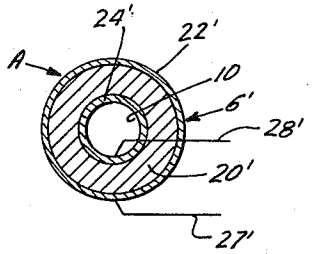


FIG. 5

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FIG. 6

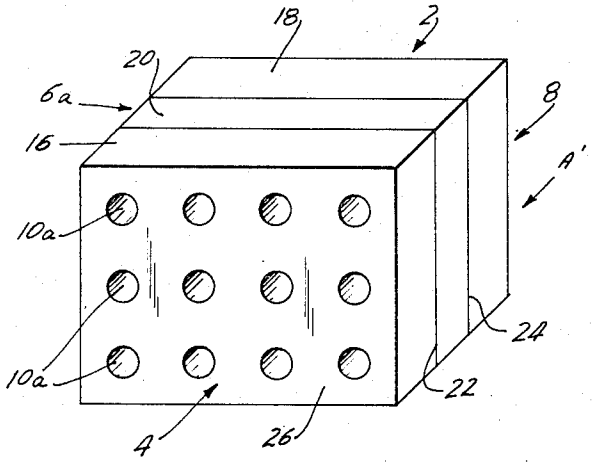
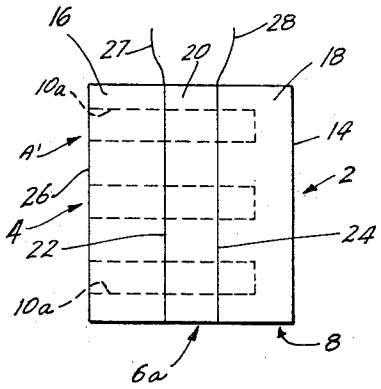


FIG. 7



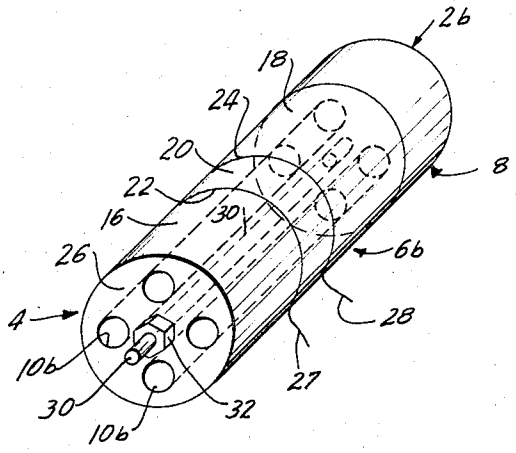
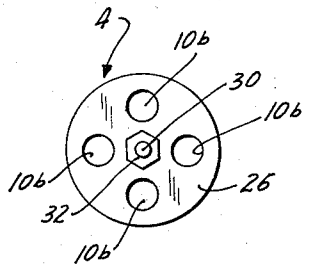


FIG. 8

FIG. 9



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DIRECTIONAL TRANSDUCER

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14 Claims. (Cl. 340—8)

ABSTRACT OF THE DISCLOSURE

An electromechanical transducer having a tubular body with the tube closed at one end and open at the other end so designed that the vibrations produced at the open end by the solid and open portions respectively cancel one another, thereby to produce a transducer which radiates substantially only from the closed end thereof.

The present invention relates to an electromechanical transducer construction with a high degree of inherent directional sensitivity. It is particularly well suited for the generation and reception of acoustic energy in underwater sound application.

Transducers of the type under discussion are usually capable of converting electrical vibratory energy into mechanical vibratory energy and converting mechanical vibratory energy into electrical vibratory energy. For purposes of explanation, the invention will be here specifically described in terms of converting electrical energy into mechanical energy, but it will be understood that this is exemplary only, and that the invention can be incorporated into transducers capable of functioning in the opposite sense, or in both senses.

There are many applications in which a high degree of directional sensitivity is desired in transducers of the type under discussion. For example, in an underwater sonar installation it is often desired that vibrations be propagated outwardly from a station in one direction only, sometimes in a relatively narrow beam. The actual vibration-generating portions of the transducer assemblies, however, are usually not directionally sensitive, that is to say, when they are caused to vibrate vibrations of appreciable magnitude emanuate from different sides of the device, thus causing vibration propagation through the surrounding medium in at least two directions. In order to inhibit the propagation of vibrations in one of those directions the vibration-producing unit is generally housed in such a fashion that the vibrations in the desired direction emanate freely from the housing while the vibrations in the other direction are, in one manner or another, attenuated by the housing. This is often done in underwater installations by providing a body of pressure release material, such as soft rubber, at that end of the device where vibrations are not desired, while providing the device with an acoustically transparent window at that end thereof from which vibrations are to emanate. Instead of using a soft rubber body to block the vibrations, it has also been proposed to utilize a mass of trapped air for the same purpose.

This prior art approach to the production of a unidirectional effect is subject to two major drawbacks. In the first place, it is a cause of appreciable expense and complexity, and results in much bulkier and heavier transducing units than would otherwise be the case, because of the need for a comparatively elaborate housing and for the provision of pressure release material or other transparently opaque elements therein. In the second place, the efficacy of pressure release material or trapped bodies of air in preventing the transmission of vibrations therethrough is very greatly affected by the pressure which is applied thereto. When high external pressures are applied, as would be the case where the device is located a substantial distance below the level of the sea, the pressure release material and the trapped bodies of air are compressed, thus increasing their characteristic impedance and diminishing their acoustic opacity.

It is the prime object of the present invention to provide an electromechanical transducer the vibration-producing unit of which is itself so constructed as to inherently have a uni-directional effect, thereby to make unnecessary the use of elaborate housings, pressure release material, trapped bodies of air, or the like. It is a further prime object of the present invention to devise such a transducer in which the uni-directional effect is virtually insensitive to the pressure exerted thereon by the surrounding medium, thereby enabling the transducer to be used in a high, or even variable, pressure environment with negligible effect on its performance.

To these ends, I so construct the actual vibration-producing unit that all or most of the vibrations produced at one end thereof are in phase with one another, that being the end from which it is desired that vibrations emanate, while at the other end thereof different sets of vibrations are produced which have a phase cancellation effect upon one another, thereby greatly minimizing and, under proper conditions of design, virtually eliminating, the propagation of vibrations from that end into the medium surrounding the unit. This is accomplished by forming the vibration-producing portion of the device in a shape which may be roughly described as tubular, by which is meant that the solid vibration-producing part, designed to vibrate in a direction here termed longitudinal, is provided with a longitudinally extending passage. Said one end of the vibration-producing body is provided with a head which closes the passage, while at the other end of the body the passage is open. That end of the body provided with the head, when it vibrates, will cause vibrations to be propagated through the medium surrounding the device. The other end of the solid portion of the device will also vibrate, but at that second end of the device vibrations will also be present at the end of the passage, those vibrations being produced by the rear face of the head and propagated through the passage by means of the medium within the passage. That medium is of a different composition from the body of the device, and therefore vibrations are propagated therethrough at a different rate than vibrations are propagated through the body of the device. The length of the passage is so chosen, in accordance with the frequency at which the device is designed to vibrate, that the vibrations propagated through the passage and present at the open end of the passage are in phase opposition or cancellation relationship with the vibrations produced by the solid portion of the device at that second end of the device. The two sets of vibrations cancel one another, or substantially so, the relative cross sectional areas of the passage and of the solid portion of the body being so chosen as to maximize the cancellation effect. Hence effective vibrations are produced at the head end of the device, but little or no effective vibration is produced at the other end thereof.

To the accomplishment of the above, and to such other objects as may hereinafter appear, the present invention relates to the construction of a directional electromechanical transducer as defined in the appended claims and as described in this specification, taken together with the following drawings, in which:

FIG. 1 is a three-quarter perspective view of one embodiment of the present invention;

FIG. 2 is a cross sectional view of the embodiment of FIG. 1;

FIG. 3 is a view similar to FIG. 2 but schematically indicating the manner or functioning thereof to produce a uni-directional effect;

FIG. 4 is a side elevational view of an alternative embodiment of the present invention;

FIG. 5 is a cross sectional view thereof taken along the line 5—5 of FIG. 4;

FIG. 6 is a three-quarter perspective view of another embodiment of the present invention;

FIG. 7 is a side elevational view of the embodiment of FIG. 6;

FIG. 8 is a three-quarter perspective view of yet another embodiment of the present invention; and

FIG. 9 is an end elevational view of the embodiment of FIG. 8.

The invention will be here specifically disclosed as embodied in an electrostrictive transducer of a type suitable for underwater operation at conventional underwater frequencies, but it will be understood that it is not limited thereto. For example, it could take the form of a magnetostrictive unit suitable for in-air operation. It comprises a body generally designated A having ends generally designated **2** and **4**. It is desired that effective vibrations be produced at the end **2** of the body A and that no effective vibrations be produced at the end **4** thereof. The body A comprises a tubular portion generally designated **6** and a head generally designated **8** at one end thereof. The tubular portion **6** comprises a solid body with a passage **10** therethrough, the passage extending from the end **4** of the unit A to the rear face **12** of the head **8**, the head **8** in effect closing the inner end of the passage **10** and having a front face **14**, at the unit end **2**, designed to produce the effective vibrations. The tubular portion **6** in the embodiment of FIG. 2 is defined by end portions **16** and **18** which may be formed of any suitable structural material such as aluminum or steel, between which a ring **20** of electrostrictive material is sandwiched, that ring **20** having electrodes **22** and **24** on opposite axial faces thereof, to which leads **27** and **28** are electrically connected. In one practical embodiment the head **8** and the portion **18** are integrally formed of aluminum, the portion **16** is formed of steel, and the portion **20** is formed of lead zirconate titanate.

When an alternating electric voltage is applied to the leads **27** and **28** the electrostrictive material of which the ring **20** is formed will cause that ring to vibrate in a longitudinal mode, from left to right as viewed in FIG. 2. These vibrations will be transmitted by the tube portions **16** and **18** to the tube end **4** and to the head **8** respectively. The broken line showings in FIG. 3 represent an instantaneous condition when the device A has expanded longitudinally. The head **8** will have moved out to the right, a positive pressure therefore being produced in the surrounding medium by the outer face **14** of the head **8**. The end surface **26** of the portion **16** will also have moved outwardly, thus also producing positive pressure in the surrounding medium. The inner face **12** of the head **8** will have moved to the right, as its face **14** thus moves, and this will have the effect of producing a negative pressure at the right hand or closed end of the passage **10**. This negative pressure will be propagated along the passage **10** through the medium which fills it. Preferably the length L of the passage **10** is such that, at the frequency at which time the unit A is caused to vibrate, an area of negative pressure will be formed at the outer end of the passage **10** whenever an area of negative pressure is formed at the inner end of that passage. Stated otherwise, the length L of the passage **10** is preferably equal to an integral number of wave lengths of the vibrations produced in the medium contained within the passage **10**, disregarding the axial thickness of the head **8**. If the thickness of the head **8** is such as to produce an appreciable phase change as between vibrations applied to the inner end thereof and vibrations produced by the outer end thereof, as may well be the case if the thickness of the head is not very much less than a wave length of the vibrations in the head material, the length of the passage **10** should correspondingly depart from that corresponding to an integral number of wave lengths of the vibrations produced in the medium contained within the passage **10**, all in order to give rise to the desired condition of phase cancellation at the outer end of the passage **10**. When the device is designed to be used for underwater purposes the outer end of the passage **10** may be left open, the passage then being filled with sea water when the device is immersed, and consequently the device will be designed with that in mind. It is entirely feasible, however, to close the passage end with an acoustically transparent window and fill the passage **10** with air, water or any other desired medium, the dimensions of the device being modified as necessary to correspond to the nature of the material contained within the passage **10**.

The negative pressures produced at the open end of the passage **10** will, as shown in FIG. 3, combine with the positive pressures produced by the end surface **26** of the tubular portion **16**, and since those two pressures are in phase opposition or cancellation relationship, being substantially 180° out of phase, they will tend to cancel or nullify one another. Through proper design of the cross sectional areas of the passage **10** and the end surface **26** of the solid portion of the tube virtually complete phase cancellation can be achieved. What is here involved is the cancellation of pressure amplitudes; pressure amplitudes are produced not only by the areas of the vibration-inducing elements but also by their velocities. Hence it may be stated that the velocity of movement and the area of the solid end surface **26** of the tube is so related to the velocity of vibrations emanating from the passage **10** and the area of the outer end of the passage **10** that the pressure amplitudes of the vibrations produced respectively by the end surface **26** of the solid portion of the tube and by the passage **10** will be essentially the same. As a result, vibrations will emanate from the head end **2** of the device A, but no vibrations will emanate from the tail end **4** thereof.

As illustrated, the electrostrictive ring **20** is located substantially midway between the outer ends of the tube sections **16** and **18**, and the axial thickness **1** of the head **8** is very much less than the wave length, in the material of which the head **8** is formed, of vibrations at the frequency of operation of the device. As a result the two ends **2** and **4** of the device A operate substantially out of phase with one another, one moving to the left when the other moves to the right. If this essentially symmetrical arrangement is not employed, appropriate modification of the length L of the passage **10** may be required in order to cause the pressures or vibrations at the open end of the passage **10** to be substantially in phase-cancelling relationship with the pressures or vibrations produced by the end surface **26** of the solid tubular portion **16**, this being the relationship which produces the uni-directional characteristic of the device.

In a typical design used for underwater transducing purposes, and where **1** is small relative to the wave length of the vibrations passing through the head **8**, the proportions of the parts would be so chosen that the mechanical resonant frequency f of the transducer would be equal to C/L where C is the velocity of vibration transmission in the medium (water) designed to fill the passage **10**. The cross sectional area of the passage **10** will be so chosen that the vibration source strength of the surface **26** is nearly equal to the vibration source strength at the mouth of the passage **10**. In practice the overall diameter D of the device should be less than one-half the wave length of vibrations in the fluid within the passage **10**, in order that there should be proper phase cancellation at the device end **4**, and the thickness t of the solid tubular portion should be sufficient so as to contain within the passage **10** the vibrations produced by the inner head surface **12**. While the actual cross sectional shape of the device has been shown as cylindrical, it be-

ing thought that this is preferred from a manufacturing point of view, this is by no means essential.

The embodiment of FIGS. 4 and 5 functions on the same phase-cancellation principle as the embodiment of FIGS. 1–3, and is also of the electrostrictive type designed for underwater use. It differs from the embodiment of FIGS. 1–3 in that its tubular portion **6'** is in one piece, and is composed substantially exclusively of a tube **20'** of electrostrictive material, with electrodes **22'** and **24'** formed on the radially inner and outer surfaces thereof and connected to terminals **27'** and **28'** respectively. The head **8** is secured to one end of the piezoelectric tube **6'** in any appropriate manner.

The application of varying electrical potentials to the leads **27'** and **28'** will cause the piezoelectric tube **6'** to vary in thickness and thus axially elongate, thereby producing vibration in a longitudinal mode comparable to that produced in the embodiment of FIGS. 1–3.

In connection with the embodiment of FIGS. 4 and 5, for example, it can be demonstrated, through mechanical transmission line theory or through the solution of the one-dimensional wave equation with the proper boundary conditions, and on the assumption that the device is to be used for underwater purposes, so that the passage **10** will be filled with sea water, that for best results the ratio of the area of the head face **14** to the area of the tubular portion face **26**, should be equal to 2.04, where the head **8** is formed of aluminum and the tube **6'** of lead zirconate titanate, and that the length L of the passage **10** should be approximately 7.5 times the thickness **1** of the head **8**, where the thickness **1** of the latter is considerably less than one quarter of the wave length of vibrations at the operating frequency passing through aluminum. These relationships will vary as different materials are employed, and as the overall design of the unit differs from that of FIGS. 4 and 5, in manners readily apparent to those skilled in the art.

FIGS. 6 and 7 disclose a unitary device made in accordance with the present invention but in which the overall external dimensions of the cross section of the device may exceed half the wave length of vibrations in the fluid within the passage **10**, and may indeed be considerably greater than that wave length. As there disclosed the body A' may have a width and height which is virtually unlimited. Its body comprises, in effect, a multiplicity of the bodies A of FIG. 1 integrally connected together, the overall body A' being provided with a plurality of axially extending passages **10*a*** appropriately spaced from one another so that the diameters of the individual passages **10*a*** as well as the spacing between their axes are both less than half the wave length of vibrations at the operating frequency in the fluid with which the passages **10*a*** are adapted to be filled. The details of the embodiment of FIGS. 6 and 7, insofar as the manner in which vibrations are produced is concerned, is of the same general type as that disclosed in FIGS. 1–3.

FIGS. 8 and 9 disclose a modification of the embodiment of FIGS. 1–3 in which, instead of having a single passage **10**, a plurality of passages **10*b*** are provided, the areal extents of the open ends of the passages **10*b*** correspond to the areal extent of the open end of the passage **10** in the embodiment of FIGS. 1–3. In addition, the passages **10*b*** are all located radially spaced from the axis of the device, and a stress rod **30** passes through the center of the tubular body portion **6*b***, is threaded into the head **8**, and has a nut **32** received over its outwardly protruding end and engaging the body surface **26**, all as is well known for the purpose of increasing the structural strength of the assembly.

From the above it will be appreciated that an unhoused transducer unit has been produced which is inherently of a unidirectional characteristic, transmitting (or receiving) readily at its end **2** and transmitting (or receiving) minimally, if at all, at its end **4**. Such housings as may be desired can, of course, be employed, but the significant fact is that a very appreciable unidirectional effect is produced apart from such effect as the housing may have. The transducers may be used individualy or in arrays and, indeed, the transducers of the present invention are very well adapted to be employed in a planar array in which, when all of the head ends **2** of the devices are pointed in the same direction, a narrow transmission beam in one direction only is produced.

While but a limited number of embodiments of the present invention have been here specifically disclosed, it will be apparent that many variations may be made therein, all within the scope of the instant invention as defined in the following claims.

I claim:

1. A directional transducer comprising a head and a tubular body extending from said head and comprising a solid portion surrounding an inner space, said tubular body having one end substantially closed by said head and having a second end, the inner space of said tubular body containing a medium having a vibration propagation speed different from that of said body, means operatively connected to said body to cause it to vibrate in a longitudinal mode at a given frequency, the tube length being such in conjunction with said given frequency that said second end of said body vibrates substantially 180° out of phase with pressure waves at said second tube end propagated through said medium in said tube from said head, whereby said transducer radiates from said head but substantially not from said second tube end in which, disregarding the effect of thickness of said head, the axial length of said tube is substantially equal to $n\lambda$ where n is any integer and λ is the wave length in the medium in said tube of vibrations at said given frequency.

2. The directional transducer of claim **1**, in which the cross sectional area of the solid portion of said tubular body is so related to the cross sectional area of said inner space of said tubular body as to produce vibrations in the surrounding medium at the open end of said tube derived respectively from the solid portion of said tubular body and the open end of the inner space of said tubular body which have substantially the same maximum pressure amplitude, and in which the thickness of said head is less than $\lambda_1/4$, where λ_1 is the wave length in said head of vibrations at said given frequency.

3. The directional transducer of claim **1**, in which the cross sectional area of the solid portion of said tubular body is substantially equal to the cross sectional area of said inner space of said tubular body.

4. The directional transducer of claim **3**, in which the thickness of said head is less than $\lambda_1/4$, where λ_1 is the wave length in said head of vibrations at said given frequency.

5. The directional transducer of claim **1**, in which the thickness of said head is less than $\lambda_1/4$, where λ_1 is the wave length in said head of vibrations at said given frequency.

6. The directional transducer of claim **1**, in which said tubular body is formed at least in part of a piezoelectric element, said vibration-causing means comprising a pair of electrodes operatively connected to separated surfaces of said element, in which, disregarding the effect of thickness of said head, the axial length of said tube is substantially equal to $n\lambda$, where n is any integer and λ is the wave length in the medium in said tube of vibrations at said given frequency.

7. The directional transducer of claim **6**, in which the cross sectional area of the solid portion of said tubular body is substantially equal to the cross sectional area of said inner space of said tubular body.

8. The directional transducer of claim **6**, in which the cross sectional area of the solid portion of said tutubular body is substantially equal to the cross sectional area of said inner space of said tubular body, and in which the thickness of said head is less than $\lambda_1/4$, where

λ_1 is the wave length in said head of vibrations at said given frequency.

9. A directional transducer having first and second ends connected by a body, said body having a passing extending from said second end toward but terminating short of said first end, means operatively connected to said body to cause it to vibrate so that said first and second ends vibrate at a given frequency at least in part longitudinally of said body, said passage containing a medium having a vibration propagation speed different from that of said body, said passage having a length such as, via said medium, to acoustically connect said first transducer end and the end of said passage at said second transducer end and in which, disregarding the effect of thickness of said head, the axial length of said tube is substantially equal to $n\lambda$, where n is any integer and λ is the wave length in the medium in said tube of vibrations at said given frequency, thereby to produce phase cancellation between vibrations propagated through said passage and vibrations of said second transducer end.

10. The directional transducer of claim 9, in which said passage is open at said second transducer end, thereby to become filled with the fluid medium surrounding said transducer.

11. A directional transducer comprising a head and a tubular body extending from said head and comprising a solid portion surrounding an inner space, said tubular body having one end substantially closed by said head and having a second end, the inner space of said tubular body containing a medium having a vibration propagation speed different from that of said body, means operatively connected to said body to cause it to vibrate in a longitudinal mode at a given frequency, the tube length being such in conjunction with said given frequency that said second end of said body vibrates substantially 180° out of phase with pressure waves at said second tube end propagated through said medium in said tube from said head, whereby said transducer radiates from said head but substantially not from said second tube end, in which the cross sectional area of the solid portion of said tubular body is so related to the cross sectional area of said inner space of said tubular body as to produce vibrations in the surrounding medium at the open end of said tube derived respectively from the solid portion of said tubular body and the open end of the inner space of said tubular body which have substantially the same maximum pressure amplitude, and in which the thickness of said head is less than $\lambda_1/4$, where λ_1 is the wave length in said head of vibrations at said given frequency.

12. A directional transducer comprising a head and a tubular body extending from said head and comprising a solid portion surrounding an inner space, said tubular body having one end substantially closed by said head and having a second end, the inner space of said tubular body containing a medium having a vibration propagation speed different from that of said body, means operatively connected to said body to cause it to vibrate in a longitudinal mode at a given frequency, the tube length being such in conjunction with said given frequency that said second end of said body vibrates substantially 180° out of phase with pressure waves at said second tube end propagated through said medium in said tube from said head, whereby said transducer radiates from said head but substantially not from said second tube end, in which the cross sectional area of the solid portion of said tubular body is substantially equal to the cross sectional area of said inner space of said tubular body.

13. The directional transducer of claim 12, in which the thickness of said head is less than $\lambda_1/4$, where λ_1 is the wave length in said head of vibrations at said given frequency.

14. A directional transducer comprising a head and a tubular body extending from said head and comprising a solid portion surrounding an inner space, said tubular body having one end substantially closed by said head and having a second end, the inner space of said tubular body containing a medium having a vibration propagation speed different from that of said body, means operatively connected to said body to cause it to vibrate in a longitudinal mode at a given frequency, the tube length being such in conjunction with said given frequency that said second end of said body vibrates substantially 180° out of phase with pressure waves at said second tube end propagated through said medium in said tube from said head, whereby said transducer radiates from said head but substantially not from said second tube end, in which the thickness of said head is less than $\lambda_1/4$, where λ_1 is the wave length in said head of vibrations at said given frequency.

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