

United States Hands

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[54] ACOUSTIC IMPEDANCE MATCHING SYSTEM

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[51] Int. Cl. **H04r 1/28, H04r 17/00**
[58] Field of Search **179/110 A, 1 SS; 181/5 J; 340/8 MM, 8 L, 8 FT; 310/8.3, 8.6, 8.7, 8.2**

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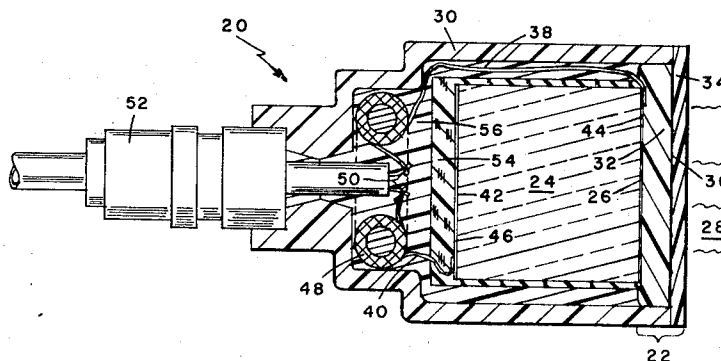
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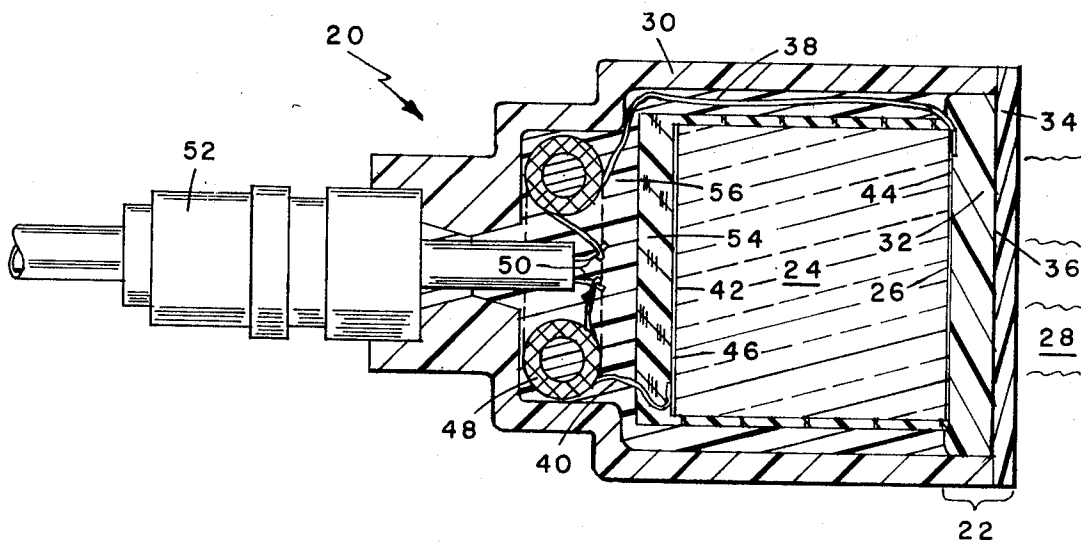
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[57] ABSTRACT

A transducer assembly incorporating a stratified medium for conducting acoustic waves from an acoustic source of relatively high impedance, such as a piezoelectric crystal, to a gaseous environment of relatively low impedance, the stratified medium including typically at least one layer of a foam structured low density plastic material, whereby uniform variations in impedance are provided progressively from the source through the layers of the stratified medium into the gaseous environment to effect an impedance match.

12 Claims, 1 Drawing Figure





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ACoustic IMPEDANCE MATCHING SYSTEM

BACKGROUND OF THE INVENTION

This invention relates to acoustic transducer assemblies and more particularly to an acoustic transducer assembly utilizing a novel impedance matching structure as the interface between the transducer and a gaseous environment.

One form of acoustic transducer assembly utilizes a piezoelectric crystal held in an open end of a cylindrical support such as a tube. Sound waves emanate from the end, or radiating aperture, of the tube when the outer surface of the crystal vibrates in response to a well-known excitation of the crystal by electrical stimulation. Such a transducer assembly is to be utilized for transmission of sound into a gaseous environment, the sound being of a high frequency such that the sound wavelength in the environment is smaller than the dimensions of the radiating aperture.

Of particular interest is the acoustic power and bandwidth of sound radiated from the end of the tube. A problem arises in the transmission of high frequency sound between a gaseous environment of low acoustic impedance and an acoustic transducer assembly such as the above-mentioned assembly comprising a high impedance piezoelectric crystal. The sound transmission problem is present irrespectively of whether the sound is radiated from the transducer assembly into the environment, or from the environment into the transducer assembly, and is manifested by a substantially reduced coupling and bandwidth of acoustic energy between the two media, the source and environment, as compared to the coupling of acoustic energy between two media having substantially the same impedance. In the case of a piezoelectric crystal and an air environment, the difference in impedance is enormous, being on the order of 10,000 to one or greater. And impedance matching between such great differences in impedance have heretofore not been practicable.

As is well known, the power and the bandwidth of sound radiated from the end of the tube is increased by the use of an appropriate acoustic impedance matching structure. Two forms of such matching structures are in common use. One form, the speaker horn, is utilized with relatively long acoustic wavelengths to increase the size of the radiating aperture to provide a radiating aperture having dimensions substantially larger than the wavelength of sound radiated from the end of the tube. The second form, typified by a layer of material having an acoustic impedance of value between the impedance of the source and the environmental impedance has been utilized with relatively short acoustic wavelengths where the radiating aperture, such as the end of the tube, has dimensions substantially larger than the wavelength of the sound radiating from the tube. In this latter case the impedance matching structure has the effect of introducing a more gradual transition in impedance in place of the sharp transition present at an interface between a high impedance source and low impedance environment. As a result reflections of sound waves propagating between the source and the environment are reduced, the transmission bandwidth is increased, and substantially greater power is transmitted into the environment for a given amplitude of pulsation of the source.

The severity of the impedance mismatch between a piezoelectric crystal and a medium such as air is readily demonstrated. For example, in the case of a piezoelectric crystal being utilized without a matching structure for transmission of sound power into air, the crystal may have to be driven at such large amplitudes of pulsation that the crystal may fracture, while with the insertion of some form of matching structure, such as a layer of cork, between the crystal and the air environment, the same sound power can be transmitted into the air by driving the crystal at substantially reduced amplitudes of pulsation which do not induce crystal fracture.

It should be noted that while the aforementioned use of cork as an impedance matching structure provides some improvement in sound transmission as compared to the absence

of any such matching structure, nevertheless, the loss in transmission of energy and bandwidth provided by this matching structure is relatively large compared to the energy transmission and bandwidth which can be obtained with transmission of sound between a source and an environment using the present invention.

It is noted that in the prior art attempts have been made to match the impedance of a piezoelectric crystal to the impedance of a medium, such as water, in which case there is a relatively small difference in impedance on the order of 10 to one. However, it has not been possible, heretofore, to accomplish wide bandwidth impedance matching for sound transmission between a high impedance source, such as a piezoelectric crystal and an air environment.

An example, of the prior art is provided by the patent to Hansel U.S. Pat. No. 2,430,013 which issued Nov. 4, 1947, wherein there is disclosed an acoustic transducer assembly containing a crystal, and further comprising a steel backing plate for the crystal as well as a double layered structure of hickory wood and magnesium metal bonded together for coupling sound between the crystal and a water environment. The impedance matching materials and device of Hansel are, however, impractical for matching the high impedance of a piezoelectric crystal to an air environment.

It is, therefore, an object of the invention to provide an improved acoustic impedance matching structure of relatively small physical size.

It is also an object of the invention to provide an acoustic impedance matching structure providing increased radiated power and bandwidth.

It is furthermore an object of the invention to provide an improved acoustic impedance matching structure for matching the acoustic impedance of a piezoelectric crystal to that of an air environment.

SUMMARY OF THE INVENTION

This invention provides a commercially feasible transducer assembly utilizing a medium for communicating wave energy between a transducer of wave energy having a relatively high wave impedance, such as a piezoelectric crystal, and an environment having a relatively low wave impedance such as a gaseous environment. The medium is stratified and propagative of waves formed by the movement of particles of the medium, and the medium has a depth along a direction of wave propagation of at least one-quarter of the mean wavelength of the propagation wave within the stratified medium. The stratified medium is formed of layers, each of which presents a predetermined characteristic impedance to the propagating wave, and the layers are arranged serially between the source and the environment along the direction of wave propagation such that there is presented to the propagating wave a progressive variation in impedance from the source through the successive layers to the environment.

The acoustic impedance matching structure employs materials, as will be described hereinafter, having low densities and low values of sound velocity such as is provided by a cellular or solid foam structured material, these being inhomogeneous materials having regions of fluid matter interspersed among regions of solid matter.

The impedance matching structure of this invention may be further improved by the use of particular bonding agents such as epoxy cement for attaching the low density material to the overall structure.

BRIEF DESCRIPTION OF THE DRAWING

The aforementioned objects and other features of the invention are explained in the following description taken in connection with the accompanying drawing wherein the FIGURE shows, in cross section, a transducer assembly embodying the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to the FIGURE, there is shown a sectional view of a transducer assembly 20 taken along its axis. Transducer assembly 20 incorporates a medium for communicating wave energy, in accordance with the invention, shown as matching structure 22 for matching the acoustic impedance of an acoustic source, herein, crystal 24 to an environment 28 which is a gas, typically air. Crystal 24, preferably barium titanate, is piezoelectric. Matching structure 22 is in acoustic contact with the crystal 24 whereby sound waves emanating from the front face 26 of the crystal 24 propagate through the matching structure 22 and into the environment 28. A tubular support structure of metal or plastic such as CPVC, chlorinated polyvinyl chloride is provided in the form of a case 30 which encloses the crystal 24 and positions the matching structure 22 relative to the crystal 24. The transducer assembly 20 may be utilized to generate sound waves and may also be used as a sensor for receiving sound waves propagating from the environment 28 through the matching structure 22 and into the piezoelectric crystal 24.

Matching structure 22 comprises layers of acoustically conductive material, and is preferably a stratified structure having two or more layers of rigid, low density sound propagating material characterized by differing acoustic impedances as are provided by differing densities and sound velocities. A better impedance match over a larger bandwidth is obtained by increasing the number of layers, until, in the limiting case the stratified structure becomes a single layer of material in which the characteristics vary continuously from a relatively high impedance at the end of the layer adjacent the source to a low impedance at the end of the layer adjacent the environment. As a practical matter, matching structures comprising two and three layers have been built.

In the preferred embodiment shown in the FIGURE, the matching structure 22 comprises two layers, a first layer 32 of solid polyurethane elastomer characterized by a density of 71.8 lbs./cu.ft. (pounds per cubic foot) and a Shore A durometer in the range 75-95, and a second layer 34 of polystyrene foam (a styrene polymer known by the trade name Styrofoam) having a closed cell composition and a density of 2 lbs./cu.ft., the latter of the two materials having the lower density and acoustic impedance and, therefore, being placed next to the environment 28. The cells (or bubbles of entrapped gas) in the polystyrene foam have dimensions which are less than one-tenth of the sound wavelength in the polystyrene foam. The first and second layers 32 and 34 are bonded together, in a manner to be described, so that sound is readily coupled between the two layers. The dimensions of the matching structure 22 for transmission of sound in a frequency bandwidth of 6,000 Hz (between the 3 db points) centered at 41,500 Hz are as follows. The first layer 32 has a diameter of 2 1/2 inches and a depth of five-sixteenth inch; the second layer 34 has a somewhat larger diameter (approximately 2 3/4 inches) to cover the end of the case 30 and has a depth of 0.26 inch.

The depth, five-sixteenth inch, of the first layer 32 is equal to approximately one-quarter of the sound wavelength in the solid polyurethane elastomer while the diameter, 2 1/2 inches, is equal to approximately two of the wavelengths. The wavelength is dependent on the speed of propagation of sound within the solid polyurethane elastomer as well as the frequency of the sound. The depth, 0.26 inch, of the second layer 34 is equal to approximately one-quarter of the sound wavelength in polystyrene foam. The quarter wavelength depth (which as is well known may be replaced by a depth of one-quarter plus an integral number of one-half wavelengths) is utilized in matching a medium of low characteristic impedance, such as air, to a medium of relatively high characteristic impedance such as the piezoelectric crystal.

The acoustic impedance match and the bandwidth over which the acoustic impedance match is obtained depend on the choice of the materials utilized in the matching structure 22. The combination of the solid polyurethane elastomer layer

in contact with the crystal 24 followed by the layer of polystyrene foam in acoustic contact with the environment 28 has been found to provide the most desirable acoustic impedance match. Polypropylene foam has also been utilized in place of the polystyrene foam. A one-tenth inch deep layer (corresponding to a one-quarter wavelength depth) of polypropylene foam, while providing a somewhat less desirable impedance match than the polystyrene foam, has the advantage of greater ruggedness which may be desirable in commercial equipment. The particular composition of the polypropylene foam is important. For example, polypropylene foam which is modified by the inclusion of rubber particles suspended within the foam is utilized, while unmodified polypropylene foam is not utilized since it results in significantly inferior acoustic performance.

It is believed that a greatly improved impedance match is provided by the stratified medium of the invention when the materials of the individual layers are selected to provide a uniformly progressive rate of change from one value of characteristic impedance to the next, such that the ratios of impedance between the source and the stratified medium, between the layers of the medium, and between the stratified medium and the gaseous environment are similar, at least to within approximately an order of magnitude. The characteristic impedance of a medium of acoustically conductive material is given by $z = \sigma \eta$ where σ is the density and η is the sound velocity within the medium for acoustically conductive materials having negligible loss (such as losses from viscous damping).

Furthermore, it is noted that, in contrast with prior art acoustic matching structures utilizing solid material for coupling sound into a water environment, the present acoustic matching structure which couples sound into an air environment utilizes a composite material composed of both regions of fluid and regions of solid matter which coact to provide a foam structure. This material provides a composite acoustic impedance which results from the coacting of the fluidic and solid regions. The foam structured materials disclosed herein, comprise both a relatively light density plastic material and bubbles of an entrapped gas which provide a composite acoustic impedance between the impedance of the gaseous environment and the impedance of the solid polyurethane elastomer, and thereby achieve the substantially similar impedance ratios between the layers of the matching structure, the source and environment. Unlike solid acoustic materials which have relatively simple sound propagation characteristics, foam structured and other similar low density acoustic materials having, apparently, similar elasticities and similar densities show a wide variation in their acoustic properties. For example, as has already been mentioned two apparently similar forms of polypropylene foam differ significantly in acoustic performance; and as a further example it is well known that low density acoustic materials are used to absorb sound in anechoic chambers while the acoustic materials of the present invention transmit sound.

It is believed that the wide variation in acoustic properties of the low density materials considered for the matching structure and the attendant difficulty of predicting their response without actually experimenting with each of them is due to nonlinearities and the necessity for a dynamic testing of the durometer (elasticity) rather than as well-known static test. For example, when a foam structured polymer material is compressed momentarily (a second), it springs back to its original dimensions, but if it is compressed for a relatively long time (an hour) it may take a permanent set with an attendant change in its density. Apparently, the durometer is frequency dependent and the elastic limit may be exceeded in a durometer measurement. The acoustic properties have also been found, experimentally, to vary with the prior history of the material particularly with respect to the presence of external pressure upon the material.

The materials utilized in the matching structure are polymers, although the invention is not necessarily limited to

polymers, and as is well known, the number of monomers in a molecule of the material is a statistical quantity and varies from molecule to molecule in a distribution dependent in large measure on the manner of manufacture. Furthermore, with foam structured materials, the sizes, quantity and spacing of the bubbles of entrapped gas vary in accordance with a statistical distribution also dependent in large measure on the manner of manufacture. The distribution of monomers and of bubbles affects the mechanical and acoustic properties of the materials, particularly with reference to wave propagation within and along the surface of these materials.

It is believed that a meaningful test of the elastance can be accomplished by applying a pulsating displacement rather than a steady force as is generally done. This avoids the tendency to produce a permanent set. By applying a pulsating displacement and measuring the resultant pulsating force (as by means of a strain gauge) at a pulsation frequency of, for example 20 Hz, or higher frequency, an elastance measurement independent of a material setting tendency can be obtained.

It is also apparent that all pressures applied to a foam structured material during a manufacturing of an acoustic transducer assembly must be accounted for in order that the density of this material in the end product be known.

Furthermore, the technique for bonding the first layer 32 to the second layer 34 significantly affects the acoustic performance of the matching structure 22. The type of adhesive utilized varies with the materials in the matching structure. In the preferred embodiment the solid polyurethane elastomer is bonded to the polystyrene foam with a film 36 of epoxy cement, the film 36 being sufficiently thin and light weight so that its effect on the acoustic impedance may be neglected. However, in bonding the aforementioned polypropylene foam to the solid polyurethane elastomer, a contact cement is utilized, the contact cement being a quick setting synthetic rosin liquid cement.

Two further models of the invention built for experimental purposes utilized, in place of the polystyrene foam: (1) a 0.165 inch thick layer of rigid PVC (polyvinyl chloride) foam, and (2) a 0.16 inch thick layer of rigid urethane foam, the latter model further utilizing an outer covering of 0.003 inch thick layer of polytetrafluoroethylene (commonly known by the trade name Teflon) bonded to the rigid urethane foam by a pressure sensitive silicone adhesive bond, which in effect gives this model the characteristics of a three layer stratified acoustic matching structure. Epoxy cement was utilized in bonding the polyvinyl chloride foam and the urethane foam to the solid polyurethane elastomer.

The crystal 24 converts the energy in electrical signals conducted by wires 38 and 40 to mechanical energy which manifests itself as pulsations of the front face 26 and the back face 42 of the crystal 24. The front and back faces 26 and 42 are provided with silver coatings 44 and 46 and the wires 38 and 40 are affixed in a well-known manner to the edges, respectively, of the front and back faces 26 and 42 in electrical contact with the silver coatings 44 and 46. The wires 38 and 40 connect with a transformer 48 which has a torroidal form and is mounted in the back end of the case 30. Transformer 48 matches the electrical impedance of the transducer assembly 20 to that of a signal source (not shown) to which it is connected by leads 50 and connector 52. Connector 52 is preferably a hermetically sealed connector having the form known as "explosion proof".

The crystal 24 has a diameter of approximately 2 inches and an axial length of approximately 2 inches to be resonant at 41,500 Hz, in the axial mode of vibration. The case 30 has an inner diameter of approximately 2½ inches to provide an annular region around the crystal 24 for surrounding the crystal 24 with a suitable mount 54 which permits the front and back faces 26 and 42 to vibrate. The mount 54 is preferably composed of a cork neoprene mixture.

In the assembling of the transducer 20, the crystal 24 is encased in the mount 54 and then inserted with the transformer 48 into the case 30. The void between the mount 54, trans-

former 48 and the case 30 is filled with an epoxy jacket 56 with the exception of the front face 26. The front face 26 is coated, as is well known, with a priming agent after which the solid polyurethane elastomer of the first layer 32 is poured into place. The solid polyurethane elastomer being thermosetting, is allowed to cure, and then the first and the second layer 32 and 34 of the matching structure 22 are bonded together in the manner described earlier.

In operation, therefore, electrical signals entering the transducer assembly 20 along leads 50 are communicated by transformer 48 and wires 38 and 40 to the front face 26 and the back face 42 of the crystal 24. In response to the electrical signals the front face 26 vibrates and launches an acoustic wave through the matching structure 22 into the environment 28. Due to the relative acoustic impedances of the first and second layers 32 and 34, the layer 36 of the contact cement, and the environment 28 as well as the impedance of the crystal 24, an acoustic impedance match is obtained over a relatively broad band of frequencies.

Table 1, shown below provides data on power transmission and bandwidth of transducer assemblies employing various matching structures. The values shown are approximate. The data is obtained by a well known procedure in which the transducer assembly 20 is mounted in the end of a closed sound reflecting tube (not shown). The tube is filled with air. An electrical signal of relatively short duration is applied to the transducer assembly 20 which in response thereto, transmits a pulse of sound into the tube. The pulse of sound travels down the tube to its closed end, whereupon the sound pulse is reflected back to the transducer assembly 20. Upon receiving the sound pulse the transducer assembly 20 produces an electrical signal indicative of the power received from the sound pulse. The power transmission data shown in Table 1 is given in decibels which represent the ratio of the power received by a transducer assembly having a designated acoustic matching structure to the power received by a transducer assembly having no matching structure. The bandwidth data is given as a percentage of the center frequency of the sound transmission band. Each transducer assembly utilizes a piezoelectric crystal. The matching structures comprise one of more sections of designated materials in the form of layers each having a depth of approximately one-quarter wavelength of the sound transmitted in the material at a frequency of 41,500 Hz.

TABLE I

	Power	Bandwidth
no matching structure	0 db	2%
solid urethane	12 db	5%
cork	24 db	9%
solid urethane and polystyrene foam (the preferred embodiment)	36 db	15%

It is understood that the above described embodiments of the invention are illustrative only and that modifications thereof will occur to those skilled in the art. For example, a transducer assembly employing a piezoelectric crystal of quartz or barium titanate or similar material (as well as a magnetostrictive transducer) may be used, and any desirable mode of vibration of the crystal or form of acoustic wave may be used. Accordingly it is desired that this invention is not to be limited to the embodiment disclosed herein but is to be limited only as defined by the appended claims.

What is claimed is:

1. A transducer assembly comprising:

a transducer; and

a stratified medium for communicating acoustic wave energy between said transducer and a gaseous environment; said stratified medium being propagative of waves and having a depth along a direction of wave propagation of at

least one-quarter of the mean wavelength of the wave in the stratified medium, said stratified medium being formed of layers each of which presents a predetermined characteristic impedance to acoustic waves, said layers being arranged serially between said transducer and said environment along the direction of wave propagation such that there is presented to the propagating wave a variation in impedance characterized by substantially similar impedance ratios from the transducer through the successive layers to the gaseous environment;

one of said layers being formed of acoustically transmissive foamable materials drawn from the class consisting of polystyrene foam, polypropylene foam, polyvinylchloride foam, and urethane foam, and

means for improving the transmissivity of said acoustic wave energy between said stratified medium and said gaseous environment, said improving means being film structured and bonded to said stratified medium at an interface of said stratified medium with said gaseous environment.

2. A transducer assembly comprising:

a transducer; and

a stratified medium for communicating acoustic wave energy between said transducer and a gaseous environment;

said stratified medium being propagative of waves and having a depth along a direction of wave propagation of at least one-quarter of the mean wavelength of the wave in the stratified medium, said stratified medium being formed of layers each of which presents a predetermined characteristic impedance to acoustic waves, said layers being arranged serially between said transducer and said environment along the direction of wave propagation such that there is presented to the propagating wave a variation in impedance characterized by substantially similar impedance ratios from the transducer through the successive layers to the gaseous environment;

at least one of said layers being a composite material comprising regions of solid matter and regions of fluid matter, said one layer having a composite acoustic impedance resulting from the coaction of the regions of solid matter and the regions of fluid matter, the dimensions of said fluid region along the direction of wave propagation being less than one-tenth of the mean wavelength of the wave propagating within said layer, the layer of said stratified medium adjacent said transducer being solid elastomer and the layer of said stratified medium adjacent the environment being foam structured;

two of said layers each having a depth of one-quarter of the mean wavelength of sound propagating through that layer, said layer adjacent said transducer being formed of polyurethane, and the second layer being formed of acoustically transmissive foamable materials drawn from the class consisting of polystyrene foam, polypropylene foam, polyvinylchloride foam, and urethane foam;

said stratified medium further including a third layer, said second layer being composed of urethane foam, and said third layer being composed of polytetrafluoroethylene and having a depth of less than one-tenth the mean wavelength of sound propagating through the layer.

3. The transducer assembly of claim 2 wherein said transducer has a surface which vibrates in response to electrical stimulation.

4. The transducer assembly of claim 3 wherein said transducer assembly further includes electrical connection means and a transformer, said transformer being in circuit between said transducer and said electrical connection means whereby

electrical signals are communicated to the transducer.

5. The transducer assembly of claim 4 wherein said transducer assembly further includes a structure for supporting said stratified medium and said transformer in spaced relation to said transducer.

6. A first medium for communicating acoustic wave energy between a gaseous environment and a second medium having an acoustic impedance higher than that of the gaseous environment, said first medium being formed of layers arranged serially between said second medium and said gaseous environment;

a first one of said layers comprising a solid polyurethane elastomer having a density of approximately 71.8 pounds per cubic foot and a Shore A durometer in the range 75-95; and

a second one of said layers comprising a polystyrene foam having a closed cell composition and a density of 2 pounds per cubic foot.

7. The medium according to claim 6 wherein the cells in the polystyrene foam have dimensions which are less than one-tenth the sound wavelength in the polystyrene foam.

8. The medium according to claim 7 wherein the depth of said first layer and of said second layer is each an odd integral number of one-quarter wavelengths of the sound wavelengths within the respective layers.

9. A first medium for communicating acoustic wave energy between a gaseous environment and a second medium having an acoustic impedance higher than that of the gaseous environment, said first medium being formed of layers arranged serially between said second medium and said gaseous environment;

a first one of said layers comprising a solid polyurethane elastomer having a density of approximately 71.8 pounds per cubic foot and a Shore A durometer in the range 75-95; and

a second one of said layers comprising a foam material drawn from the class consisting of a polypropylene foam with rubber particles suspended therein, polystyrene foam, polyvinylchloride foam, and urethane foam.

10. The medium according to claim 9 in which said second layer comprises urethane foam and a third one of said layers comprises polytetrafluoroethylene.

11. A first medium for communicating acoustic wave energy between a gaseous environment and a second medium having an acoustic impedance higher than that of the gaseous environment, said first medium comprising:

a plurality of layers arranged serially between said second medium and said gaseous environment;

said first medium being propagative of waves and having a depth along a direction of wave propagation of at least one-quarter of the mean wavelength of the wave in said first medium;

one of said layers being formed of acoustically transmissive foamable materials drawn from the class consisting of polystyrene foam, polypropylene foam, polyvinylchloride foam, and urethane foam; and

means for improving the transmissivity of said acoustic wave energy between said first medium and said gaseous environment, said improving means being film structured and bonded to said first medium at an interface of said first medium with said gaseous environment.

12. The first medium according to claim 11 wherein one of said layers is a composite material comprising regions of solid matter and regions of fluid matter, said regions of fluid matter being prestressed cells of fluid.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,674,945 Dated July 4, 1972

Inventor(s) Edward Hands

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 2, line 49, change "propagation" to -- propagating --.

Column 4, line 57, change "wire" to -- wide --.

Column 4, line 62, change "as" to -- a --.

Column 8, line 42, change "polytetrafluorethylene" to -- polytetrafluoroethylene.--.

Signed and sealed this 20th day of November 1973.

(SEAL)

Attest:

EDWARD M. FLETCHER, JR.
Attesting Officer

RENE D. TEGMEYER
Acting Commissioner of Patents