

April 25, 1950

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2,505,364

COMPRESSION WAVE TRANSMISSION

Filed March 9, 1946

2 Sheets-Sheet 1

FIG. 1.

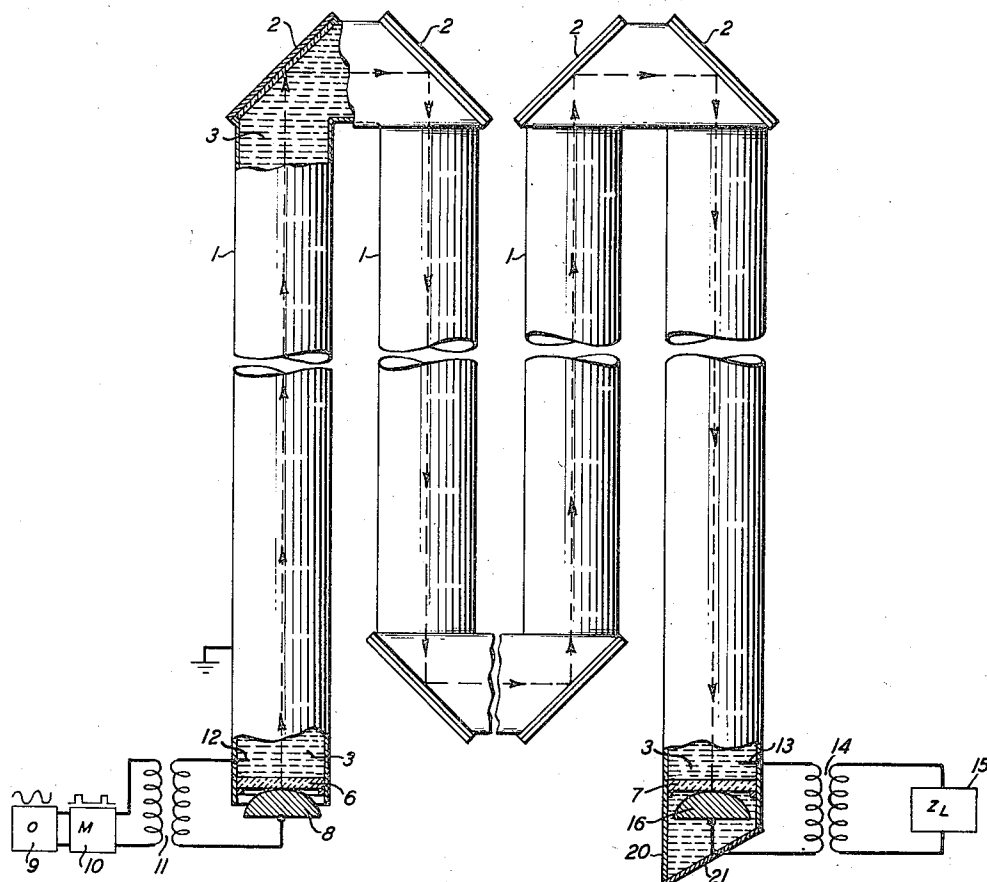


FIG. 4.

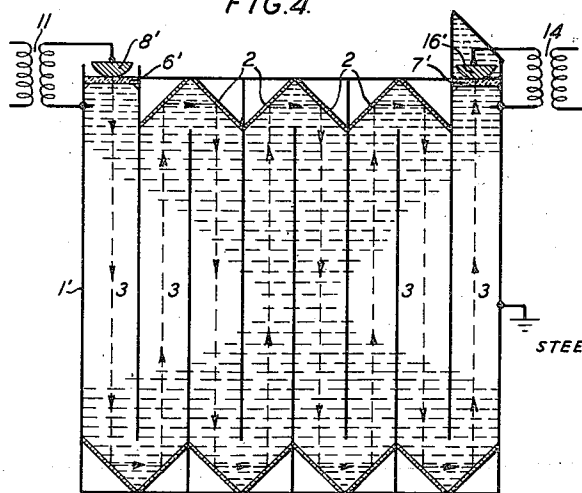


FIG. 2.
ETCHED OR GROUND
SURFACE

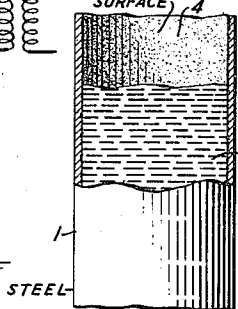
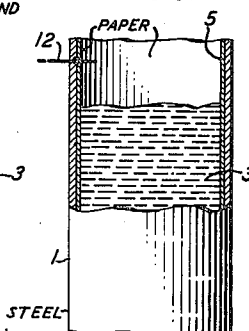


FIG. 3.



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2 Sheets-Sheet 2

FIG.5.

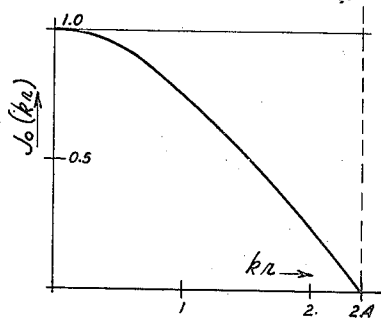
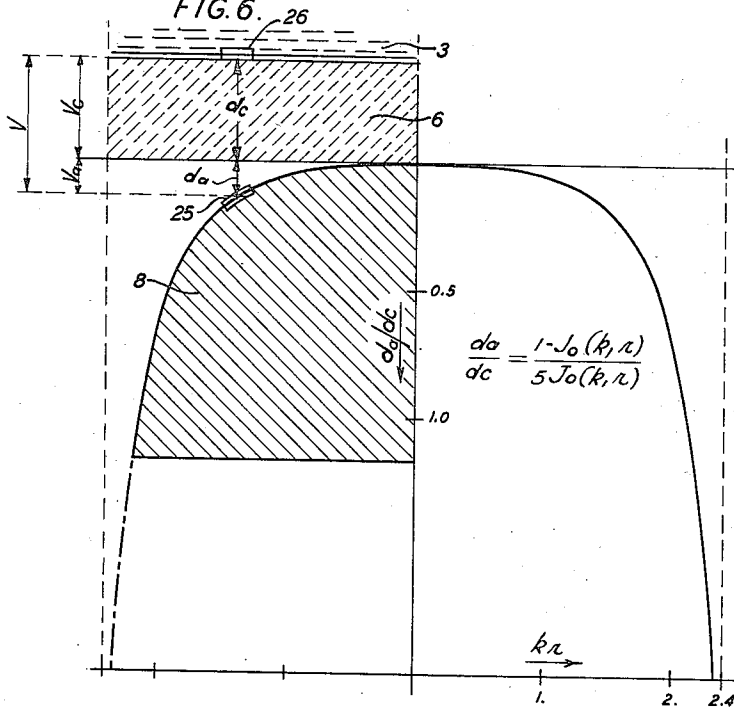


FIG. 6.



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COMPRESSION WAVE TRANSMISSION

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Application March 9, 1946, Serial No. 653,255

9 Claims. (Cl. 178—44)

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This invention relates to compression wave transmission and particularly to systems in which a compression wave developed by signal pressures in one region of a liquid confined in a conduit travels a considerable distance—usually a large number of wavelengths—thereafter to actuate a receiver or pick-up device located at another region of the liquid.

It is an object of the invention to reduce the transmission loss or attenuation in such a system.

A related object is to transmit a sharp pulse of energy from end to end of the conduit without substantial alteration of the pulse shape.

A subordinate object is to provide apparatus of the character described which shall be rugged, simple, and compact.

Problems arise in the communications art to solve which it becomes necessary to develop or introduce a definite time interval or delay of preassigned magnitude between a signal appearing in one part of a system and a like signal in another part. To secure this delay it is known to send a compression wave traveling from end to end of a fluid confined in a conduit. The signal is usually launched at one end of the conduit by an electromechanical transducer such as a piezoelectric crystal, guided to the far end by the conduit, and there picked up by another transducer. The time interval between actuation of the first transducer by the electric signal and actuation of the second transducer by the compression wave; i. e., the propagation time in the fluid, is the desired delay, which may be utilized in various ways and for various purposes.

In the past, systems of this kind have been characterized by considerable attenuation and phase distortion. When the path of the traveling wave is a large number of wavelengths long, as it must be for large time delays, these difficulties may result in a received signal which bears only a remote resemblance to the original signal and which, furthermore, may be so attenuated as to be seriously marred by random or noise effects. These difficulties are attributable to transmission losses in the fluid itself, to absorption of the wave energy by the conduit walls, and to the unequal propagation speeds of waves of the various modes which are normally excited by transducers of conventional variety.

Accordingly, subsidiary objects for effectuating the principal objects of the invention are as follows: To reduce energy losses by absorption in the conduit walls; and to restrict the wave energy to the fundamental or zero-order mode, all higher order modes being absent or of

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negligible energy, so that distortion of transmitted signals is kept as low as possible.

To these ends, a fluid medium is selected which has the lowest possible intrinsic energy loss or attenuation characteristic for the desired frequency range. Investigation of a number of different fluids indicates that for carrier frequencies in the 5-megacycle range, liquid mercury has the lowest internal losses. A secondary advantage in mercury is that its mechanical impedance per square centimeter is sufficiently high to permit operation over a wide frequency range.

This high intrinsic impedance, however, introduces a problem of another sort. In systems of standard design, employing fluids of lower impedance, energy losses by absorption in the conduit walls are avoided by making the wall impedance high, so that there is an impedance mismatch and consequently a high reflection coefficient, at the side boundaries of the fluid medium. But with a liquid such as mercury, no material for the conduit walls can be found whose impedance is of a still higher order.

In accordance with the invention this problem is in turn solved by making the wall impedance low compared with the fluid impedance, in which case an equally good impedance mismatch and reflection coefficient are obtained.

Applicant has discovered two kinds of boundary wall surface, superficially different but functionally similar which serve excellently. Measurements show that in each case the impedance of the surface to mercury compression waves is negligibly small; indeed, that it is of the same small order as that of air at atmospheric pressure.

One of these surfaces is a ground or etched surface on a hard substance such as steel, glass, brass, Bakelite or the like. The other is a lining of paper or other matted fibrous material, fitted snugly to the inside walls of the conduit and retained in place in any suitable fashion which does not involve saturation with glue or other hard adhesive which would destroy the matted structure.

The feature which is common to both of these surfaces is the occlusion or entrapment of a low impedance layer of air, or other ambient gas, between the wall of the conduit and the body of the mercury. In the case of the ground or etched surface it appears that the mercury, possibly by reason of its very high surface tension, bears against the high points or peaks of the surface, its boundary film hanging from them as a tent hangs from its tent poles, and does not come into intimate contact with the low points of the

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surface; i. e., does not "wet" the low points. Thus minute pockets of air are entrapped in the low parts or valleys of the surface, which air pockets form the major portion of the interfacial area and so constitute the governing factor in determining the impedance of the boundary surface.

In the case of the paper lining, air or other gas is entrapped in minute pockets among the fibres; and while the conduit wall proper determines the form or shape of the boundary surface in the gross sense, the trapped air determines its impedance.

In each case the effective boundary impedance is the average value over a given area of the impedance at each part of that area, and while the impedances at the high points or tips of the ground or etched surfaces and at individual fibres of the matted surface may be fairly high, their sum is small compared with the sum of the impedances of the other parts where the mercury bears only against air and where the impedance is negligible.

The exact type of paper is not critical, as long as the separation of the interstices in the matted fibrous structure is small compared to the wavelength to be propagated. Nor is the exact grain size of the etched or ground surface critical, as long as the surface is grossly smooth but finely rough, i. e., the separation between high points is on the average small compared to the wavelength to be propagated. The grain of the surface is preferably of such fineness that the average spacing between adjacent high points is of the order of a fraction, say $\frac{1}{5}$ to $\frac{1}{50}$ of the wavelength in the mercury. In any event, tool marks due to machining without grinding or etching, and spaced apart by distances of the order of a wavelength or so, have been found unsatisfactory, whereas etched or ground surfaces of steel, glass, Bakelite or any other hard substance have been found within wide margins of substance and grain to serve excellently.

With the high impedance mercury medium and low impedance conduit walls of the invention, the oscillatory component of the wave pressure at the walls vanishes ideally and actually is very low; whereas, for effective propagation of substantial amounts of energy this pressure in the body of the fluid column must be comparatively high. These conditions are compatible with various modal pressure distributions over a cross-section of the conduit. Of all these one is greatly to be preferred above all the others, i. e., the one in which the energy is all confined to the fundamental mode in which the pressure at a radius r from the central axis is proportional to the zero order Bessel function $J_0(kr)$ for a tube of circular cross-section, and to

$$\cos \frac{\pi x}{2l_x} \cos \frac{\pi y}{2l_y}$$

for a tube of rectangular section, where the factors k , l_x , l_y , are discussed below. This arises from the fact that the phase velocity depends on the modular constants k ,

$$\frac{\pi}{2l_x}, \frac{\pi}{2l_y}$$

so that if a sharp pulse is delivered to the head end of the conduit and carried the length of the tube by waves of more than one mode it will have suffered serious phase distortion and become spread out, possibly to the point of unrecogniz-

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ability, by the time it reaches the far end. This will be evident from the following analysis. The wave equation may be written in cylindrical coordinates for the conduit of circular cross-section

$$\frac{\partial^2 \Phi}{\partial r^2} + \frac{1}{r} \frac{\partial \Phi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \Phi}{\partial \varphi^2} + \frac{\partial^2 \Phi}{\partial z^2} = \frac{1}{v^2} \frac{\partial^2 \Phi}{\partial t^2} \quad (1)$$

where r , φ , z , t have their customary meanings as follows:

t is the time;

v is the propagation velocity in an infinite medium;

Φ is the velocity potential;

z is axial distance along the conduit from the driving end;

r is radial distance from the central axis, and

φ is angular distance about the central axis.

Restricting attention to waves of axial symmetry, the third term on the left-hand side of the equation is zero, and the solution for advancing waves may be written:

$$\Phi = A_0 J_0(k_1 r) \cos \left[\omega \left(t - \frac{z}{v_1} \right) \right] + A_1 J_0(k_2 r) \cos \left[\omega \left(t - \frac{z}{v_2} \right) \right] + \dots \quad (2)$$

or, in general

$$\Phi = \sum_n A_n J_0(k_n r) \cos \left[\omega \left(t - \frac{z}{v_n} \right) \right] \quad (3)$$

where

A_n is an amplitude coefficient,

k_n is the modular constant for the n th mode,

$k_n a$ ($= S_n$) is the n th root of the zero order Bessel function,

a is the radius of the tube,

n is the mode number,

$$\frac{\omega}{2\pi} = f \text{ is the driving frequency}$$

and

$$v_n = \frac{\omega}{\sqrt{\omega^2 - k_n^2}} \text{ is the propagation velocity for the } n\text{th mode.} \quad (4)$$

As is well known, the pressure p is derivable from the velocity potential Φ and has the same distribution over any cross-section, though displaced in time phase. From the last expression it is evident that the phase velocity depends on the mode number. This results in phase distortion which increases progressively along the conduit. Similar considerations hold for conduit cross-sections other than circular.

At extremely low frequencies and long wavelengths reliance may be placed on rapid attenuation of higher order modal waves to prevent, or at least to minimize, this sort of phase distortion. It is shown in "Electromechanical Transducers and Wave Filters" by W. P. Mason, at pages 106-110 that when the longest side of a conduit of rectangular cross-section is less than one-half wavelength long, higher order modes cannot be propagated over long distances. The same result obtains for a circular cross-section conduit when the diameter is less than 0.6 times the wavelength. But in the ultrasonic frequency range of principal interest such a minute cross-section would be the merest capillary. Manufacturing considerations demand that the diameter or shortest side of the cross-section measure at least several wavelengths. Applicant has had

success with circular cross-section conduits whose diameter is of the order of an inch; i. e., about 100 wavelengths. Consequently, if higher modal oscillations are to be avoided they must be prevented from coming into being in the first instance.

This prevention is accomplished in accordance with the invention by causing the driving transducer face to exert pressures on the fluid medium which at all times and at all points of contact conform to the pressure distribution which characterizes the zero order oscillation mode. By way of example, this pressure distribution is given for the circular cross-section conduit by

$$p \sim J_0(k_1 r) \quad (5)$$

where

$$k_1 = \frac{S_1}{a} = \frac{2.4}{a}$$

a being the conduit radius, and S_1 the first root of $J_0(x)$, and by

$$p \sim \cos \frac{\pi}{2l_x} x \cos \frac{\pi}{2l_y} y \quad (6)$$

for the tube of rectangular cross-section, l_x and l_y being the half-lengths of the sides, and the origin being at the mid-point of the cross-section. Because of the high degree of damping of the crystal vibrations by radiation into the mercury, the movement of the crystal at each point of its face is substantially proportional to the voltage impressed on that point. Applicant makes use of this fact to obtain precise control of the crystal movement by a novel shaping of the driving electrode. In accordance with the invention the driving electrode is rounded or domed to an appropriate shape and placed in central contact with the crystal so that there exists a separation between it and the crystal of a magnitude which increases progressively in a radial direction and in accordance with a certain formula.

For the zero order Bessel function pressure distribution, the electrode shape is given by the formula:

$$\frac{d_a}{d_c} = \frac{1 - J_0(k_1 r)}{\frac{K_c}{K_a} J_0(k_1 r)} \quad (7)$$

where

K_c is the dielectric constant of the crystal,

K_a is the dielectric constant of the medium separating the crystal from the driving electrode, d_c is the axial length (thickness) of the crystal, and

d_a is the axial length of the separating medium.

The corresponding formula for an electrode actuating a crystal which drives plane waves into a liquid column of rectangular cross-section is

$$\frac{d_a}{d_c} = \frac{1 - \cos \frac{\pi x}{2l_x} \cos \frac{\pi y}{2l_y}}{\frac{K_c}{K_a} \cos \frac{\pi x}{2l_x} \cos \frac{\pi y}{2l_y}} \quad (8)$$

If for any reason it is desired not to employ the domed driving electrode, or if despite its use travelling waves of higher order modes exist in the liquid medium, then it is of advantage to employ a domed electrode for the receiving crystal because a piezoelectric receiving element so constructed responds only to the desired zero order waves.

The above mathematical expressions, which are derived below, represent the ideal electrode forms for crystals generating waves in ideal conduits.

As the actual conduit departs from the ideal, so the optimum electrode shape departs from the shape given by the above formulae. This diminishes the importance of exactly conforming the electrode to the shape given by the formulae. Good results may be obtained with a rough approximation, i. e., with an electrode having its front face curved approximately to the shape of an oblate spheroid or even a conventional door knob.

The invention will be more fully understood from the following detailed description of a preferred embodiment illustrated in the drawings, of which

Fig. 1 shows a compression wave transmission system in accordance with one form of the invention;

Figs. 2 and 3 show, to an enlarged scale, a portion of the conduit of Fig. 1, broken open to reveal the low loss, high impedance propagation medium and two alternative forms of the low impedance conduit boundary walls of the invention;

Fig. 4 shows a geometrical arrangement alternative to Fig. 1;

Fig. 5 is a diagram showing the optimum pressure distribution over the face of a crystal driving a liquid column of circular section; and

Fig. 6 is a diagram showing the ideal form of a driving electrode for a crystal driving a tube of circular cross-section, together with its mathematical expression.

Referring now to the figures, Fig. 1 shows a conduit or tube 1 of substantial overall length, bent back on itself for compactness. It may be constructed of steel tubing and block fittings at the bends to reduce reflection losses. There should be as few changes in diameter as possible, i. e., the inside diameter of each bend fitting should be equal to that of the straight portions. The bend fittings are provided with reflecting plates 2 placed at angles of 45 degrees to the oncoming wave. The tube 1 is broken open to show one of these reflectors in place.

Fig. 2 shows the inner construction of the conduit 1 in one form to an enlarged scale. The outer wall has been broken away to show the mercury medium 3 which has been broken away, in turn, to show the ground or etched wall surface 4 of the tube. The surfaces of the reflectors 2 are preferably the same as the surfaces of the inner walls of the tube. The grain of these surfaces may be of a fineness of approximately 200 to 1000 points to the inch, measured in any direction.

Fig. 3 is similar to Fig. 2, the tube wall 1 and the mercury 3 being broken away to show the paper lining 5 for the conduit walls and reflecting faces which affords an alternative construction to the etched or ground surfaces of Fig. 2. It is undesirable and unnecessary to employ any adhesive to hold the paper in place. The hydrostatic pressure of the mercury is sufficient for this purpose.

A pair of bend fittings may be conveniently made from a block of steel through which two holes are drilled of diameter equal to the inside diameter of the tubes, intersecting each other accurately at right angles. The block is then cut in half along its diagonal and a reflecting plate fastened, as by screws, over the opening at the intersection of the drilled holes. Care should be exercised to hold the reflecting plate in correct 45-degree alignment with the axis of the tube.

The tube 1 is provided at its head end with a driving crystal 6 and at its receiver end with a

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receiving crystal 7. The crystals 6, 7 may be mounted in the tube by clamping between threaded washers or in any convenient manner. The crystals may be of any desired type which is capable of vibrating axially in the thickness mode. For example, they may be of the well-known X-cut variety described in "Electromechanical Transducers and Wave Filters" by W. P. Mason, (Van Nostrand 1942) at page 198. They are preferably one-half wavelength in thickness at the operating frequency. At a frequency of 5 megacycles, for example, this is approximately 0.05 centimeter for X-cut, thickness mode, quartz crystals.

The tube 1 is filled with mercury 3 which not only serves as the transmission medium but serves also as one electrode for each of the crystals 6, 7. It may be connected to ground, thus avoiding any difficulties which might arise by reason of a potential difference between the conduit and ground.

One electrode for the driving crystal may be supplied by the mercury 3 in contact therewith, mercury being a good conductor of electricity. The other electrode is the external electrode 8, shaped as hereinafter described. These electrodes are supplied with voltage from a suitable source, for example a source of high-frequency carrier waves, divided from an oscillator 9, and modulated by a complex wave of lower frequency, schematically indicated as a square wave, by a modulator 10. The modulated output may be supplied by way of a transformer 11 to the electrode 8 which may be directly connected to the secondary winding of the transformer 11 and to the mercury column 3 by way of one electrode 12 which passes through the tube wall 1 and the paper lining 5, if present. When the etched or ground surface 4 is employed, electric connection with the mercury 3 may be directly established by way of the tube wall 1.

One electrode of the output crystal 7 is provided by the mercury 3, electric contact with one terminal 13 of an external load circuit 14, 15, being established as described above. For best results the impedance offered by the load circuit 14, 15 to the crystal generator comprising the elements 3, 7, 16, is preferably of a relatively low value. The other output crystal electrode 16 may be of conventional form and may be connected to the other terminal of the load circuit. However, improved results may be secured when the output electrode 16 is domed according to the same formula as the input electrode.

Beyond the output crystal 7 and its electrode 16 is a mercury end cell which may comprise an extension 20 of the tube 1 terminated by a plate 21 which preferably lies at an angle to the tube axis. All walls of this end cell may be of absorbent material. The absorbent walls and the end plate 21 together serve to reduce reflections by the crystal 7 back into the mercury column 3 and so to prevent any establishment of standing waves and propagation of energy through the tube in the undesired direction.

Fig. 4 shows modified apparatus in which the cross-section is rectangular. This offers certain advantages of compactness as compared with the arrangement of Fig. 1. In function in the character of the wall surfaces in the mercury end cell and in the associated circuits, it may be identical with the apparatus of Fig. 1. The crystals 6' and 7' may be cut to rectangular peripheral shape and may otherwise be the same as the

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crystals 6 and 7 of Fig. 1. The external electrodes 8' and 16' may be domed, but the formula expressing their shape differs from that which expresses the shape of the electrodes 8 and 16 of Fig. 1. Those of Fig. 1 are shaped in accordance with the Formula 7 while those of Fig. 4 are shaped in accordance with the Formula 8, specialized, in each case, for air as the medium between the crystal and the external domed electrode.

Air serves adequately as the spacing material between crystal and electrode because high voltages are not involved, and it offers advantages of convenience. With air and quartz as the media, the fraction

$$\frac{K_c}{K_a} = 5 \text{ approximately}$$

Fig. 5 is a plot of the well-known zero-order Bessel function $J_0(kr)$ which reaches the value of 1.0 for $kr=0$ and reaches the value zero for $kr=2.40$. The right-hand portion of Fig. 6 is a plot, to the same scale, of the function

$$\frac{d_a}{d_c} = \frac{1 - J_0(kr)}{5J_0(kr)} \quad (9)$$

i. e., of the thickness function 7 for air as a medium between a quartz crystal and a metal electrode. The left-hand portion of Fig. 6 is a cross-sectional diagram to the same scale of one-half of the driving electrode of the invention, domed in accordance with the above equation. The magnitudes d_c and d_a are indicated on the figure.

With the help of Fig. 6 the manner in which the Expressions 7 and 9 for the circular tube electrode air-gap are arrived at will be clear. Thus, consider an elementary condenser formed of the two electrode elements 25, 26 and the two dielectrics (quartz and air) between them. If the voltage between the electrodes is V, the charge on one is $+q$ and on the other $-q$, and the total capacitance is C, then

$$q = CV = C_a V_a = C_c V_c \quad (10)$$

where

V_c is the voltage across the crystal,

V_a is the voltage across the air space,

C_c is the capacitance of the crystal portion,

C_a is the capacitance of the air space portion, and

$$C = \frac{C_a C_c}{C_a + C_c} \quad (11)$$

from the law governing the capacitance of condensers in series. From these equations,

$$V_c = \frac{C}{C_c} V = \frac{C_a}{C_a + C_c} V \quad (12)$$

Now the capacitance of each condenser is proportional to its area and the dielectric constant of the medium, and inversely to its thickness, i. e.,

$$C = \frac{KA}{4\pi d}$$

where A is the area of the elementary condenser. Therefore, since the factor

$$\frac{A}{4\pi}$$

is common to numerator and denominator of (12),

$$V_e = \frac{\frac{K_a}{d_a}}{\frac{K_a}{d_a} + \frac{K_e}{d_e}} V \quad (13)$$

or

$$\frac{V_e}{V} = \frac{d_e}{d_e + \frac{K_e}{K_a} d_a} \quad (14)$$

As explained above, to secure a crystal pressure on the mercury column whose radial distribution is proportional to $J_0(k_1 r)$, it suffices to apply to its faces a voltage having this same radial distribution per unit of voltage applied to the electrodes. Therefore, we may equate

$$\frac{V_e}{V} \text{ to } J_0(k_1 r)$$

Thus,

$$\frac{V_e}{V} = J_0(k_1 r) = \frac{d_e}{d_e + \frac{K_e}{K_a} d_a} \quad (15)$$

whence

$$d_a [J_0(k_1 r) - 1] + \frac{K_e}{K_a} J_0(k_1 r) d_a = 0$$

or

$$\frac{d_a}{d_e} = \frac{1 - J_0(k_1 r)}{\frac{K_e}{K_a} J_0(k_1 r)} \quad (7)$$

From the above example it will be apparent to those skilled in the art how a domed electrode may be designed to excite zero order mode (plane) waves in a conduit of cross-section other than circular; in particular, a conduit of rectangular cross-section, for which the electrode form is given by Formula 8.

If for any reason it be convenient to employ the domed driving electrode of the invention, or if despite its use and because of departures from the ideal conditions in which the above analysis rigorously holds, or for any other reason, traveling waves having higher order modal pressure distributions reach the receiving crystal, and if the latter is provided with a plane external electrode of conventional form, then these higher order components will appear as distortion components in the output. When, however, the external electrode 16 of the receiving crystal 7 is domed to the same form as the driving crystal 6, then such higher order components of the travelling wave do not appear in the external circuit. By an analysis closely paralleling that given above for the driving crystal, it can be shown that the electric charge Qr which appears on the elementary condenser plate 25 due to piezoelectric action of the compression waves in the mercury acting on the receiving crystal is proportional to the product of the charge appearing on the crystal due to this action and a form factor due to the dome shape of the electrode. In particular,

$$Qr = Qp J_0(k_1 r) \quad (16)$$

for the cylindrical conduit, and

$$Qr = Qp \cos \frac{\pi x}{2l_x} \cos \frac{\pi y}{2l_y} \quad (17)$$

for the tube of rectangular cross-section, where

Qp is the charge released on the crystal surface due to piezoelectric action and all other symbols have the meanings given them above.

Now a wave of circular symmetry but of higher order than the lowest will give rise to a charge Qp whose radial distribution is given by the higher order Bessel functions:

$$J_0(k_2 r), J_0(k_3 r), \dots J_0(k_n r)$$

or any combination of these, where

$$k_2 = \frac{5.52}{a}, k_3 = \frac{8.65}{a}, \text{ etc.}$$

a being the radius of the conduit, as before; i. e., successive values of ka are the successive roots or zeros of the J_0 function.

Considering the second order function by way of example, (16) becomes

$$Qr = A_2 J_0(k_2 r) J_0(k_1 r) \quad (18)$$

where A_2 is a constant of proportionality.

The total resulting charge on the external electrode 16, and therefore the current in the external load circuit 15 which should be of relatively low impedance is then obviously the sum for all elementary areas of the electrode of the charges (18) appearing on each one. Thus

$$Q = \int_0^{2\pi} \int_0^a Qr r dr d\theta \quad (19)$$

$$Q = 2\pi A_2 \int_0^a r J_0(k_2 r) J_0(k_1 r) dr \quad (20)$$

The Expression 20 is known to have the value zero. Reference may be made to any standard text on Bessel functions or to Byerly's "Fourier Series and Spherical Harmonics" (Ginn and Co., 1893) page 228. The same considerations and a parallel analysis hold for the tube of rectangular cross-section, in which case the piezoelectric charge Qp is given by the higher order trigonometric functions

$$\cos \frac{2\pi x}{2l_x} \cos \frac{\pi y}{2l_y}, \cos \frac{\pi x}{2l_x} \cos \frac{2\pi y}{2l_y}, \cos \frac{2\pi x}{2l_x} \cos \frac{2\pi y}{2l_y}, \text{ etc.}$$

or any combination of them. Those skilled in the art will recognize that the surface integral, over the surface of the external electrode, of the product of a factor of any one of these forms by a factor of the form

$$\cos \frac{\pi x}{2l_x} \cos \frac{\pi y}{2l_y}$$

representing the contribution of the correctly domed electrode, is identically zero.

The propagation speed of compression waves in unconfined mercury is 1.5×10^5 centimeters per second at standard temperature and pressure. At a frequency of 5 megacycles per second, the wavelength is 0.03 centimeter. Under these conditions a transmission line of the type described, one inch in diameter, provided with a half wavelength, thickness mode, quartz crystal at each end and a driving electrode of the type described can carry signal energy, for example short pulses, of a fundamental frequency of 5 megacycles for a distance of 24 feet, i. e., over 200,000 wavelengths, without excessive transmission loss or distortion, to give rise in the output load circuit to a faithful replica of the input signal, delayed by 5 milliseconds with respect thereto. The apparatus is characterized by simplicity, ruggedness, compactness and reliability in operation.

The conduit may, of course, be extended in a straight line, if desired. Usually folding will be resorted to for the sake of compactness.

The invention has been described in terms of an embodiment in which driving pressure and output current were both obtained from piezoelectric crystals, and one feature of the invention is a novel electrode for such a crystal. It will be understood by those skilled in the art that other types of transducers, for example, an electromagnetically actuated diaphragm, or array of diaphragms, can also be employed, and that actuation of such diaphragms in such a manner as to suppress oscillations of higher modes is within the spirit of the invention; that the transducer comprising the crystal plate and the domed electrode therefor may find uses independent of the wave guiding conduit in connection with which it has been described; and that advantage may equally be taken of the low wall impedance feature of the invention when the driving means is a transducer other than a crystal or when the wave carrying fluid medium is other than mercury.

In the foregoing and in the claims the words "ground" and "etched" which, grammatically speaking are past participles of the verbs to "grind" and to "etch," are employed as adjectives to describe the character of a grossly smooth but finely rough surface. The process by which such a surface is obtained is of no importance for the present application.

What is claimed is:

1. In compression wave transmission apparatus, a conduit of circular cross-section, a fluid of high characteristic impedance substantially filling said conduit, the inner surfaces of the walls of said conduit offering a low impedance to said fluid, and an electromechanical transducer at one end of said conduit for generating longitudinal waves in the fluid, which transducer comprises a piezoelectric crystal disc having a face in contact with the fluid and normal to the conduit axis, and an external electrode in cooperative association with the other face of said crystal, the face of said external electrode in contact with said crystal being domed to the form

$$\frac{d_a}{d_c} = \frac{1 - J_0(k_1 r)}{K_a J_0(k_1 r)}$$

where

d_a is the separation of the domed electrode from the crystal,

d_c is the crystal thickness,

K_c is the dielectric constant of the crystal,

K_a is the dielectric constant of the separating medium,

$$k_1 = \frac{2.4}{a}$$

and

a is the radius of the crystal disc.

2. In compression wave transmission apparatus, a conduit of rectangular cross-section, a fluid of high characteristic impedance substantially filling said conduit, the inner surfaces of the walls of said conduit offering a low impedance to said fluid, and an electromechanical transducer at one end of said conduit for generating longitudinal waves in the fluid, which transducer comprises a thin rectangular piezoelectric crystal having a face in contact with the fluid and normal to the conduit axis and an external electrode in cooperative association with the other face of said

crystal, the face of said external electrode in contact with said crystal being domed to the form

$$\frac{d_a}{d_c} = \frac{1 - \cos \frac{\pi x}{2l_x} \cos \frac{\pi y}{2l_y}}{\frac{K_c}{K_a} \cos \frac{\pi x}{2l_x} \cos \frac{\pi y}{2l_y}}$$

where

d_a is the separation of the domed electrode from the crystal,

d_c is the crystal thickness,

K_c is the dielectric constant of the crystal,

K_a is the dielectric constant of the separating medium,

l_x is the half length of one edge of the rectangular crystal wafer, and

l_y is the half length of an adjacent edge of the rectangular crystal wafer, the origin being at the center of the crystal wafer.

3. Compression wave transmission apparatus which comprises a supporting conduit having at least two substantially straight portions of uniform cross-section interconnected by a bend, at least one reflector mounted in said bend and oriented to direct wave energy incident thereon from one straight portion into an adjacent straight portion, a liquid of high intrinsic impedance, high surface tension, and low absorptivity to gases substantially filling said conduit and being supported thereby and by said reflector, thereby constituting a bent liquid column adapted to support compression waves propagated from end to end thereof, a piezoelectric crystal driving element mounted at an end of said conduit in position to launch compression waves into said liquid column, a wave receiver at the other end of said conduit, the internal wall surfaces of said conduit and of said reflector having a roughness of grain size of the order of $\frac{1}{5}$ to $\frac{1}{50}$ of a compression wavelength in said liquid, the spaces between the high points of said rough surfaces constituting minute pockets covering the major part of the area of juxtaposition of said surfaces with said liquid, and a gas entrapped in said pockets, said gas providing a low impedance reflecting boundary throughout substantially the whole surface of said liquid column with the exception of those surfaces at which it is in contact with said driving element and with said receiver, whereby compression wave energy launched into said liquid column by said driving element travels to said receiver without substantial absorption by said interior wall surfaces or by said reflector.

4. In compression wave transmission apparatus, a wave guide conduit, a liquid of high intrinsic impedance and high surface tension substantially filling said conduit, the interior surfaces of the conduit walls being roughened to a texture such that substantial areas of said interior surfaces remain unwetted by said liquid, whereby a low-impedance reflecting boundary is presented to said liquid, means for applying high frequency pressures to said liquid at one part of said conduit, and means for utilizing the energy of high frequency compression waves propagated through said liquid to another part of said conduit.

5. In compression wave transmission apparatus, a wave guide conduit, a liquid of high intrinsic impedance and high surface tension substantially filling said conduit, the interior surfaces of the conduit walls being ground to a texture such that substantial areas of said interior surfaces remain unwetted by said liquid, whereby a low-impedance reflecting boundary

is presented to said liquid, means for applying high frequency pressures to said liquid at one part of said conduit, and means for utilizing the energy of high frequency compression waves propagated through said liquid to another part of said conduit.

6. In compression wave transmission apparatus, a wave guide conduit, a liquid of high intrinsic impedance and high surface tension substantially filling said conduit, the interior surfaces of the conduit walls being etched to a texture such that substantial areas of said interior surfaces remain unwetted by said liquid, whereby a low-impedance reflecting boundary is presented to said liquid, means for applying high frequency pressures to said liquid at one part of said conduit, and means for utilizing the energy of high frequency compression waves propagated through said liquid to another part of said conduit.

7. In compression wave transmission apparatus, a wave guide conduit, a liquid of high intrinsic impedance and high surface tension substantially filling said conduit, a thin layer of a matted, fibrous material lining the interior surfaces of the conduit walls and of a texture such that substantial areas of said interior surface lining remain unwetted by said liquid, whereby a low-impedance reflecting boundary is presented to said liquid, means for applying high frequency pressures to said liquid at one part of said conduit, and means for utilizing the energy of high frequency compression waves propagated through said liquid to another part of said conduit.

8. In compression wave transmission apparatus, a wave guide conduit, a liquid of high intrinsic impedance and high surface tension substantially filling said conduit, a thin layer of paper lining the interior surfaces of the conduit walls and of a texture such that substantial areas of said interior surface lining remain unwetted by said liquid, whereby a low-impedance reflecting boundary is presented to said liquid, means for applying high frequency pressures to said liquid at one part of said conduit, and means for utilizing the energy of high frequency compression waves propagated through said liquid to another part of said conduit.

9. Compression wave transmission apparatus which comprises a supporting conduit having at least two substantially straight portions interconnected by a bend, at least one reflector mounted in said bend and oriented to direct wave energy incident thereon from one straight portion into an adjacent straight portion, a liquid of high intrinsic impedance, high surface tension, and low absorptivity to gases substantially filling said conduit and being supported thereby and by said reflector and providing a bent path for compression waves propagated from end to end thereof, a piezoelectric crystal driving element mounted at an end of said conduit in position to launch compression waves into said liquid, and a wave receiver at the other end of said conduit, the front face of said reflector being roughened to a texture such that it remains substantially unwetted by said liquid, whereby a low-impedance reflecting surface is presented to said liquid.

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