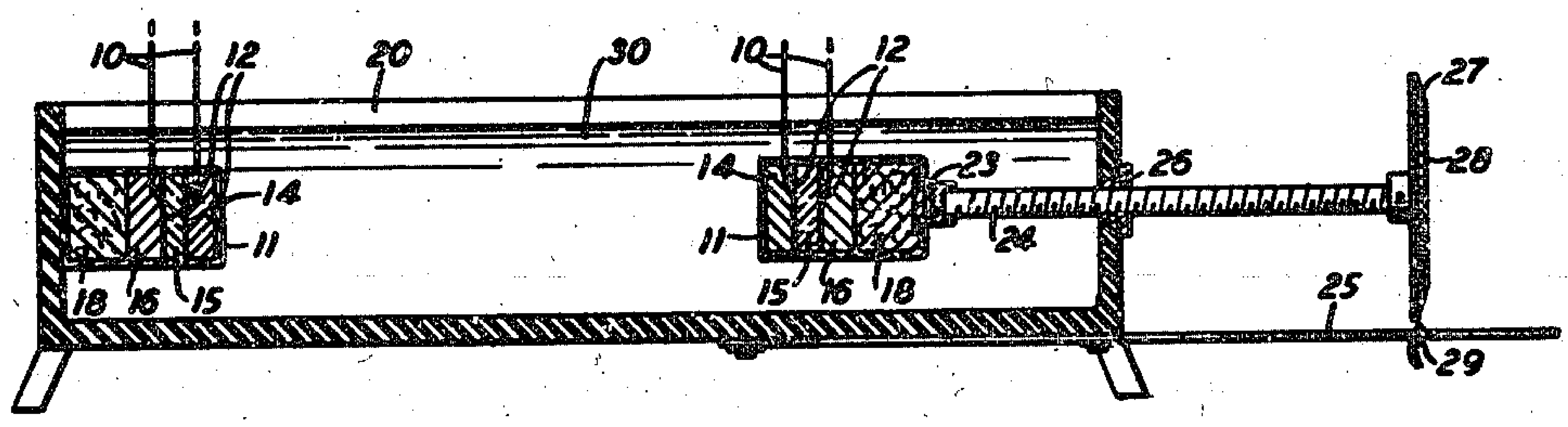
Sept. 16, 1947. W. L. BOND ET AL 2,427,348

PIEZOELECTRIC VIBRATOR

Filed Aug. 19, 1941

FIG. 1



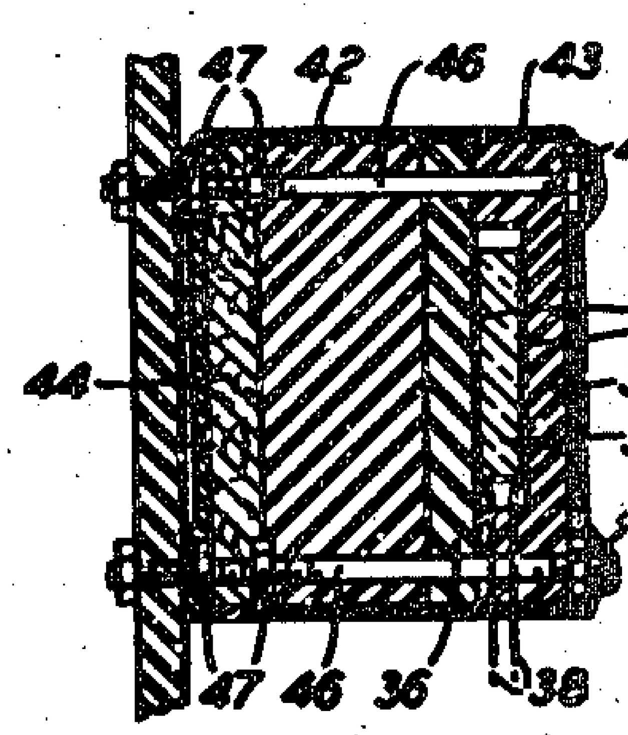
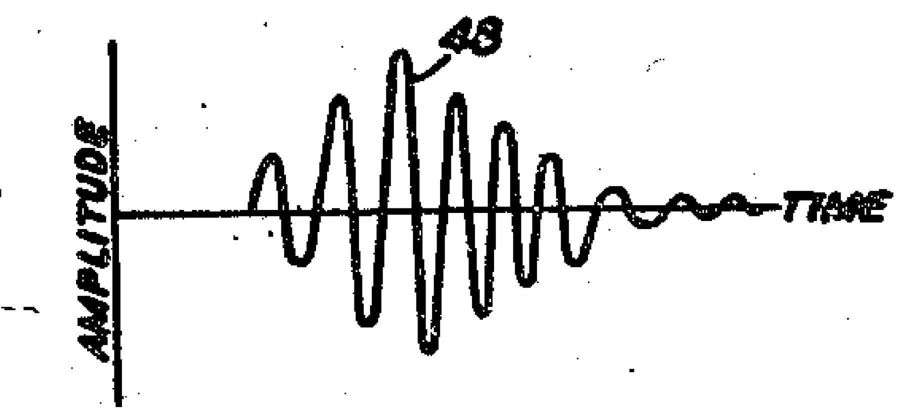


FIG. 2

FIG. 3A



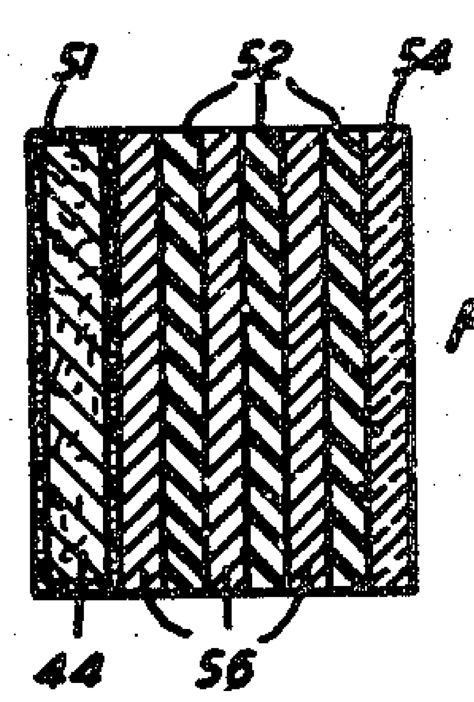


FIG. 5

FIG. 3B

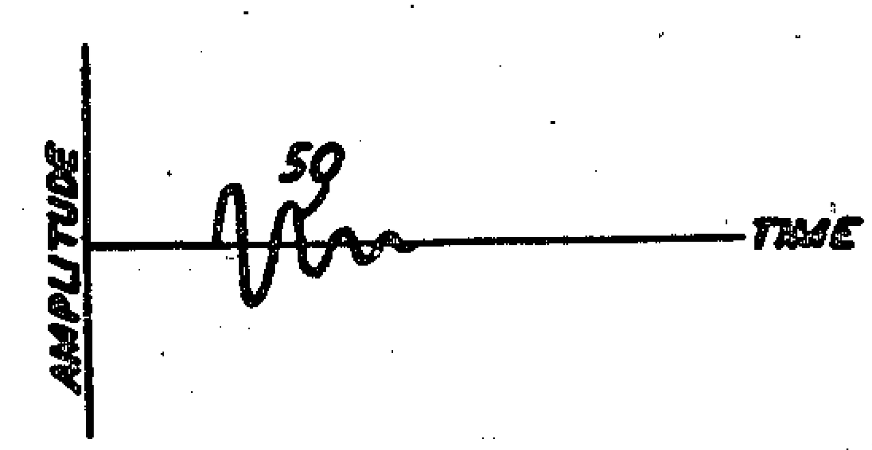
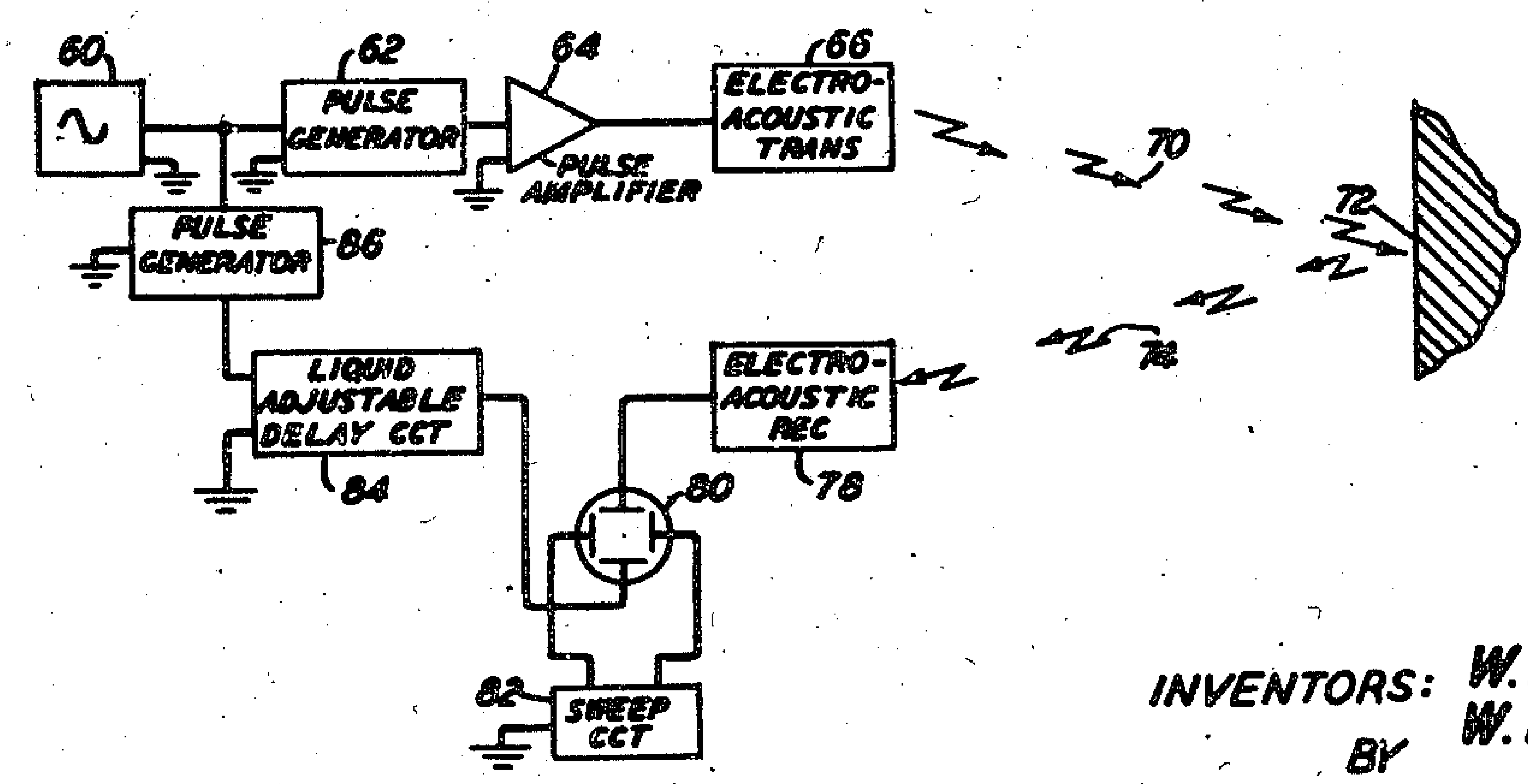


FIG. 4



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PIEZOELECTRIC VIBRATOR

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4 Claims. (Cl. 177—386)

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This invention relates to improved energy radiating and absorbing devices of the piezoelectric type and to improved pulse timing arrangements employing such devices. More particularly it relates to improved methods and means for reducing or eliminating unwanted reflections of compressional wave energy at the surfaces of a piezoelectric crystal and to improving the response characteristics thereof to the end that harmful echoes, back reflections and the like, of compressional wave energy, are substantially minimized and the efficiencies of the crystal and the system in which it is employed are increased.

It is known in the art to employ piezoelectric crystals to convert electrical wave energy into compressional (or acoustic) wave energy and the reverse.

In systems employing crystals in this manner, however, a number of difficulties have been encountered, among which are relatively low efficiency, echo effects resulting from reflections from the crystal surfaces, echo effects resulting from radiation by the crystal in directions other than a particular desired direction and unwanted resonant and transient effects in the vibratory response of the crystal.

It has been found that the above-mentioned and possibly additional undesirable effects largely result from or are aggravated by substantial "acoustic impedance" or compressional wave impedance differences between the crystal and the medium in which it is used.

The "acoustic impedance" or compressional wave impedance (Z_a) of a material is usually defined as the product of the velocity of propagation, V, of acoustic or compressional waves through the material and the density of the material ρ, i. e.,

$$Z_a=\rho V \qquad (1)$$

For convenient reference representative values of the acoustic or compressional wave impedances for a number of materials which may be employed in systems illustrative of the principles of the invention are tabulated below:

Material (c. g. s. units)	$Z_a=\rho V$
Methyl methacrylate	2.84×10^5
Polystyrene	2.64×10^5
Cellulose acetate	3.26×10^5
Molded phenol formaldehyde	3.75×10^5
Urea formaldehyde	4.2×10^5
India ebony	4.4×10^5
X-cut quartz	14.4×10^5
Aluminum	13.8×10^5
Tungsten	83.0×10^5
Water	1.44×10^5
Steel	40.0×10^5
Rochelle salt	5.76×10^5
Kerosene	1.04×10^5
85% permalloy, 15% phenol formaldehyde [1]	12.8×10^5
85% tungsten, 15% phenol formaldehyde [1]	14.0×10^5
30% permalloy, 70% phenol formaldehyde [1]	4.55×10^5
30% tungsten, 70% phenol formaldehyde [1]	4.55×10^5

[1] Percentages given are by weight.

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In systems employing piezoelectric crystals to radiate or receive acoustic or compressional waves in a liquid, steps should be taken to alleviate the effects of a mismatch of impedance between crystal and liquid.

This can best be done by inserting between the liquid and the crystal a layer of material having an acoustic or a compressional wave impedance which is substantially the geometric mean of the impedances of the crystal and the liquid, the thickness of the layer of material in the direction of propagation being substantially one-quarter wave-length of the frequency of the energy, or of the mean or predominant frequency where a band of frequencies is being propagated. An odd multiple of the quarter wave-lengths in thickness may be used provided the acoustic or compressional wave energy absorption (or attenuation) of the material is not undesirably high.

Such a layer of material then acts as an impedance transformer and provides an improvement in the impedance match between the impedance of the crystal and that of the liquid and substantially reduces reflection losses therebetween and therefore materially reduces echo effects and similar undesirable reflective phenomena which can otherwise arise in many systems employing piezoelectric crystals in connection with compressional wave transmission systems.

By way of example, for a quartz crystal, having a compressional wave impedance of 14.4×10^5 c. g. s. units, immersed in water of 1.44×10^5 c. g. s. units impedance, a material having an acoustic impedance of

$$10^5\ \sqrt{1.44\times14.4}=4.55\times10^5$$

c. g. s. units should be interposed between the crystal and the liquid.

To avoid electrical difficulties it is preferable that the material placed adjacent the crystal should be non-conducting. Plastics such as phenol, formaldehyde, methyl methacrylate, polystyrene and the like fulfill this requirement but in general have high absorption (i. e., dissipation) of compressional wave energy and low compressional wave impedance. Metals on the other hand have low absorption and high compressional wave impedance but are highly conductive.

It has been found possible to combine metals and plastics either in alternate layers or in the form of metallic particles suspended in a plastic to obtain composite materials which will provide characteristics intermediate those of the constituent materials. For example, the plastic, phenol formaldehyde, with 30 per cent by weight of powdered Permalloy suspended therein (so-called 85 per cent Permalloy, i. e. 85 per cent Ni, 15 per cent Fe, in alloy form, being used) has a compressional wave impedance of substantially 4.55×10^5 c. g. s. units which, as mentioned above, is suitable for a material to act as an impedance transforming layer between a quartz crystal and water. The material is, furthermore, electrically non-conductive and has a lower absorption than phenol formaldehyde alone.

For Rochelle salt piezoelectric crystals employed to radiate or absorb compressional waves in water, a material having a compressional wave impedance of $10^5 \sqrt{1.44 \times 5.76} = 2.88 \times 10^5$ c. g. s. units should be interposed between the crystal and the water. From the tabulation given above it is seen that methyl methacrylate has substantially the desired compressional wave impedance. In this particular case the enclosure of the crystal should be moisture-proof since Rochelle salt is soluble in water.

In general, by suspending metallic particles in a plastic, as suggested previously, any compressional wave impedance intermediate that of the plastic and that of the metal may be realized. The acoustic impedance varies directly with the proportion of metal to plastic in the composite material and the absorption or dissipation will vary inversely with the proportion of metal.

For systems in which a path through a liquid is included in the energy circuit and piezoelectric crystals are used to introduce and abstract energy from the liquid, a liquid consisting of a mixture of water and alcohol, of water and acetone or of water and ethylene glycol may be used. When the proper proportions of alcohol (12.5 volumes to 100 volumes of water), acetone (10.5 volumes to 100 volumes of water), or ethylene glycol (13 volumes to 100 volumes of water) are used the liquid will have, substantially, a zero coefficient of variation of velocity with temperature at 55° C. mean temperature as will be described in more detail hereinafter. For such systems phenol formaldehyde is a desirable plastic to use in the manufacture of impedance matching materials of the invention since it is not soluble in the liquids such as alcohol, acetone or ethylene glycol which it may be found desirable to use.

In many systems also it will be desirable to radiate or receive energy from only one side of the crystal in which case it is not only desirable to match the compressional wave impedance on the radiating (or receiving) side of the crystal, but it is also desirable both to match the impedance and to provide for absorbing energy which reaches the opposite or "passive" side, either by virtue of the electrical drive on the crystal itself or by reception of direct or reflected energy from the medium in which the crystal is immersed. It should be noted that some of the energy received by the first-mentioned or "active" side of the crystal will pass through the crystal to the opposite side and may cause objectionable echoes unless the precautions, just described above, are taken.

A further advantage may under particular circumstances also be obtained by deliberately damping the crystal, where it is desired to employ crystals in pulse timing circuits since an undamped crystal generates a pulse having its maximum amplitude near the center of the pulse whereas a damped crystal will generate a pulse having maximum amplitude near the start of the pulse. Reflections of the latter type of pulse are less likely to interfere with the directly transmitted or wanted pulse signals and also since the timing is best done at the start of the pulse a very substantial improvement in operation and reliability is thus effected. This matter will be discussed in more detail hereinafter.

A particular object of the invention is to provide an improved compressional wave impedance match between a piezoelectric crystal and the medium surrounding it in systems where the function of the crystal is to radiate or absorb compressional wave energy.

Another object is to reduce or eliminate the tendencies of a piezoelectric crystal to produce unwanted resonance and transient effects.

Another object is to provide novel arrangements for effecting a better impedance match between piezoelectric crystals and various compressional wave conducting mediums.

Another object is to eliminate the troublesome effects of back radiation in unidirective systems employing piezoelectric radiators and absorbers.

Another object is to reduce or eliminate the reflections of energy at the surfaces of a piezoelectric radiator or absorber surrounded by compressional wave conducting media.

Another object is to provide improved pulse timing piezoelectric crystal devices.

Other and further objects will become apparent during the course of the following description and in the appended claims.

The principles of the invention and a number of applications thereof will be more readily understood in connection with the following detailed description of illustrative embodiments shown in the accompanying drawings in which:

Fig. 1 shows a pair of piezoelectric crystals immersed in a liquid medium and provided with compressional wave impedance corrective front and back members;

Fig. 2 shows in detail a specific type of piezoelectric crystal mounting illustrating an application of certain principles of the invention;

Figs. 3A and 3B show wave trains representing compressional wave pulses which can be employed in piezoelectric crystal timing systems and will be employed in explaining advantages of particular arrangements of the invention;

Fig. 4 shows in block diagrammatic form a simple pulse-type distance measuring system in which a unit of the general type illustrated by Fig. 1 may be advantageously employed to assist in timing the reflected pulses; and

Fig. 5 illustrates the combination with a crystal of a composite member comprising alternate layers of plastic and metallic material the composite member having particular impedance and damping properties to provide improved over-all operation of the piezoelectric crystal pulse timing arrangements of the invention.

In more detail, Fig. 1 shows two piezoelectric crystals 15 one at the left end and the other at the right end of a tank 20 containing a liquid 30 therein. The crystals can be of any of the well-known piezoelectric materials such as quartz, Rochelle salt or tourmaline. Conducting leads 10 and electrodes 12 provide means for making appropriate electrical coupling with the crystals.

On the more central face of each crystal a layer of material, member 14, is positioned. Member 14 can be, as was previously explained, an acoustic impedance transforming device to match the impedance of the crystal with that of the liquid and it can further introduce energy absorption or damping of the crystal, if desired, as will be discussed presently. If impedance transformation alone is desired, the thickness of member 14 is preferably one-quarter wave-length (or a low odd number of one-quarter wave-lengths) of the frequency being transmitted through the liquid, or of the mid-frequency (or predominant frequency) if a group of frequencies is being transmitted. If Rochelle salt crystals are employed, member 14 may be a simple plastic, for example, methyl methacrylate, since a small impedance transformation will suffice. If the crystals employed are quartz, however, a larger transformation will be necessary and as was previously explained, member 14 can then comprise a plastic in which metal particles are suspended, for example, phenol formaldehyde with 30 per cent of powdered Permalloy (85 per cent Ni) to match quartz and water. Alternatively, member 14 may be a laminated member, alternate laminations being of plastic and of metal, respectively, as will be described in detail presently.

On the side of the crystal opposite member 14 in each case a member 16 is positioned, with a second member 18 adjacent the member 16 as shown in Fig. 1. Member 16 is similar to member 14 but its function is to match the compressional wave impedance of the crystal to that of the member 18 rather than to that of the liquid. One of the possible constructions suggested for member 14 can obviously be selected for member 16 depending upon the particular impedance matching problem presented. Member 18 is an absorber of compressional wave energy, for example felt, the function of which is to absorb energy and thus prevent its reflection back to its associated crystal or to the crystal at the other end of the tank. Reflections or echoes are generally objectionable in communication or measuring circuits as they tend to distort or obscure the desired signals or to provide misleading signals and the substantial elimination at the "back" sides of the crystals of reflections is highly desirable for many purposes.

In cases where it is desirable to exclude the liquid from direct contact with the crystal and associated impedance corrective and energy absorbing members, for example when Rochelle salt crystals soluble in water are used, a thin membrane of rubber or similar material can be employed to form a liquid tight envelope 11 without appreciably damping the action of the assembly. The effect of such a membrane from the standpoint of impedance, if appreciable, can be taken into account in the over-all design of the assembly.

Where the time of travel of a compressional wave, generated by one crystal in response to electrical stimulation, through the liquid 30 to the other crystal, is employed in timing some other phenomena, for example, the time interval required for an energy pulse to travel to a distant surface and return to its point of origin, it is convenient to be able to adjust the distance between the crystals in tank 20. For this purpose, one crystal can be supported through a rotatable collar 23 on a rod 24 extending through a threaded bushing 26 in the side of tank 20. Rod 24 is threaded for the greater part of its length so that by turning knob 28, the longitudinal position of the crystal supported on rod 24 may be adjusted over an appropriate range. Knob 28 carries a suitable scale 27 and a slidable index pointer 29 carried on a fixed rod 25 is provided to facilitate use of scale 27. A micrometer arrangement of any of the types well known in the art may be employed to afford precise adjustment, if desired.

As previously mentioned, three particularly suitable liquids for use in devices of the type illustrated by Fig. 1 are water with approximately 12.5 volumes of alcohol to 100 volumes of water, 10.5 volumes of acetone to 100 volumes of water, and 13 volumes of ethylene glycol to 100 volumes of water. These liquids all have a zero temperature coefficient of velocity at 55° C. and a slow parabolic variation of velocity on either side of that. For example, a rough thermostat set to keep the temperature to ±6° C. will hold the velocity constant to one part in 3,000. Of these mixtures the one employing ethylene glycol is particularly advantageous since it will evaporate very slowly, and if the mixture is taken to −40° C. it will even then freeze in only a very mushy form which will not injure the apparatus. The respective velocities of these three mixtures are alcohol-water, 1557 meters per second at 55° C., acetone-water, 1565 meters per second and ethylene glycol-water 1594 meters per second.

The velocity of a three-component mixture containing alcohol, ethylene glycol and water can be made to vary from 1557 meters to 1594 meters by changing the relative proportion of alcohol and ethylene glycol and still maintain a zero coefficient at 55° C. This is advantageous in matching the velocity of the liquid to standard screw threads in the variable delay circuit of Fig. 1. This three-component mixture may also be employed to assist in the final adjustment of the impedance match between the piezoelectric devices and the liquid. An impedance change as great as 15 per cent can thus be effected.

In Fig. 2, details of a particular form of crystal mounting, embodying a number of principles of the invention, are shown.

Crystal 34, having electrodes 40 and conductive leads 38 to afford convenient electrical coupling thereto, is enclosed between members 36 and 32 which can be of plastic material; for example methyl methacrylate, polystyrene, phenol formaldehyde, urea formaldehyde or the like, which may have suspended therein metallic particles in the event that it is desired to impart a greater compressional wave impedance to them. Member 32 in addition to forming part of the holder can also act as a compressional wave impedance transformer and, if desired, can also contribute compressional wave energy absorption. Members 36 and 42 can likewise be plastics, or plastics with metal particles suspended therein, or alternatively they can be of laminated construction with alternate laminae of plastic and metal, and member 44 is a compressional wave energy absorbing member, for example felt, the function of which is to absorb the energy reaching it. The assembly is held together by bolts 46 and nuts 47, which bolts may further serve to facilitate mounting the arrangement in operating position either in a tank such as 20 of Fig. 1 or on a vessel, buoy, or the like for use in submarine signaling systems. The assembly is preferably sealed to be liquid tight either by fusing the edges of the plastic members together by a hot iron where they come together or by enclosing the assembly in a thin membrane 43 of rubber or the like. If member 44 is of felt or other liquid absorbing material it will, of course, be necessary to enclose it, at least, in some liquid-proof enclosure, if it is to be submerged.

Where radiation or absorption from both sides of crystal 34 is desirable, members 42 and 44 can be omitted and members 32 and 36 can function as impedance transformer and/or compressional wave damping means for the two sides of the crystal, respectively, in substantially identical manners.

The curve 48 of Fig. 3A indicates the amplitude response with time of an undamped piezoelectric crystal of the types contemplated for use in arrangements of the invention. Obviously, reflected echoes of an energy pulse resulting from such response, arriving a half pulse length or so in advance of a succeeding directly transmitted pulse can entirely mask the initial vibrations of the latter pulse and cause a false indication in pulse timing arrangements of the invention. However, if the crystal is damped, for example by placing in contact with it a material of relatively high compressional wave energy absorption (dissipation or resistance), its amplitude response can be changed to that represented by curve 50 of Fig. 3B, and combinations of echo pulses and directly transmitted pulses will in general produce indications which are distinguishable from single pulses of either type and (except where the two are in synchronism, or very nearly so) separate indications of the arrival of the two types of pulses can be obtained so that the likelihood of erroneous and misleading indications is substantially reduced. It is for this reason that it is under proper circumstances desirable to introduce absorption or loss in the auxiliary members associated with the crystal to damp its action as suggested in connection with Figs. 1 and 2 above.

In Fig. 4 a pulse-reflection type of distance measuring system is indicated in block diagram form. Oscillator 60 furnishes a sine wave to pulse generators 62 and 86 which generate one pulse for each cycle of the sine wave. Pulse amplifier 64 amplifies the pulses furnished by generator 62 and actuates electroacoustic transmitter 66, to send out a series of acoustic pulses 70 having the periodicity determined by the oscillator 60. Obviously, this periodicity should be such that reflected pulses from a surface at the greatest distance to be measured will arrive back at acoustic receiver 78 before the next succeeding pulse is emitted by transmitter 66.

Reflections 74 of the pulses 70 from a distant surface 72 are received in electroacoustic receiver 78, converted into electrical pulses and applied to a vertical deflecting plate of cathode ray oscilloscope 80. The horizontal deflecting plates of the oscilloscope are connected to a sweep circuit 82 which furnishes, preferably, a saw-tooth wave deflecting voltage which deflects the ray of the oscilloscope across the target in synchronism with the emission of pulses by transmitter 66. Pulse generator 86 provides the liquid, adjustable, delay

circuit 84 with a series of pulses which are in synchronism with the pulses of generator 62. The delay circuit output is supplied to the other vertical deflecting plate of the oscilloscope 80 and the delay circuit is adjusted until the pulses furnished by it are in synchronism with the pulses furnished by receiver 78. The adjustment of circuit 84 required to produce this synchronism is therefore a measure of the time of travel and therefore the distance traveled by the pulses to the reflecting surface 72 and back and the dial of the delay circuit can therefore be calibrated to read the distance directly.

Obviously, a radio transmitter and antenna and a radio receiver and antenna could be substituted for the corresponding acoustic transmitter and receiver, respectively, of Fig. 4, in which case the dial of the adjustable delay circuit should be calibrated in terms of the time of travel of electromagnetic waves, rather than acoustic waves.

Suitable apparatus units for all component apparatus of the system of Fig. 4 are well known to the art, whether acoustic or electromagnetic waves are employed, except for the adjustable delay circuit which is, of course, of the type described in detail above in connection with Fig. 1. For example, see copending application of D. Pollack, Serial No. 409,600, filed September 5, 1941, entitled Phase and distance measuring systems, for a pulse reflection type of distance measuring circuit employing electromagnetic waves.

Fig. 5 illustrates in detail the method of building up a laminated member for use adjacent to a piezoelectric crystal for impedance matching and damping corrective purposes.

In Fig. 5 a piezoelectric crystal 54 has a backing comprising layers of a plastic 52 and layers of a metal 56. The thickness of each layer is a wave-length of the frequency to be used, or of the mid-frequency of the band if a band of frequencies is to be used. Assuming radiation or reception of compressional wave energy from the back of the crystal is not desired, a layer of felt 44 or other absorbing material may be added at the left of the laminated member as shown in Fig. 5. Where Z_{01} is the compressional wave impedance of the plastic used and Z_{02} is the impedance of the metal used, the effective impedance of the laminated structure, Z_L, is given by the following equation:

$$Z_L = \sqrt{Z_{01} Z_{02}}$$

The layer of plastic next to the crystal may, of course, be part of a box-like structure in which the crystal may be assembled as for the crystal of Fig. 2 and as suggested in connection with Fig. 2 the laminated structure may be member 42 of Fig. 2, a member 44 of felt or other absorbing material being added if no radiation or reception from that side of the crystal is desired. Member 44 is preferably enclosed in a thin membrane 51 of rubber or other moisture-proof material.

Numerous other arrangements embodying the principles of the invention and fairly within the scope thereof will occur to those skilled in the art. The scope of the invention is defined in the appended claims.

What is claimed is:

1. In an electrocompressional wave pulse transmission system, a device for converting energy of one type to energy of the other type comprising a piezoelectric crystal immersed in a fluid having a substantially different impedance than the crystal, a member of material adjacent an emitting or

receiving side of said crystal, said member having an acoustic impedance intermediate that of said crystal and the said fluid, said intermediate impedance being substantially the geometric means of the crystal and fluid impedances, a second member of material adjacent the opposite side of said crystal having an impedance substantially the geometrical mean value between that of said crystal and a third member of energy absorbing material said third member being placed adjacent the second-mentioned member whereby energy is transferred between said crystal and said fluid with substantially no reflection and energy reaching the said second member will be absorbed and troublesome reflections thereof will be eliminated.

2. A piezoelectric vibrator for submarine compressional wave signaling systems comprising a quartz crystal embedded in phenol formaldehyde, the phenol formaldehyde having in suspension therein 30 per cent by weight of Permalloy powder, whereby reflection of energy between the vibrator and the water in which it is to be used will be substantially eliminated.

3. In a compressional wave pulse transmission system, a sending and receiving device which comprises the combination of a piezoelectric vibrating member having a compressional-wave impedance exceeding that of the medium in which it is to be employed, a second member positioned against a vibrating surface of said piezoelectric member, said second member having a compressional-wave impedance substantially equal to the geometric mean of the compressional-wave impedances of said piezoelectric member and said medium, a third member positioned against the surface of said piezoelectric member opposite the first-stated vibrating surface and a fourth member positioned adjacent the said third member, said third member having a compressional-wave impedance which is substantially equal to the geometric mean of the compressional-wave impedances of said piezoelectric member and said fourth member, said fourth member being of a material which absorbs substantially all compressional-wave energy reaching it, the energy absorption of said second, third and fourth members collectively being sufficient to dampen the response of said piezoelectric member to a pulse of energy so that said response will be of maximum amplitude initially and will rapidly decrease, whereby unwanted reflections of energy in said system will be substantially reduced and interference from such unwanted reflections as may occur will be far less troublesome.

4. In an electrocompressional-wave delay circuit for use in pulse timing systems, said circuit being of the type in which an electrical energy pulse is converted into a compressional-wave energy pulse at a first point in a compressional-wave transmitting medium of known propagation characteristics and reconverted into an electrical energy pulse at a second point a known distance from said first point and the time of travel of said pulse through said transmitting medium is employed as a standard of comparison by which the

pulse travel time of another pulse following a path of unknown length is measured, the combination of an electrocompressional-wave vibrating member having a compressional-wave impedance substantially different from the impedance of said medium, means adjacent one vibrating surface of said member for effecting an impedance match between said member and said medium, said means comprising a second member of a material having a compressional-wave impedance which is substantially the geometric mean of the impedance of said first-mentioned member and said medium, means adjacent a second surface of said first member for effecting the transfer of energy from said second surface without reflection therefrom and for absorbing such energy, said means comprising a third member placed adjacent the second surface of said first member and substantially matching the impedance of said first-mentioned member and a fourth member of compressional-wave energy absorbing material placed adjacent said third member to absorb energy reaching said third member, and means for conditioning the response of said vibrating member to energy pulses to provide response of initial maximum amplitude and rapidly decreasing amplitude, said last-stated means comprising adequate damping properties in one or more of the said four members whereby unwanted reflections of the energy pulses in the delay circuit are largely eliminated and the interfering properties of such unwanted reflections as may still be obtained are substantially reduced.

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