Jan. 28, 1947. W. P. MASON 2,414,827

COMPRESSIONAL WAVE RADIATOR AND RECEIVER

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FIG. 1

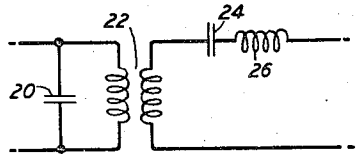


FIG. 2

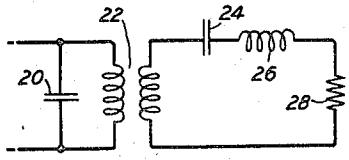


FIG. 3

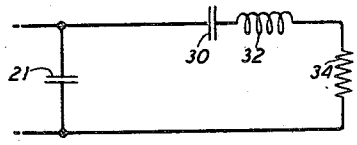


FIG. 4

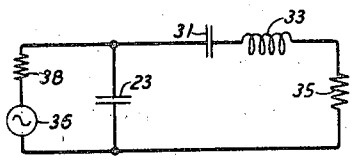


FIG. 5

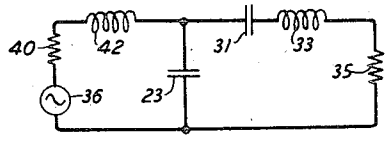
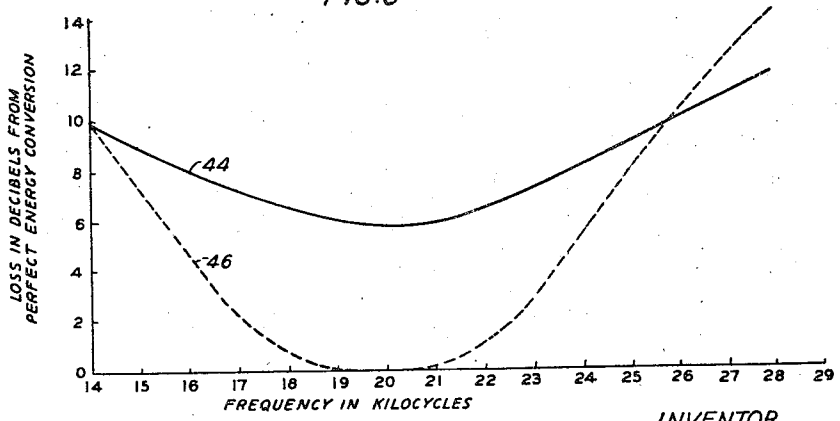


FIG. 6



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FIG. 7

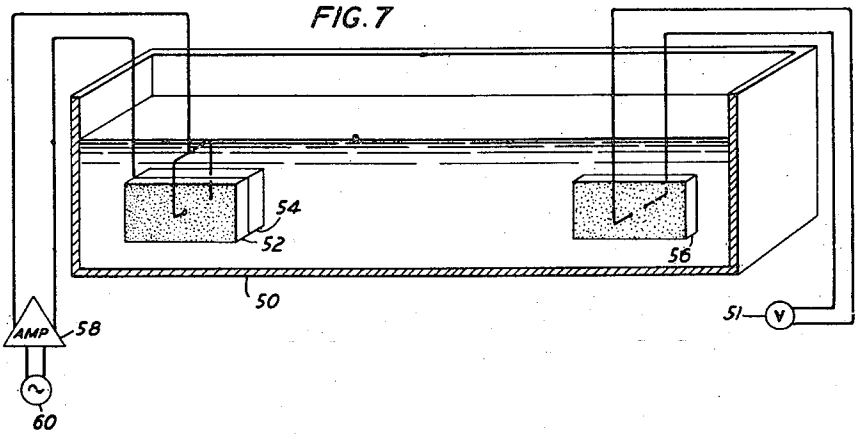


FIG. 8

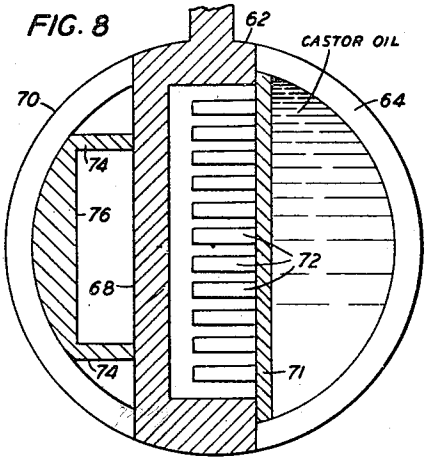


FIG. 9

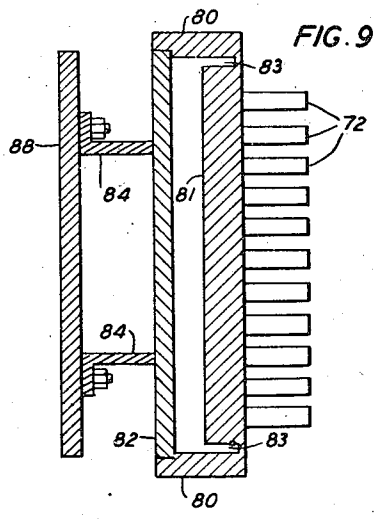


FIG. 10

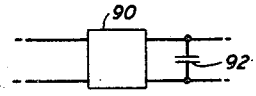


FIG. 11

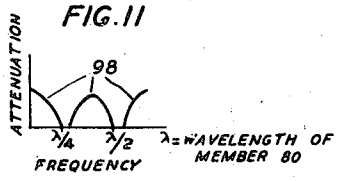
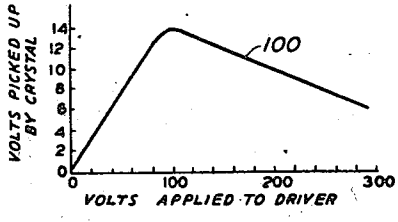


FIG. 12



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FIG. 13

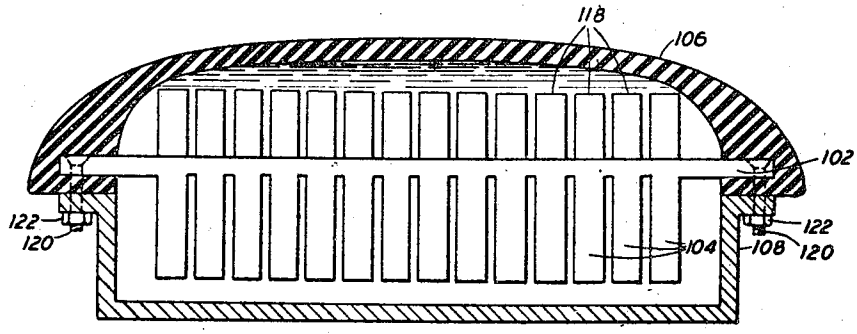


FIG. 14

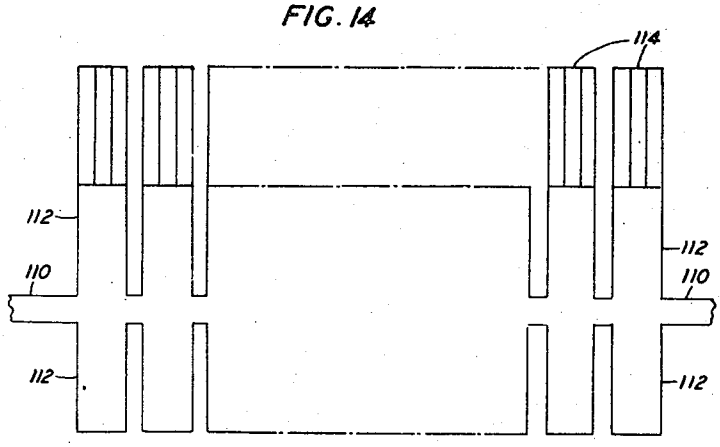
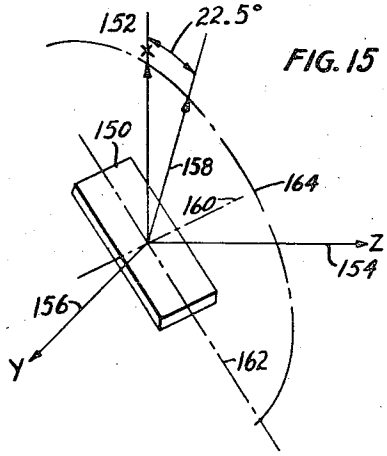


FIG. 15



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UNITED STATES PATENT OFFICE

2,414,827

COMPRESSIONAL WAVE RADIATOR AND RECEIVER

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Application October 3, 1941, Serial No. 413,429

7 Claims. (Cl. 171—327)

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This invention relates to submarine compressional wave radiators and receivers. More particularly, it relates to improved piezoelectric devices for use as submarine compressional wave radiators and receivers and mountings for such devices, the improved features cooperating to effectively increase the power carrying capacity and efficiency of the devices.

Objects of the invention are to provide piezoelectric devices for use in submarine compressional wave systems which will have greater uniformity, efficiency, stability with temperature, power capacity and directional discrimination than devices of this class previously employed in the art.

Features of the invention are the correlation of peculiar properties of crystals having specific alignments of faces and axes with the specific requirements of the services for which they are intended, the use of auxiliary inductances to annul unwanted crystal capacitances and thus improve the impedance and radiation properties of the crystals, the substantial elimination of peripheral energy dissipation, and the improvement of the mounting of the crystal assemblies so as to substantially reduce back-radiation or the reception of energy from the back of the radiator.

While Rochelle salt piezoelectric crystals are admirably well adapted for use in compressional wave systems employing relatively small amounts of power, it has been the practice heretofore to resort to electromagnetic, magnetostrictive or mechanical means when it has been necessary to emit substantial amounts of compressional wave power.

The principal difficulties encountered in the past with Rochelle sale piezoelectric crystal actuated devices when subjected to substantial power have been the heating and destruction of the crystal, low efficiency in converting electrical to compressional wave power and changes in the crystal characteristics with temperature changes resulting either from changes in the temperature of the surrounding medium or from the heating of the crystal.

The present invention relates to improved arrangements for reducing the above-mentioned difficulties and to improved mountings which substantially reduce "back-radiation" and similar undesirable phenomena.

As will appear hereinunder, it has been found entirely practicable to construct Rochelle salt piezoelectric crystal radiators which will transmit as much power as the best magnetostrictive compressional wave radiators. Moreover, the radiators of the invention have greater efficiency and greater stability with temperature variations.

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The improved performance characteristics have been achieved principally by the incorporation of a few relatively simple changes in the axial orientation of the faces of the crystals, the current carrying capacities of the electrodes and terminals, greater freedom from adsorbed moisture on the surface of the crystals, and by changes in the mechanical mounting of the crystals.

Further features and objects of the invention will become apparent during the course of the following description and in the appended claims.

The principles of the invention will be more readily understood from the following detailed description in conjunction with the appended drawings in which:

Figs. 1 to 5, inclusive, are schematic diagrams of equivalent electrical circuits employed in explaining certain crystal characteristics and the correlation of the crystal characteristics with other elements in arrangements of the invention;

Fig. 6 shows curves illustrating the improvement in conversion efficiency of electrical into compressional wave energy effected by properly correlating the crystal characteristics with those of other elements in the arrangements of the invention;

Fig. 7 illustrates an arrangement for testing the power carrying capacity of piezoelectric crystals;

Fig. 8 illustrates a design of submarine compressional wave radiator employing a plurality of crystals to drive a diaphragm;

Fig. 9 illustrates an improved mechanical mounting for a plurality of crystals to reduce back-radiation from the mounting;

Figs. 10 and 11 represent the equivalent structure and pass-band characteristics of the mechanical filter mounting of Fig. 9;

Fig. 12 illustrates the variation of radiation of a piezoelectric Rochelle salt crystal with increasing driving voltage;

Figs. 13 and 14 illustrate alternative mechanical mountings designed to eliminate objectionable back-radiation of piezoelectric crystal compressional wave emitters and receivers; and

Fig. 15 illustrates a modified type of crystal cut representing a compromise between 45 degree X and Y-cut crystals.

Piezoelectric Rochelle salt crystal compressional wave projectors commonly employ quarter wavelength crystals glued to a metal backing plate.

The equivalent electromechanical circuit of a crystal clamped on one end and driving a load

at the other is shown in Fig. 1 of the accompanying drawings and is derived in applicant's papers entitled "Dynamic measurement of the constants of Rochelle salt" and "The location of hysteresis phenomena in Rochelle salt crystals." These papers were both published in the Physical Review; the first mentioned, in volume 55, pages 775 to 789, inclusive, dated November 12, 1938, and the second in volume 58, pages 744 to 756, inclusive, dated October 15, 1940.

In detail, in Fig. 1 condenser **20** is the static capacity of the crystal which is longitudinally clamped, condenser **24** represents the compliance of the crystal when the electrical side is short-circuited and inductance **26** represents the effective mass of the crystal, which is half the static mass. The transformer **22** represents the electromechanical coupling and introduces an effective ratio of transformation φ between the electrical and mechanical portions of the system. This ratio determines the force exerted on a load when a potential is applied on the electrical side.

In terms of the fundamental constants of a 45 degree Y cut longitudinally vibrating Rochelle salt crystal, chosen for reasons which will become apparent hereinafter, expressed in centimeter-gram-second electrostatic units,

$$\text{Condenser } 20=\frac{l_w l_y K}{4\pi l_t}$$

$$\text{Condenser } 24=C_M=\frac{8}{\pi^2}\left(\frac{l_y S'_{22}}{l_w l_t(1-k^2)}\right)$$

$$\text{Inductance } 26=L_M=\frac{\rho l_w l_y l_t}{2}$$

$$k=\frac{f_{25}}{2C_{55}S'_{22}}\sqrt{\frac{S'_{22}K}{4\pi}}$$

$$\phi=\left(\frac{f_{14}l_w K}{2C_{55}S'_{22}4\pi}\right) \qquad (1)$$

where

K=12.5=dielectric constant of 45 degree Y cut Rochelle salt
$S'_{22}=9.31\times10^{-12}$=inverse of Young's modulus along the length
ρ=1.775=density of Rochelle salt
$f_{25}=5.17\times10^{4}$=piezoelectric constant of Rochelle salt
k=coefficient of electromechanical coupling=0.279
$C_{55}=3.04\times10^{10}$=shear elastic constant
l_y=length of crystal along direction of vibration in centimeters
l_w=width of crystal in centimeters
l_t=thickness of crystal in centimeters.

With these constants, the values of the elements become

$$\text{Condenser } 20=C_0=\frac{.996 l_w l_y}{l_t}\text{ e. s. u.}=\frac{1.108\times10^{-12}l_w l_y}{l_t}\text{ farads}$$

$$\text{Condenser } 24=C_M=\frac{8.16\times10^{-12}l_y}{l_w l_t}$$

$$\text{Inductance } 26=L_M=.8875 l_w l_y l_t \qquad (2)$$

The impedance transformation ratio $\varphi=9.084\times10^{4}l_w$ e. s. u.$=.0941\ l_w$ in practical units.

The transformer **22** transforms from mechanical impedance units (expressed as a ratio of force in dynes to velocity in centimeters per second) to electrical impedance units.

If the crystal is used to drive water, and the radiating surface is a half wave-length or greater, which will be the case for a projector, the mechanical end of the representation will be terminated in a radiation resistance **28**, the resistance R of which is equal to

$$R=1.5\times10^{5}l_w l_t \text{ mechanical ohms} \qquad (3)$$

The complete representation is shown in Fig. 2.

We are usually interested in the electrical impedance as measured from the electrical terminals of the crystal. For this case the mechanical elements can be "taken through" the electromechanical transformer, and the resulting elements, as shown in Fig. 3, will be

$$\text{Condenser } 21=C_0=\frac{1.108\times10^{-12}l_w l_y}{l_t}\text{ farads}$$

$$\text{Condenser } 30=C_1=\frac{7.34\times10^{-14}l_y l_w}{l_t}\text{ farads}$$

$$\text{Inductance } 32=L_1=\frac{98.5 l_y l_t}{l_w}\text{ henries}$$

$$\text{Resistance } 34=R=1.666\times10^{7}\frac{l_t}{l_w}\text{ ohms} \qquad (4)$$

For 396 crystals in parallel, each having the dimensions l_y=3.0 centimeters; l_w=2.5 centimeters; l_t=.635 centimeters such as might be used on a projector, the equivalent circuit indicated in Fig. 4 as measured from the electrical side would be

$$\text{Condenser } 23=C_0=5160\times10^{-12}\text{ farads}=5160\ \mu\mu f$$

$$\text{Condenser } 31=C_1=342\times10^{-12}\text{ farads}=342\ \mu\mu f$$

$$\text{Inductance } 33-L_1=0.189\text{ henry}$$

$$\text{Resistance } 35=R=10{,}400\text{ ohms} \qquad (5)$$

As is well known to those skilled in the art, an X-cut, or a Y-cut, piezoelectric crystal is a rectangular plate of crystal having a width substantially exceeding its thickness and a lengtl substantially exceeding its width, the plate being cut from the natural crystal so that its surfaces of largest area are perpendicular to the X axis, or to the Y axis, of the natural crystal, respectively. These relationships are, for example, defined and illustrated in an article entitled "Piezoelectric frequency control" by F. R. Lack, published in the Journal of the Society of Motion Picture Engineers, volume 23, No. 4 for October 1934, see particularly page 190, Figs. 2 to 5 inclusive. The X, Y and Z axes (sometimes designated as the *a*, *b* and *c* axes, respectively) are the electric, mechanical and optical axes, respectively, of the natural crystal. It is further well known to those skilled in the art that a 45-degree X-cut crystal is an X-cut crystal, the longitudinal axis of which is at an angle of 45 degrees with respect to the Y and Z axes and similarly that a 45-degree Y-cut crystal is a Y-cut crystal, the longitudinal axis of which is at an angle of 45 degrees with respect to the X and Y axes. These and related crystals are illustrated and discussed, for example, in applicant's patents 2,147,712 issued February 21, 1939; 2,178,146 issued October 31, 1939; 2,227,268 issued December 31, 1940; and 2,292,388, 2,292,885 and 2,292,886 all three of which issued August 11, 1942, and in other patents and published articles too numerous to be listed here.

Calculated response characteristics

If the projector is to be connected directly to an amplifier 36, the best amplifier impedance will be 1,550 ohms, resistance 38, to match the electrical impedance of the projector. The complete network with the amplifier impedance matching the projector is shown in Fig. 4.

The response to be expected from such a radiator can be calculated by solving for the currents in the equivalent network of Fig. 4. Due to the fact that the reactance of the condenser across the terminating resistance is only 1,548 ohms, only about 25 per cent of the electrical energy of the amplifier will get into the acoustic energy of the water. The response over a frequency range is shown by curve 44 of Fig. 6. The maximum response occurs at slightly above the resonant frequency of 20 kilocycles rather than at the resonant frequency of the device. The 45 degree X cut crystal when used alone as a projector will be able to get more energy into the water since the shunting reactive component will be larger with respect to the terminal resistance than for the 45 degree Y cut. About half the electrical energy will be converted into acoustic energy using the X cut crystal.

If, however, we employ a series inductance of suitable value, 42 of Fig. 5, with the Y cut crystal projector, this shunt reactance will be annuled and a considerably better efficiency of conversion will be obtained. The series inductance also lowers the impedance looking into the projector and provides a more uniform frequency radiation characteristic. The best series reactance to use is one which equals the shunt reactance at the resonant frequency of the crystal. Under these circumstances the best impedance to work from will be equal to the square of the shunt reactance divided by the terminating resistance which in this case will be 230 ohms, resistance 40. The complete circuit to use for a 45 degree Y cut projector is then shown in Fig. 5. From this network we can show that the ratio of the current in the output of this network to the current that would be transmitted from the 230 ohm input to the 10,400 ohm output through a perfect transformer is

$$\frac{i_{0N}}{i_{0T}}=\sqrt{\frac{\frac{\omega^2 R}{\omega^3}}{\left[1-7.54\left(\frac{\omega_R}{\omega}-\frac{\omega}{\omega_R}\right)^2\right]^2+\left[.0736\frac{\omega_R}{\omega}+4.475\left(\frac{\omega_R}{\omega}-\frac{\omega}{\omega_R}\right)\right]^2}} \qquad (6)$$

Hence at the resonant frequency of the crystal the power loss is less than 0.1 decibel. This neglects the resistance associated with the coil, but if the coil is resonably well designed it will have a Q of at least 100, and the power loss in it will not exceed 5 per cent so that a 95 per cent efficiency should be obtained. A plot of equation (6) over a frequency range is shown by curve 46 of Fig. 6. Hence over a band from 17.5 kilocycles to 22.5 kilocycles radiation or reception should take place with at least 70 per cent efficiency.

A radiator using the usual 45 degree X cut crystal can also be improved in efficiency by using a series coil having a reactance equal to the static capacitative reactance of the crystal at the resonant frequency of the crystal. The improvement however is not as great. Since the Y cut Rochelle salt crystal has no dielectric hysteresis, and any mounting or plating resistances will absorb a smaller part of the total energy on account of the higher impedance of the crystal,

the crystal will stand a higher power input load than will an X cut crystal. The motion of a crystal for a radiator delivering 1,000 watts acoustic energy is only 8.21×10^{-5} centimeters on the end and all measurements indicate that the displacement is linear with voltage. It appears therefore that a 45 degree Y cut crystal can deliver acoustic or compressional wave power up to the cavitation point.

The shunt capacitance can be annulled also by using a coil in parallel. The resulting amplifier impedance, however, is 10,000 ohms and results in a considerably higher voltage for the same acoustic power output, which may be objectionable. For the series coil connection it is imperative that all series resistances due to plating connections etc. should be very low for the full current as the low impedance will pass through these resistances and power losses will tend to heat the crystal. In this connection a source of series resistance was recently discovered which is effective for crystals with tin-foil platings held on by a glue. When Canada balsam was used as the adherent, a series resistance of 100 ohms per square centimeter was observed due to the poor dielectric properties of the adherent. For a projector of 396 crystals, this would amount to .0675 ohm in series with the 230 ohm termination. Since the power generated by this resistance is dissipated over a small volume this may cause heating of the crystal surface. This loss can be eliminated by using sputtered or evaporated electrodes.

In a medium of substantially constant temperature three causes for the heating of the piezoelectric crystals under relatively large power loads appear to predominate. The first of these is internal heating by power dissipated in the crystal in the form of hysteresis losses, the second is peripheral heating from contact or conductive resistance in the electrodes or between the crystal, the electrodes and the leads connecting thereto, while the third is due to adsorbed moisture on the surface of the crystal which may cause a breakdown across the crystal surface when a sufficiently high voltage is placed across the electrodes. In general, if the temperature of a Rochelle salt crystal is raised to 40° C. a fourth factor, namely, its leakage resistance, becomes appreciable and further heating, resulting from power dissipation through this leakage resistance, takes place, hastening deterioration and leading ultimately to the destruction of the crystal.

Applicant has discovered that 45 degree Y cut Rochelle salt crystals have negligible hysteresis losses and since internal heating of the crystal results almost entirely from hysteresis losses the power carrying capacity of a Rochelle salt piezoelectric vibrator can be appreciably improved by employing 45 degree Y cut crystals.

On the other hand, 45 degree Y cut Rochelle salt crystals have an impedance which is in the order of fifteen to twenty times as great as 45 degree X cut Rochelle salt crystals. A high impedance may result in objectionably high voltages being necessary in order to pass the desired amount of power so that in many instances a compromise cut can be employed to advantage. By way of example, a crystal with its major plane normal 22.5 degrees from the X axis, as illus-

trated in Fig. 15 where crystal 150 represents a 45 degree X-cut crystal which has been rotated about its lateral axis 160 by 22.5 degrees, 152, 154 and 156 being the X, Y and Z axes, respectively, 162 being the longitudinal axis of the crystal and 158 being the normal to the major plane of the crystal. Such a crystal will have a considerably lower impedance than a 45 degree Y cut crystal but will still have relatively small hysteresis losses. It should also be noted that 45 degree Y cut crystals, and approximations to that cut, have much smaller variations with temperature of capacity and compressional wave energy output than 45 degree X cut crystals. Since submarine signaling systems have to operate in sea water the temperature of which may vary substantially, this latter property is important.

As mentioned above, the temperature of the crystal can obviously also be raised by peripheral heating effects and it has been found that many structural details satisfactory for low power operation such as electrodes glued to the crystal, very thin electrodes, relatively high resistance connections between the leads and the electrodes and the like can result in the generation of substantial heat adjacent to the crystal. For high power operation, therefore, it has been found necessary to employ substantially thicker electrodes in direct contact with the crystal and to make good electrical connections between the leads and the electrodes. With such precautions carefully observed peripheral heating effects can be minimized. Here it should be noted that the use of a higher impedance crystal reduces the heating effects of series resistances since they are then relatively smaller compared with the "useful impedance" of the circuit. This is a further consideration in favor of the use of 45 degree Y cut crystals or compromise cuts of relatively high impedance.

In preparing crystals to withstand high voltages, it is essential that all the adsorbed moisture on the crystal surfaces be removed. This can be done by keeping the crystals at low humidity and by evacuating them for a few minutes before they are surrounded by air-free castor oil. In this way any tendency to break down across the crystal surfaces can be eliminated.

The avoidance of internal and peripheral heating effects also assists in the avoidance of leakage resistance heating effects since the latter do not become troublesome with dry Rochelle salt crystals until the temperature of the crystal has risen to 40° C. or above. Auxiliary cooling measures such as providing for the rapid removal of heat by conduction or convection, etc. may obviously also be employed particularly where the device is submerged in sea water the normal temperature of which is substantially below 40° C.

By the combined use of the above-described structural features to prevent undue heating and to provide more favorable impedance relations, applicant has been able to very substantially increase the power carrying capacity of Rochelle salt piezoelectric crystals so that he has been able to generate submarine compressional waves of power content fully as great as may be generated by magnetostrictive radiators of the art. Furthermore, the electrical power input required for applicant's devices is substantially less than that required by magnetostrictive devices for corresponding compressional wave power.

In Fig. 7 an arrangement for testing the power carrying capacity of crystals used as submarine radiators is indicated. Tank 50 contains a liquid, which may for example be sea water, in which two crystals 52 and 54 are immersed at one end of the tank and a single crystal 56 at the other end. Crystals 52 and 54 are identical and are poled to vibrate in synchronism. An alternating current source 60 is amplified by amplifier 58 which in turn drives the crystals. The power reaching receiving crystal 56 operates a voltmeter to provide a measure of the power radiated by crystals 52 and 54. If Rochelle salt crystals are employed they must be enclosed in a water-proof member since they are soluble in water. A thin rubber membrane will suffice to prevent the water from reaching the crystal. If quartz crystals are used or if some liquid such as kerosene is substituted for the water such precautions will be unnecessary.

The curve 100 of Fig. 12 is a typical performance curve for a piezoelectric crystal radiator. The energy radiated rises rapidly with the increased input energy until a maximum is reached—when cavitation occurs and thereafter the actual energy radiated decreases as indicated in Fig. 12 with further increase of input energy to the crystal.

This limitation to the radiation of power may be overcome by driving a diaphragm by a large number of substantially identical crystals which are connected electrically in parallel and glued to the diaphragm since this increases the area and allows more power to be radiated before the cavitation point is reached. A design of this type is shown in Fig. 8 in which a plurality of crystals 72 are glued to diaphragm 71. Diaphragm 71 is held on frame 82 and the radiator is given a spherical shape by rubber members 70 and 64. Pieces 74 support shaping member 76 and are slightly less than one-half wave-length of the mean radiated frequency long and are further attached to nodal points of member 62 so as to reduce back-radiation in a manner to be explained more fully hereinafter. The space between diaphragm 71 and rubber member 64 is filled with castor oil for the purpose of conducting the sound generated by the diaphragm to the sea water. Castor oil is used because it is a vegetable oil which will not cause the rubber to deteriorate, and because it has nearly the same acoustic impedance as sea water, and will not cause any reflection at the rubber surface. As previously mentioned, it also serves to exclude moisture after the crystal has been dried which in turn is essential since absorbed moisture induces leakage and heating of the crystals.

The principles involved in the effective reduction of back-radiation from supersonic submarine radiators are further illustrated in Fig. 9 in which a plurality of crystals 72 are mounted on a backing plate or disc 81 which with the crystals represents a resonant system a half wave-length long at the mid-frequency of the band to be transmitted. Member 81 is notched or slotted as shown at 83, adjacent to supporting ring member 80 so that a minimum of energy will be transmitted to member 80.

Member 80 is made slightly less than half a wave-length long and with the stiffness of the slotted portion 83 of member 81 and the propagation in member 80 forms a mechanical filter section the electrical equivalent of which is indicated in Fig. 10 where capacity 92 represents the compliance of the slot and the block 90 represents an electrical mesh of impedance Z_0 and propagation constant θ, equivalent to the impedance of and propagation through member 80.

This type of filter section is known to have a pass band when the length of member 80 is just over the quarter wave-length point and also when it is just over the half wave-length point as illustrated in Fig. 11. It will attentuate a maximum if the length is slightly more than three-eighths of a wave-length. For example, assuming a mid-band frequency of 24 kilocycles, one wave-length will be 8.36 inches for compressional waves in steel having a velocity of 2×10^5 inches per second. Three-eighths of a wave-length then is 3.14 inches and members 80 should be approximately 3.50 inches to be slightly more than three-eighths of a wave-length long.

An additional filter section is formed by diaphragm 82 which at its periphery connects to ring 80. To provide maximum attenuation, diaphragm 82 is proportioned to be resonant at the mid-band frequency, (assumed, for example, as 24 kilocycles) and is supported by members 84 which are placed at nodal points on member 82 so as to avoid drawing energy therefrom. A further member may then act as a mounting plate for the assembly and substantially no back-radiation should take place from such a structure since no substantial energy reaches the mounting plate 88. Of course, if it is deemed necessary members 84 may be made slightly more than three-eighths of a wave-length to further reduce the possibility of energy reaching plate 88.

The motion of a diaphragm such as member 82, clamped at the edge is defined by the equation for its displacement W at its center which is

$$W=\frac{p}{2\rho h\omega^2}\left[\frac{I_1(kR)J_0(kr)+J_1(kR)I_0(kr)}{I_1(kR)J_0(kR)+J_1(kR)I_0(kR)}-1\right] \quad (7)$$

where p is the pressure on the diaphragm, ρ the density, $2h$ the thickness, ω the frequency, r the radius at any point, R the outside radius, J_0, J_1, I_0, I_1 Bessel's functions of the zero and first order for real and imaginary arguments respectively, and k is given by

$$k=\sqrt{\frac{\omega}{\sqrt{\frac{Eh^2}{3\rho(1-\sigma^2)}}}} \quad (8)$$

where σ=Poisson's ratio and E=Young's modulus.

The clamped diaphragm will have resonant frequencies when

$kR=m$ where $m_1=3.195$; $m_2=6.3$; $m_3=9.43$; $m_4=12.58$, etc

In terms of the fundamental constants.

$$f=\frac{m^2}{4\pi\sqrt{3}}\sqrt{\frac{E}{\rho(1-\sigma^2)}}\frac{t}{R^2} \quad (9)$$

For example for steel $E=2\times10^{12}$; $\rho=7.7$; $\sigma=.29$. Hence the first resonant frequency is given by

$$f=\frac{(3.195)^2}{4\pi\sqrt{3}}\sqrt{\frac{2\times10^{12}}{7.7(1-.084)}}\frac{t}{R^2}=\frac{2.5\times10^5 t}{R^2} \quad (10)$$

For example, for one plate calculated; t=.635 centimeter, R=15.6 centimeters, so that the fundamental resonant frequency is 653 cycles.

This requires too many harmonics to reach a resonant frequency at 24 kilocycles. After some calculation it appeared that the fourth harmonic would be feasible to obtain. This has a frequency

$$f=\frac{(12.58)^2\times5.33\times10^5}{4\pi\sqrt{3}}\frac{t}{R^2}=\frac{3.69\times10^6 t}{R^2} \quad (11)$$

The radius R to agree with this value becomes 16.05 centimeters. Hence the thickness to make the fourth harmonic come at 24 kilocycles becomes t=1.672 centimeters=.66 inch.

The nodes of the fourth harmonic can be calculated by making the numerator of (7) when put over the common denominator vanish, i. e.,

$$I_1(kR)[J_0(kr)-J_0(kR)]+J_1(kR)[I_0(kr)-I_0(kR)]=0 \quad (12)$$

These were calculated and the nodes came at

$$\left(\frac{r}{R}\right)_1=.193;\ \left(\frac{r}{R}\right)_2=(.4375);\ \left(\frac{r}{R}\right)_3=.69 \quad (13)$$

Taking the third node the center of the support should come 4.35 inches from the center or 2.84 inches from the outside. The support is preferably welded on to produce a narrow supporting surface.

While it is obviously possible to design the remainder of the support in accordance with filter theory, however, since it is normally surrounded by rubber which will tend to damp out resonances and to some extent thus eliminate filter action, no further substantial reduction in back-vibration will usually be effected. The support designed as described above will reduce the back-vibration by from 15 to 20 decibels or more.

Further examples of mounting arrangements designed to reduce back-radiation are illustrated in Figs. 13 and 14.

In Fig. 13 a row of crystals 118 is shown mounted on a steel plate 102 on the rear side of which, opposite each crystal, a steel backing block 104 is provided. Each crystal is a quarter wave-length and likewise each steel backing block is a quarter wave-length of the mean frequency to be radiated by the assembly. Since the speed of compressional waves in the two materials (Rochelle salt and steel, for example) is substantially different the physical lengths for the crystals and for the steel backing blocks will be different, though both are one-quarter wave-length of the same frequency.

The relatively thin mounting plate 102 is, by the above described arrangement, placed at a nodal position with respect to vibrations established by the crystals and can consequently be fastened by bolts 120 and nuts 122 to the housing 108 and substantially no vibration will be transmitted to the housing 108, or to adjacent rows of crystals mounted in the same manner on plate 102. Since radiators of this type commonly employ several hundred crystals it is decidedly advantageous to reduce interaction between individual crystals and groups of crystals so that the failure, or irregular response, of a few crystals will not grossly affect the operation of the entire device.

A rubber cap 106 is employed to exclude sea water and will be filled with castor oil, or some other suitable medium, which is free from moisture and is suitable to transfer the compressional wave energy from the crystals to the cap, through which it is propagated into the surrounding sea water in which the radiator assembly is submerged.

To prevent any substantial amount of effective back-radiation from the steel backing blocks 104, the casing 108 will have sufficient clearance and normally will contain, aside from blocks 104, only air, or some other medium such as felt, which will effectively prevent the effcient transfer of compressional wave energy. In exceptional instances casing 108 can be evacuated to further reduce possible back-radiation.

A similar crystal mounting arrangement is illustrated in Fig. 14 and differs from that of Fig. 13 in that the crystals and backing blocks are

each a half wave-length. Nodal support is obtained by making the supporting plate 110 come at a node of motion of the backing resonator, and hence little energy will be transmitted to the supports. Since the glued joint between the crystals and the metal resonator comes at a loop of the motion, very little strain is put on it, and consequently the mechanical loss is small. Such a construction is advantageous for higher frequencies.

It is, of course, obvious that a plurality of any other type of vibrators, for example magnetostrictive vibrators, can be substituted for the crystals in the above, or analogous, mounting arrangements and that back-radiation from such an assembly would thereby be substantially eliminated.

With structures embodying the above disclosed and illustrated principles of the invention, radiators employing a plurality of piezoelectric crystals may be readily constructed which will radiate equally as much compressional wave energy as the most powerful magnetostrictive radiators and which will require a very substantially smaller amount of electrical driving energy. The radiator assemblies of this invention will furthermore radiate a substantially negligible amount of power toward the rear. The same devices can, of course, be employed for receiving as well as radiating compressional wave energy. For both radiating and receiving the directional properties of the devices will be greatly enhanced by the elimination of unwanted radiation or reception through the casing of the device. This is particularly valuable in submarine detecting systems since the propeller noise of the ship carrying the detecting system is frequently sufficiently great to seriously limit the effective operation of systems of the prior art.

Numerous applications of the principles of the invention will occur to those skilled in the art. No attempt to exhaustively cover all applications of these principles has here been made. The scope of the invention is defined in the following claims.

What is claimed is:

1. In a high-power piezoelectric radiator for compressional wave systems, a Rochelle salt crystal arranged to vibrate longitudinally at a predetermined frequency, a backing member having its longitudinal axis coincident with that of the crystal and cemented to one end of said crystal, the length of said backing member along the longitudinal axis of said crystal being proportioned to induce a node at a particular point along the combination of said crystal and said backing member when the crystal is driven at the predetermined frequency, and mechanical means for supporting the combination of crystal and backing member at said nodal point.

2. In a high frequency compressional wave system, the combination of a piezoelectric vibratory member and a backing member therefor, the first-stated member being cemented to the second-stated member, the combination being proportioned to induce a vibratory node at a point on said backing member, whereby it can be supported with minimum transfer of energy to the supporting means employed, the combination being further proportioned to induce a vibratory loop at the juncture between said crystal and said backing member whereby the strain on said juncture is substantially reduced.

3. In a high frequency compressional wave system, the combination of a piezoelectric vibratory member and a backing block therefor, the member and block being cemented together and being proportioned to produce a vibratory loop at the juncture between them whereby mechanical strain on the juncture is substantially reduced.

4. In a compressional wave signaling system, a radiator and receiver of compressional wave energy including a vibratory member and a mechanical mounting for said member, said mounting including a portion carrying said vibratory member and intermediate portions through which vibratory energy must pass to reach the housing of said mounting from said vibratory member, the transmission of energy through at least one of said intermediate portions being parallel with the longitudinal axis thereof, said intermediate portions being proportioned to form a multiband pass filter having substantial attenuation with respect to the wave-length of the energy of the system to effectively reduce the amount of such energy which can pass therethrough.

5. The combination of claim 4, the length of the said intermediate portions of said mechanical mounting which transmit energy longitudinally being slightly greater than three-eighths wave-length of the energy of the system.

6. A piezoelectric compressional wave radiator comprising a plurality of substantially identical piezoelectric crystals spaced from each other and mounted on a thin metallic mounting plate, the longitudinal axes of the crystals being normal to the plate, the length of each of the crystals along its longitudinal axis being one-quarter wave-length of the mid-frequency to be radiated, an individual metallic backing block for each crystal, each backing block being of substantially the same cross-sectional area as the crystal and being disposed squarely in opposition to the crystal on the opposite side of the mounting plate with its longitudinal axis substantially coincident with that of the crystal, the longitudinal axial length of each backing block being one-quarter wave-length of the mid-frequency to be radiated, whereby when the crystals vibrate longitudinally a node of longitudinal vibration is induced at the mounting plate, substantially no energy is transmitted thereto and mechanical coupling between individual crystals on said mounting plate and dissipation of energy in the mounting structure is substantially reduced.

7. A compressional wave energy radiator, comprising a plurality of electromechanical vibrating members spaced with respect to each other and mounted on a thin resilient mounting plate, the longitudinal axes of said members being at right angles to said plate, the longitudinal axial length of each of said members being substantially one-quarter wave-length of the median frequency of the energy to be radiated by said member, a resilient backing block associated with each member, the backing block having substantially the same cross-sectional area as its associated vibrating member and being mounted opposite it on the mounting plate with its longitudinal axis substantially coincident with that of the member, the longitudinal axial length of said backing block being substantially one-quarter wave-length of the median frequency of the energy to be radiated by its associated vibrating member, whereby mechanical coupling between said vibrating members and dissipation of energy through said mounting plate are substantially reduced.

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