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HIGH POWER PIEZOELECTRIC BEAM GENERATING SYSTEM WITH
ACOUSTIC IMPEDANCE MATCHING

Filed June 29, 1961

Fig-1

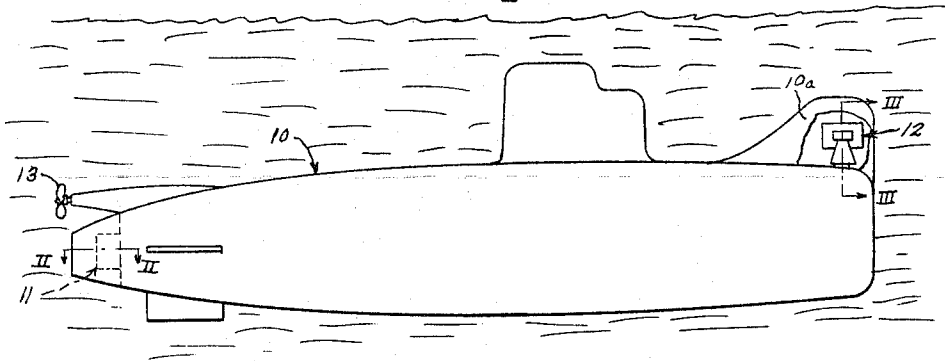


Fig-2

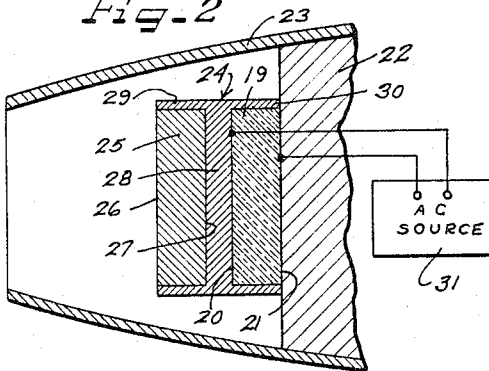


Fig-3

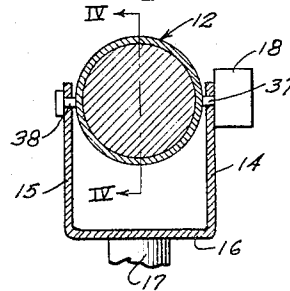


Fig-4

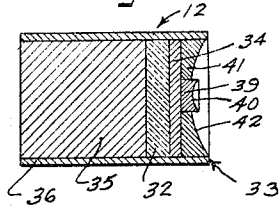


Fig-5

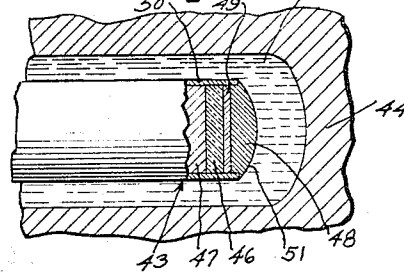
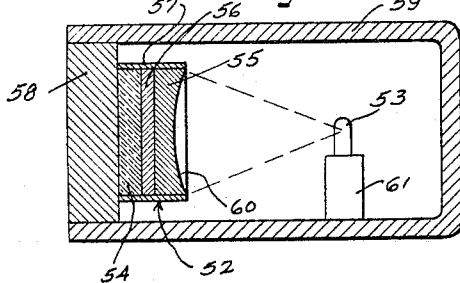


Fig-6



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HIGH POWER PIEZOELECTRIC BEAM GENERATING SYSTEM WITH ACOUSTIC IMPEDANCE MATCHING

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8 Claims. (Cl. 310—8.3)

This invention relates to acoustic beam generating systems and more particularly to systems which are very compact and yet extremely powerful to obtain results not heretofore possible.

This invention was evolved as a result in part of a consideration of the factors which impose limitations on the power output of acoustic transducers. Such limitations have not, of course, prevented the widespread use of such transducers, to generate both sonic and ultrasonic beams, and have not been generally considered to be a serious problem. According to this invention, a transducer system is provided which has extremely high power capabilities, to not only extend the previous uses of sonics and ultrasonics but to open up entirely new uses and applications.

With regard to limitations of prior art transducer systems, such systems have been limited with respect to required electric field strengths, depolarization problems and heat losses. For example, when using transducer materials such as quartz to take advantage of low mechanical loss characteristics, it has been essential to operate at high electric field strengths to obtain a high power output per unit area. For other materials of relatively low electrical impedance characteristics, i.e., the piezoceramics, the limitation is imposed by the field strength level at which depolarization takes place and by the rate of heat production in the material if operated at high power levels. The highest power outputs per unit area that have been achieved thus far have been obtained with very small size transducers. Correspondingly high outputs per unit area have not been achieved with larger size transducers because of design limitations and hence the total power output of a transducer of reasonable size has been quite limited.

According to this invention, means are interposed between a transducer element and a medium into which a beam is transmitted to greatly reduce the impedance presented to the transducer element and consequently to greatly increase the power output obtained for a given electrical driving field strength. With such means, the output is limited only by tension stresses produced in the transducer element and by heat developed within the element. The heating effect can be minimized by employing a material with low loss characteristics such as quartz. The tension stress limitation is overcome by operating the transducer under high compression.

An important feature of the invention is in the construction of the coupling means.

Another important feature of the invention is in the operation of the system under water at a depth large enough to obtain uniform high compression and to overcome the limitation with respect to tension stresses.

A further feature of the invention is in the use of the system to provide a force field screen for undersea vehicles and stationary devices.

A further feature of the invention is in the use of the system to propel a submarine.

Still another important feature of the invention is in the use of the transducer system in boring through solid material.

A still further feature of the invention is in the use of the transducer system to develop extremely high temperatures.

Another feature is in the construction of the coupling means in a manner to form an acoustic lens to focus the beam.

This invention contemplates other and more specific objects, features and advantages which will become more fully apparent from the following detailed description taken in conjunction with the accompanying drawing which illustrates preferred embodiments and in which:

FIGURE 1 illustrates diagrammatically a submarine having two transducer systems constructed according to the principles of this invention, used for propelling the submarine and for transmitting a high power acoustic beam toward another object;

FIGURE 2 is a sectional view, on an enlarged scale, taken along line II—II of FIGURE 1, illustrating one of the transducer systems;

FIGURE 3 is another sectional view, also on an enlarged scale, taken along line III—III of FIGURE 1, and illustrating another acoustic beam generating system;

FIGURE 4 is a sectional view taken along line IV—IV of FIGURE 3;

FIGURE 5 is a sectional view illustrating the application of a transducer system constructed according to the principles of this invention, in boring through a solid; and

FIGURE 6 is a sectional view illustrating an acoustic beam generating system constructed according to the principles of this invention, used in developing high temperatures.

Referring to FIGURE 1, reference numeral 10 generally designates a submarine having two transducer systems 11 and 12 thereon, constructed in accordance with the principles of this invention. Transducer system 11 is designed for propulsion purposes, to be used in addition to or instead of a conventional propeller 13. The system 11 is arranged to transmit a high power acoustic beam rearwardly.

System 12 is designed for transmitting a high power acoustic beam toward another submarine vehicle or a stationary object for deflection, repulsion or destructive purposes. A universal mounting is provided to permit transmission of the beam in any desired direction. In particular, the generator of the system 12 is mounted for pivotal movement about a horizontal axis between a pair of upright arms 14 and 15 of a support 16 which is secured to a shaft 17 journaled by the submarine for pivotal movement about a vertical axis. Rotation of the unit about the horizontal axis may be controlled by a suitable unit 18 and rotation about the vertical axis may likewise be effected by suitable means. The system 12 may in some cases be used for propulsion purposes in addition to or instead of the system 11 and the propeller 13. Likewise, the system 11 may be used in some circumstances for repulsion, deflection or destructive purposes. For streamlining, the system 12 is enclosed in a sound transparent dome 10a.

Referring now to FIGURE 2, the system 11 comprises a transducer element 19, preferably a slab or multiplicity of slabs of appropriately cut quartz to provide the required radiating area and having opposite faces 20 and 21 if thickness vibration (employed at higher ultrasonic frequencies) in response to application of a varying electric field between the opposite faces 20 and 21 is the desired configuration or if lower acoustic frequency operation is desired, wherein longitudinal mode vibration is often employed, appropriately cut crystal elements of ammonium dihydrogen phosphate or like material can be used. The transducer element 19 is secured to a support and backing member 22 which, in turn, is secured within a hollow generally cylindrical housing member 23 forming an extension of the outer shell of the submarine. Preferably, a suitable cement is used to secure the face 21 against the surface of the member 22, and the supporting

member and its coupling to the housing are designed to extract a minimum fraction of the vibratory energy produced by the transducer element 19.

According to this invention, coupling means 24 are provided between the face 20 of the transducer element 19 and the liquid medium—water or other material—into which the acoustic beam is transmitted. The coupling means 24 comprises a first plate or slab 25 disposed parallel to the element 19 and having opposite faces 26 and 27, and a second coupling plate or slab 28 disposed between the plate 25 and the element 19. To insure good acoustic coupling, the opposite faces of the member 28 and the faces 20 and 27 of the transducer 19 and the plate 27 are preferably ground plane and in addition cement or a fluid couplant may be disposed between the engaged faces. Alternately the member 28 may be a liquid which can be circulated through a heat exchanger for removal of thermal energy. In addition, the configuration is provided with cylindrical flanges 29 and 30 extending axially to encompass the plate 25, the slab 28, and the transducer 19.

According to this invention, the slabs 25 and 28 are of such materials and dimensions so that in combination with the medium receiving the radiation, they present a low acoustic impedance to the transducer element 19. It is found that the best results are obtained with the thickness of each of the plates 25 and 28 being equal to a quarter wave length, or an odd number of quarter wave lengths, and with the outer plate 25 having a high characteristic acoustic impedance compared to the characteristic impedance of the liquid medium and the plate 28 having a much lower characteristic impedance. Under such conditions, the acoustic impedance presented to the face 20 of the transducer 19 is low in relation to the impedance presented by the liquid medium to the face 20 of the transducer element 19 if they are in direct contact. The characteristic impedance of a given material may be determined by finding the product of its density and the velocity of sound transmission therein. By way of example, the outer plate 25 may be steel and the inner plate 28 may be a plastic material such as polyethylene or polystyrene or a liquid such as water. With such materials, and with water as the medium receiving the radiation, the impedance presented to the face 20 of the transducer 19 may be only about $\frac{1}{30}$ the impedance presented by water to the face 20 if no intermediate coupling slabs are interposed, that is when the medium receiving the radiation is in direct contact with the transducer element 19. It should be noted again that in some circumstances, the inner plate 28 need not be solid and a liquid or a semi-solid having a low characteristic impedance may be used.

With the acoustic impedance transformation obtained through the coupling means 24, a much larger amplitude of oscillation of the face 20 of the transducer 19 is produced for a given amplitude of change in electric field strength than for the case where the medium to receive the radiation is in direct contact with face 20. The electric field is of course obtained by connecting a suitable A.C. source 31 to electrodes on the opposite faces 20, 21 of the transducer 19, as diagrammatically illustrated. The electrodes may be thin sheets of metallic foil deposited on the faces 20, 21 as is well known. To obtain maximum power output, the A.C. source 31 should have an appropriately low internal impedance, because the effective electrical impedance of the transducer 19 is decreased in proportion to the decrease in mechanical impedance presented to the face 20.

The support and backing member 22 may be of such material and dimensions as to present the greatest possible rigidity at the operating frequency. For example, it may have a thickness equal to an odd integer number of quarter wave lengths backed by air.

In order to realize an increase in momentum for propulsion, for a given expenditure of acoustic energy it is necessary for the face 6 of the plate 25 to radiate into

a medium of reduced sound velocity immediately in contact with the face 26 but one whose velocity increases gradually to that of the bulk medium as the distance from the plate increases. The gradual increase in velocity is necessary in order to prevent reflection of acoustic energy back to the plate 25. A specific example of such a medium is a liquid containing a graded population of gas bubbles with the density greatest at the face 26 and decreasing gradually with the distance behind the face. The housing 23 is extended rearwardly a substantial distance beyond the rear face 26 of the plate 25 in order to confine the medium in the region of reduced sound velocity. In some cases if desired, the open rearward end of the housing 23 may be closed by a diaphragm or the like and a liquid other than water may be introduced into the space within the housing, to obtain the desired characteristic.

For very high intensity output it is highly desirable that the system be operated under high pressure and therefore at depths under the sea. By way of example, hydrostatic pressure is approximately 50 atmospheres at a depth of 1500 feet in water. At this pressure, a sound field intensity of 1000 watts per centimeter can be realized without causing cavitation in the medium. If the transducer has an active face of approximately 4 feet in diameter, the total acoustic power in the beam at this intensity is 10,000 kilowatts. At greater operating depths, the system could be driven at higher levels. Since the magnitude of the radiation pressure exerted by a sound field is proportional to the intensity which is in turn proportional to the square of the acoustic pressure amplitude and since the maximum operating acoustic pressure amplitude is proportional to the depth it is clear that the force of the maximum radiation pressure which can be concentrated on a given cross-section object without producing cavitation is proportional to the square of the operating depth.

Referring now to FIGURES 3 and 4, the transducer unit 12 is arranged to develop a long pencil-like concentrated beam in order to produce high forces on relatively small objects over a considerable distance range. The unit 12 comprises a transducer 32, similar to the transducer 19 of FIGURE 2, a lens means 33 which serves the same general function as the plate 25 of FIGURE 2 and also concentrates the acoustic energy into a beam, an intermediate coupling medium 34 having the same function as the medium 28 of FIGURE 2, and a support and backing member 35, all being enclosed within a cylindrical housing 36 which is supported from the arms 14 by shaft elements 37 and 38. The lens means 33 comprises a center element 39 having a concave surface 40 and an outer ring-shaped element 41 surrounding the center element 39 and having a concave surface 42. The surfaces 40, 42 are so contoured as to produce a long pencil-like concentrated beam. By using a plurality of concentrically related elements in the manner shown, it is possible to obtain the proper concentration of the beam and at the same time obtain a thickness of each individual element which more closely approximates the optimum thickness, i.e., a quarter wave length or an odd number of quarter wave lengths, discussed above in connection with FIGURE 2. In any event it is desirable that the average thickness of each of the elements 39, 41 be equal to a quarter wave length or an odd number of quarter wave lengths.

Referring now to FIGURE 5, reference numeral 43 generally designates a transducer unit designed for carrying out earth boring operations, by operating at sufficiently high sound intensities as to liquefy solid material 44 into liquid 45. The unit 43 comprises a transducer 46 on a backing and support member 47, an outer member 48 and a coupling plate 49 intermediate the transducer 46 and the outer member 48, all supported within a generally cylindrical housing 50. The same considerations in choice of materials and dimensions apply to the elements 46, 47, 48 and 49 as apply to the elements 19, 22, 25 and 28, discussed above in connection with FIGURE 2. The

outer member 48 has a convex face 51 in order to create a divergent beam to liquefy a region of the solid material having a diameter greater than that of the transducer unit 43.

The unit 43 is capable of operating at power levels sufficient to liquefy the solid material through which the device is to pass by raising the temperature appropriately. This arrangement has the distinct advantage over methods employing thermal conductivity principles since the latter procedures are limited by the rate at which heat is conducted from the surface of the material to the interior. However, sound employed in the fashion as illustrated permits liquefaction to occur simultaneously throughout a volume of solid material and the device is then movable through the liquefied medium. The liquefied medium may be removed by suitable means. The acoustic frequency employed is important in determining the amount of material to be liquefied at any one time and consequently the rate of movement of the device through the medium. In general, since the acoustic absorption coefficient increases with frequency, the choice of a specific operating frequency is made on the basis of the total power output of the transducer and the rate of desired travel through the solid structure.

Referring now to FIGURE 6, reference numeral 52 generally designates a unit arranged for heating an object or medium 53 to a high temperature. The unit 52 comprises a transducer 54, an outer transmitting member 55, an intermediate coupling plate 56, all disposed in a cylindrical housing 57, and a backing and support member 58 for the transducer 54, the member 58 being disposed within one end of a housing 59 to form a wall thereof. The outer transmitting member 55 has a concave face 60 for converging the beam at a site in the object 53 to be heated, the object 53 being disposed on a suitable support 61.

The same considerations apply to the choice of materials and dimensions as discussed above in connection with FIGURE 2. It is important that the mean or average thicknesses of the members 55 and 56 be equal to a quarter wave length, or an odd number of quarter wave lengths, and that the characteristic acoustic impedance of the member 55 be high while the characteristic impedance of the member 56 is low. To avoid the production of tension forces, the housing 59 is filled with a liquid under high pressure.

With the arrangement of FIGURE 6, it is possible to produce extremely high temperatures. By way of example, using an operating frequency of one megacycle and a lens member 55 designed to concentrate the entire energy of a four foot diameter transducer into a focused beam of the order of a centimeter or a few millimeters in diameter, intensities may be realized on the order of 100,000 kilowatts per square centimeter. It should be noted that high temperature research and applications have been limited by the fact that methods available up to the present time permit temperatures of extremely tenuous media to be raised to high values but difficulty is experienced if media of high densities such as characterize solids and liquids are to be raised to very high temperatures. The acoustic intensities realized from transducers of the type described make possible the study of dense materials in the temperature range above 10,000 degrees Kelvin.

It will be understood that in each of the systems of FIGURES 3, 4, 5 and 6, and A.-C. source is connected to the transducer in the manner as illustrated diagrammatically in FIGURE 2. To take advantage of the high power capabilities of the systems, the A.-C. source should in the case of water or similar liquids, supply energy at a power level corresponding to at least 50 watts per square centimeter area of the vibratory surface of the transducer element. Much higher intensity levels, on the order of 1,000 to 100,000 watts per square centimeter or more are possible.

It will be understood that modifications and variations may be effected without departing from the spirit and scope of the novel concepts of this invention.

I claim as my invention:

1. In a generator for transmitting an acoustic wave into a fluid medium, an electromechanical transducer having a vibratory surface, matching means having one face engaged with said surface and an opposite face engaged with said liquid medium arranged to produce a large vibratory movement of said opposite face in response to a small amplitude electric driving function applied to the transducer as compared to the configuration wherein the electromechanical transducer is in direct contact with the said fluid medium, and means for operating said generator in a high pressure fluid medium to apply uniform compression thereto, said matching means including a first section defining said opposite face and having a high characteristic acoustic impedance compared to the characteristic acoustic impedance of the fluid medium and a second section between said first section and said transducer having a lower characteristic impedance than that of said first section.

2. In a generator for transmitting an acoustic wave into a fluid medium, an electromechanical transducer having a vibratory surface, matching means having one face engaged with said surface and an opposite face engaged with said liquid medium arranged to produce a large vibratory movement of said opposite face in response to a small amplitude electric driving function applied to the transducer as compared to the configuration wherein the electromechanical transducer is in direct contact with the said fluid medium, and means for supporting said generator at a large depth undersea to apply uniform compression thereto, said matching means including a first section defining said opposite face and having a high characteristic acoustic impedance compared to the characteristic acoustic impedance of the fluid medium and a second section between said first section and said transducer having a lower characteristic impedance than that of said first section.

3. In a generator for transmitting an acoustic wave into a fluid medium, an electromechanical transducer having a vibratory surface, matching means having one face engaged with said surface and an opposite face engaged with said liquid medium arranged to produce a large vibratory movement of said opposite face in response to a small amplitude electric driving function applied to the transducer as compared to the configuration wherein the electromechanical transducer is in direct contact with the said fluid medium, a housing supporting said transducer and matching means therewithin, and high pressure liquid within said housing to apply uniform compression to said matching means and said transducer, said matching means including a first section defining said opposite face and having a high characteristic acoustic impedance compared to the characteristic acoustic impedance of the fluid medium and a second section between said first section and said transducer having a lower characteristic impedance than that of said first section.

4. In a generator for transmitting an acoustic wave into a fluid medium, an electromechanical transducer having a vibratory surface, matching means having one face engaged with said surface and an opposite face engaged with said liquid medium arranged to produce a large vibratory movement of said opposite face in response to a small amplitude electric driving function applied to the transducer as compared to the configuration wherein the electromechanical transducer is in direct contact with the said fluid medium, and an A.-C. source for supplying energy to said transducer at a power level corresponding to at least 50 watts per square centimeter area of said surface, said matching means including a first section defining said opposite face and having a high characteristic acoustic impedance compared to the characteristic acoustic impedance of the fluid medium and a second

section between said first section and said transducer having a lower characteristic impedance than that of said first section.

5. In a generator for transmitting an acoustic wave into a fluid medium, a quartz transducer, a support and backing member secured to one face of said transducer, and matching means having one face secured to the other face of said transducer and having an opposite face engaged with said liquid medium arranged to produce a large vibratory movement of said opposite face in response to a small amplitude electric driving function applied to the transducer as compared to the configuration wherein the electromechanical transducer is in direct contact with the said fluid medium, said matching means including a first section defining said opposite face and having a high characteristic acoustic impedance compared to the characteristic acoustic impedance of the fluid medium and a second section between said first section and said transducer having a lower characteristic impedance than that of said first section.

6. In a generator for transmitting an acoustic wave into a fluid medium, an electromechanical transducer having a vibratory surface, and matching means having one face engaged with said surface and an opposite face engaged with said liquid medium arranged to produce a large vibratory movement of said opposite face in response to a small amplitude electric driving function applied to the transducer as compared to the configuration wherein the electromechanical transducer is in direct contact with the said fluid medium, said matching means including a first section having a thickness equal to $(2n-1)/4$ wave lengths, n being an integer number, said first section having a high characteristic acoustic impedance compared to the characteristic impedance of said fluid medium, said matching means including a second section between said first section and said transducer and having a lower characteristic acoustic impedance than that of said first section.

7. In a generator for transmitting an acoustic wave into a fluid medium, an electromechanical transducer having a vibratory surface, and matching means having one face engaged with said surface and an opposite face engaged with said liquid medium arranged to produce a large vibratory movement of said opposite face in re-

sponse to a small amplitude electric driving function applied to the transducer as compared to the configuration wherein the electromechanical transducer is in direct contact with the said fluid medium, said matching means including a first section having a thickness substantially equal to $(2n_1-1)/4$ wave lengths, and a second section between said first section and said transducer and having a thickness substantially equal to $(2n_2-1)/4$ wave lengths, n_1 and n_2 being integer numbers, said first section having a high characteristic acoustic impedance compared to the characteristic impedance of the said fluid medium and said second section having a lower characteristic acoustic impedance than that of the first section.

8. In a generator for transmitting an acoustic wave into a fluid medium, an electromechanical transducer having a vibratory surface, and matching means having one face engaged with said surface and an opposite face engaged with said liquid medium arranged to produce a large vibratory movement of said opposite face in response to a small amplitude electric driving function applied to the transducer as compared to the configuration wherein the electromechanical transducer is in direct contact with the said fluid medium, said matching means including a first section defining said opposite surface and having a high characteristic acoustic impedance compared to the characteristic acoustic impedance of the fluid medium and a second section between said first section and said transducer having a lower characteristic impedance than that of said first section.

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