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2,865,016

LOW FREQUENCY BROAD BAND UNDERWATER TRANSDUCER

Filed May 31, 1956

2 Sheets-Sheet 1

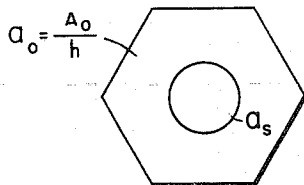


Fig. 1

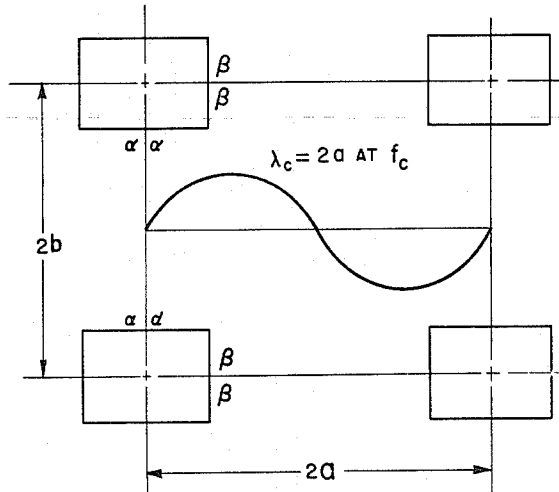


Fig. 2

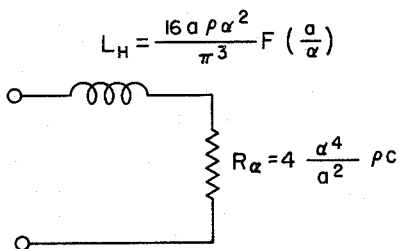


Fig. 4

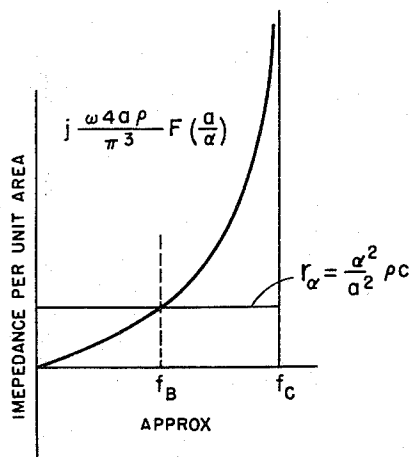


Fig. 3

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Fig. 5

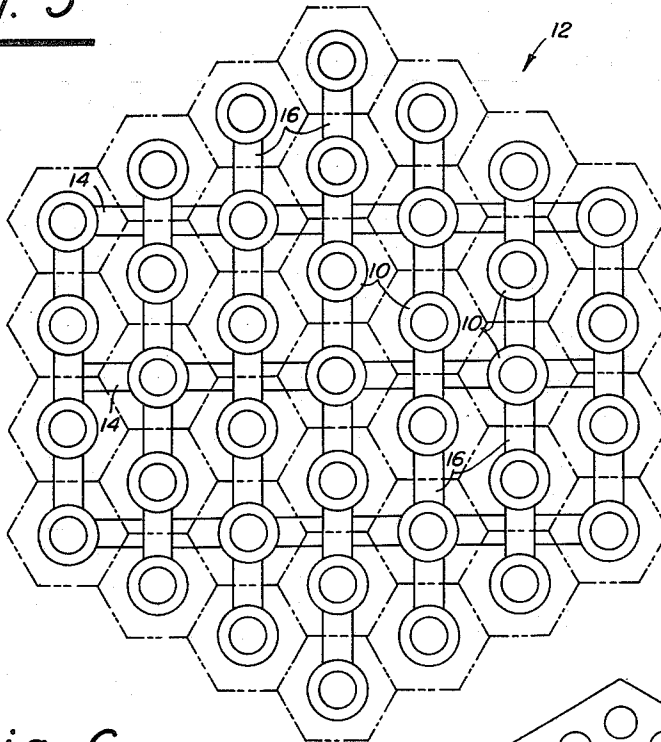


Fig. 6

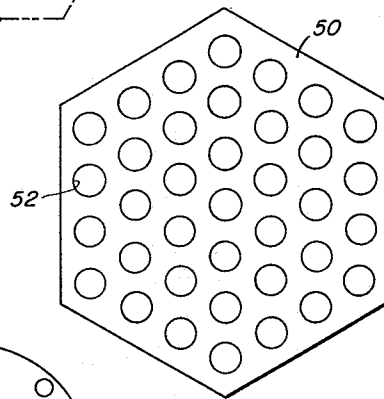
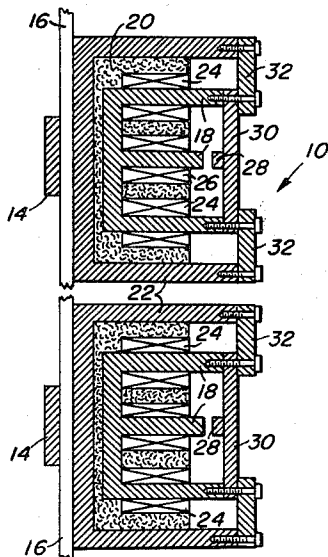


Fig. 8

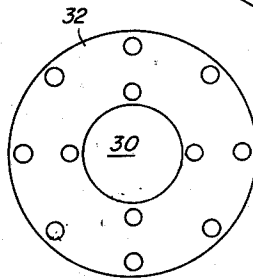


Fig. 7

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LOW FREQUENCY BROAD BAND UNDERWATER TRANSDUCER

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Application May 31, 1956, Serial No. 588,581

4 Claims. (Cl. 340—9)

(Granted under Title 35, U. S. Code (1952), sec. 266)

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

This invention relates to the production and reception of compressional wave energy and more particularly to efficient broadband transmission and reception at low frequencies in a fluid of high impedance.

The problem which is effectively solved by the disclosed apparatus is the matching of the impedance of a relatively low impedance transducer to the impedance of a propagating medium (such as water) which has a much higher impedance. This problem is of particular importance in broad band transducers for use at frequencies in the region below 2000 cycles per second. Electroacoustic transducers of inherently high impedance, piezoelectric crystals, barium titanate and magnetostrictive devices are not suitable for low frequency operation or for larger bandwidths. Those transducers, moving coil and variable reluctance drivers, which may be suited for low frequency operation have inherently low impedances and it has previously been considered impossible to match the impedance of such drivers to the impedance of water. The present invention solves this problem of impedance matching by using a transducer comprising a multiplicity of unconnected vibratory radiating elements of the desired low frequency electromagnetic type operated in phase and in parallel in such a fashion that each is presented with a mechanical impedance load of a magnitude sufficiently low for structures of practical size, and at the same time is presented with an impedance having a suitably high ratio of mechanical resistance to mechanical reactance. This impedance matching is accomplished by (1) impedance division and (2) impedance transformation. The division of impedance is effected simply by arranging a group of radiators in parallel to cover a minimum total area which is determined by the lowest frequency to be radiated. However, impedance division alone is not sufficient practically to obtain the required impedance matching. This invention therefore incorporates acoustical impedance transformation for each of the individual radiators. This transformation for individual radiators is achieved by virtue of the interaction or mutual support of a large group of adjacent radiators when the distance between adjacent radiators is small, less than one wave length at the highest frequency to be radiated. This impedance transformation is proportional to the fourth power of the ratio between the center to center distance of adjacent radiators and a linear dimension (such as radius) of the individual radiators.

An object of this invention is to present to a transducer a radiation impedance having a high ratio of resistance to reactance at low frequencies.

Another object of this invention is to provide a practical means for the efficient radiation of acoustic energy into a high impedance fluid, such as water, over relatively broad bands of frequencies in the lower audio frequency region.

A further object of this invention is to provide a

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method and means for efficiently coupling electro-acoustic transducers of inherently low mechanical impedance to a fluid load of high impedance.

A further object of this invention is to provide means whereby a multiplicity of small simple electroacoustic transducers may be used to provide large amounts of power in a specified frequency region.

Other objects and many of the attendant advantages of this invention will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein:

Fig. 1 represents one of many radiating cells of which the disclosed transducer array is composed;

Fig. 2 is a diagrammatical representation of a portion of an infinite rectangular array of radiators;

Fig. 3 graphically depicts the relation between impedance and frequency for the array of this invention;

Fig. 4 comprises a simplified equivalent acoustic circuit of the impedance presented to an individual driver;

Fig. 5 is a front view of an array constructed in accordance with the principles of this invention;

Fig. 6 is a sectional view of a portion of the array of Fig. 5;

Fig. 7 is a front view of one unit of Fig. 6; and

Fig. 8 shows, to a reduced scale, a rigid baffle for the array.

While electromagnetic transducers, such as the moving coil or variable reluctance driver, have been successfully used in air at low frequencies, certain dimensions of such devices must be 73,000 times as great for the case of water as for the case of air when a single transducer is used. Thus the design of underwater transducers of these classes poses a problem of quite a different order of magnitude than for the case of loudspeakers.

As will be shown later a certain linear dimension of these types is directly proportional to the product of the frequency at the upper edge of a band to be transmitted by the total resistance in mechanical ohms inherent in the radiation impedance of the fluid facing the device. This total resistance is proportional to the density of the fluid (high for water) and to the total area to be driven by the transducer. This becomes very large for low frequencies as the perimeter of this area must be at least equal to the wave length in the fluid of the lowest frequency in the band to be radiated at high efficiency. Thus certain required dimensions for a single transducer would become completely impractical for certain ranges of frequency and bandwidth.

In order to present the proper mechanical impedance load of the proper type to a structure of practical size this invention provides a combination of impedance division and impedance transformation.

The division of impedance is accomplished simply by arranging a group of separate radiators in parallel covering the minimum area above noted as set by the lowest frequency to be radiated. They should cover this area in a symmetrical manner, and the preferred arrangement is that the centers of the diaphragms of these radiators should be at the centers of a close packed nest of hexagons. This in turn builds up a large hexagon whose area should be that of a single circular radiator designed to work down to the lowest frequency. A square pattern may also be used, but a set of diaphragms of equal area equispaced on a square pattern will not cover as large a percentage of the total area as will the same sized diaphragms with the same center to center spacing in a hexagonal pattern. Neither will the overall square approximate as well to the basic circular area as does the hexagon. The latter is, therefore, considered to be the preferred pattern for most practical applications of this invention.

However, even if 100 separate radiators are used that would still leave a factor of 73,000 divided by 100, or 730 which must be taken care of by some other procedure for bringing the design problem of efficient broadband underwater devices into the same order of design difficulty as has been met in the case of loudspeakers. One order of magnitude might be more or less completely taken care of by extending standard design procedures to the limit but broadly there will be a factor of around 50 to 750 which must be taken care of by some form of impedance transformation between the acoustic fluid and the electromagnetic type of driver. It will lie in the upper region of this range for the moving coil type of driver which has an extremely low mechanical impedance and in the lower part for the case of the variable reluctance type of driver, inherently having a higher mechanical impedance.

It is possible to provide the required impedance transformation in one of two ways; mechanical or acoustical. Mechanical impedance transformation may be provided between the driving element and the diaphragm next to the water by any one of a number of well known devices, such as levers and tapered mechanical filters or transmission lines of various types. These are, in general, difficult to design and construct for any considerable amount of transformation and hence are not considered the preferred form in the execution of our invention. They might in some cases be used as an additional adjunct in meeting exceptionally difficult requirements.

Acoustical transformation has been used in the past in the form of a horn between the diaphragm and the fluid into which energy is to be radiated. Such horns are quite out of the question for underwater applications as their dimensions must be large compared to the wave lengths used and for a given lower cut off frequency the rate of taper in the horn must be nearly five times as gradual for the case of water as compared with that of air. Instead it is proposed to use a new form of acoustic transformation which becomes operable only in the case of a large group of parallel operating radiators and only when the dimensions employed are small compared to the wave lengths involved. The hydraulic press may be regarded as the direct current case of this kind of acoustic impedance transformation and hence it will be referred to in the remainder of this disclosure as "hydraulic" transformation.

The manner in which a single projector, or more realistically projecting system, it built up according to this invention will next be simply described, to be followed by a more detailed development of the principal design rules controlling its proportioning for meeting specific transmission requirements. The type of transmission requirement which the projector is designed to meet calls for efficient uniform transmission from a lower band edge frequency, f_A , to an upper band edge, f_B . There may then be defined a band width ratio, n , equal to f_B divided by f_A . Thus when $n=2$, the transmission band is one octave wide; $n=4$, 2 octaves, $n=8$, 3 octaves; etc.

The locations of the band edges provide the transmission requirements of the design of a projector. Another important requirement is the total power to be projected. Here there may be noted another objective satisfied by this invention, that is, even for large powers such as several kilowatts, the power to be handled by each of the multiple drivers may be made so small that problems of structural strength are easily kept within reasonable limits.

While there is some interaction between the upper and lower band edge requirements upon the structural design, especially for narrow bands, it is possible to regard two main features of the design as associated principally with one or the other. Thus the lower edge, f_A , determines the overall size of the structure while the upper edge, f_B , establishes the permissible masses and compliances of any driving structure working into a given number of mechanical ohms resistance of the radiation impedance.

Consider a close packed circular array of radiators having a total diameter, D , which determines a minimum area, A_0 , necessary to radiate efficiently down to a frequency f_A . This requires a perimeter, πD , to this area at least as large as the wave length, λ_A , of f_A , for the case in which a single piston in an infinite baffle is used as a radiator. As pistons are not practical underwater devices, a diaphragm (which is peripherally clamped) would have to be used of the same effective area, which would be about three times this basic area. Herein appears another objective attained by this invention that, even assuming such a large diaphragm could be supplied with a driver, the problems raised by the appearance of higher modes of vibration within a wide band would be very serious. This is avoided by the use of multiple small diaphragms to cover the area.

This circular area is covered by a multiple set of smaller radiators of some selected number, h , arranged in a hexagonal pattern. The number, h , is not continuously variable but moves in steps because of the nature of the pattern. Possible values of h are thus, 7, 19, 37, 61, 91, 127, etc. If these individual radiators have hexagonal shapes, thus perfectly covering the area, and moved in phase, the first prime characteristic of the invention is satisfied; that of impedance division. The total radiation resistance facing the whole required area, A_0 , is $A_0 \rho c$, where ρ is the density of the fluid and c is the velocity of sound in it. The impedance driven by each separate unit is this quantity divided by h .

The second prime characteristic of the invention, hydraulic impedance transformation is introduced in an array having the same basic overall area, A_0 , and the centers of the individual radiators are maintained at the same positions. However, the effective areas of the individual radiators are appreciably reduced in magnitude. An approximate relation for the effect of this arrangement is rather simply derived for the low frequency assumption that Pascal's law holds. In other words, for distances small compared to a wave length the pressure in a fluid is essentially constant.

Consider in Fig. 1, a single hexagonal cell, taken from the pattern of shrunken radiators of area

$$a_0 = \frac{A_0}{h} \quad (1)$$

and the shrunken radiator of effective area, a_s . Consider the cell to be bounded by infinitely thin walls of infinitely high impedance and about $1/4$ to $1/2$ wave length high. Let the impedance facing the cell be r_0 and that facing the shrunken radiator be r_s . Then for the constant pressure assumption the respective velocities at the original and shrunken faces will be

$$v_0 = \frac{Pa_0}{r_0}$$

and

$$v_s = \frac{Pa_s}{r_s}$$

where p is the pressure.

Then

$$\frac{V_0^2}{V_s^2} = \frac{a_0^2 r_s^2}{a_s^2 r_0^2} \quad (2)$$

For equal energy leaving the cell to that supplied by the piston

$$V_0^2 r_0 = V_s^2 r_s \quad (3)$$

or

$$\frac{V_0^2}{V_s^2} = \frac{r_s}{r_0} \quad (4)$$

Hence

$$\frac{r_s}{r_0} = \frac{a_0^2 r_s^2}{a_s^2 r_0^2} \quad (5)$$

or

$$\frac{r_0}{r_s} = \frac{a_0^2}{a_s^2}$$

Thus in such a cell the impedance facing the shrunken

radiator is to the impedance facing the cell as the square of their areas. When such a cell is considered as part of an infinite array it will be noted that the pressure changes on both sides of all cell walls are equal so no motion of the cell wall would result. Hence all such walls may be removed and the process of hydraulic transformation is thus seen to depend on the mutual support rendered to each other by a large group of mutually adjacent radiators. As the areas are proportional to the linear dimensions, it will be seen that the hydraulic impedance transformation increases as the 4th power of the linear shrinkage ratio.

This would indicate that extremely large ratios of hydraulic impedance transformation would be attained by indefinitely shrinking the sizes of the individual radiators. A closer look at the situation indicates that there will be two physical limitations on how far the process may be carried. One is a matter of the power to be projected. The more the radiating surface is shrunken in size the greater will be its displacement and hence its velocity and acceleration. Thus cavitation will occur at lower powers than for a single large radiator. However, when designed for the necessary large area for uniform efficiency down to the lower band edge, f_A , the displacement per watt is extremely small and considerable transformation will be found permissible.

The second limitation may be arrived at intuitively by considering the case of a transmission line in which uniformly distributed inductance is replaced by lumped loading. The effect is to introduce a limitation of bandwidth at the upper frequencies, the point of limitation being established by the number of loading coils per wave length at that point. Thus one would expect that, if uniformly distributed drive were to be replaced by concentrated drive, the distance between drive centers would have to be some fraction of a wave length at the upper band edge frequency, f_B .

A rigorous proof and solution of the factors presented in the preceding heuristic exposition may be derived from a consideration of the wave equations for the case of a rigid piston in an infinite rectangular array of pistons mounted in a rigid plane baffle. For the purposes of this solution there was assumed an infinite array, as depicted in Fig. 2, of rectangular pistons having sides 2α and 2β and spaced horizontally and vertically by distances of $2a$ and $2b$ respectively. From this solution it is found that the radiation impedance per unit area, z , takes the form

$$z = \rho c \frac{\alpha\beta}{ab} + j \frac{4\rho c}{\pi^2} \frac{ab}{b\alpha} \sum_{m=1}^{\infty} \frac{\sin^2 \frac{m\pi\alpha}{a}}{m^2 \sqrt{-4 + \left(\frac{m\lambda}{a}\right)^2}} + j \frac{4\rho c}{\pi^2} \frac{b\alpha}{a\beta} \sum_{n=1}^{\infty} \frac{\sin^2 \frac{n\pi\beta}{b}}{n^2 \sqrt{-4 + \left(\frac{n\lambda}{b}\right)^2}} + j \frac{8\rho c}{\pi^4} \frac{ab}{\alpha\beta} \sum_{m,n=1}^{\infty} \frac{\sin^2 \frac{m\pi\alpha}{a} \sin^2 \frac{n\pi\beta}{b}}{m^2 n^2 \sqrt{-4 + \left(\frac{m\lambda}{a}\right)^2 + \left(\frac{n\lambda}{b}\right)^2}} \quad (6)$$

where the plus sign is to be used with the radicals below a critical frequency to be defined below and z is the impedance in mechanical ohms (c. g. s. system) per unit area, $2a$ and $2b$ are the spacings between centers in the array, and 2α and 2β are the sides of one radiator. ρ and c have their usual meaning of density and velocity of sound and m and n are the running indices.

For the purposes of a symmetrical multiple array the dimensions in the two directions should be alike; that is, $a=b$ and $\alpha=\beta$. It will then be observed that the first

two summations become equal to each other. Then the impedance per unit area becomes,

$$z = \rho c \frac{\alpha^2}{a^2} + j \frac{8\rho c}{\pi^2} \left\{ \sum_{m=1}^{\infty} \frac{\sin^2 \frac{m\pi\alpha}{a}}{m^2 \sqrt{-4 + \left(\frac{m\lambda}{a}\right)^2}} + \frac{a^2}{\alpha^2 \pi^2} \sum_{m,n=1}^{\infty} \frac{\sin^2 \frac{m\pi\alpha}{a} \sin^2 \frac{n\pi\alpha}{a}}{m^2 n^2 \sqrt{-4 + \left(\frac{m\lambda}{a}\right)^2 + \left(\frac{n\lambda}{a}\right)^2}} \right\} \quad (7)$$

The magnitude of

$$\frac{\alpha}{a}$$

may be termed a shrinkage ratio.

Equation 7 consists of a constant resistance term

$$r = \frac{\alpha^2}{a^2} \rho c$$

for all frequencies plus a j term which may represent only reactance or a mixture of resistance plus reactance depending on whether the radicals in the denominators of the summations are real or imaginary. Examination shows that there is a critical frequency for $m=1$ below which all contributions to the impedance are purely reactive. Call this frequency, f_c , and its wave length, λ_c . It is defined by $\lambda_c = 2a$, the spacing between centers. For higher values of m , smaller values of λ (higher frequencies) are required to make the radical imaginary and thus make contributions to the resistance component. Hence, below f_c all terms contribute only to reactance and the general nature of this impedance is shown by Fig. 3.

It is readily sketched in below the frequency f_c . It consists first of the constant resistance term

$$r = \frac{\alpha^2}{a^2} \rho c$$

and of a reactance term approximately proportional to frequency at low frequencies and tending to infinity at f_c . Above f_c the impedance becomes complicated.

Below f_c the only term which contributes to resistance is then the first term

$$\rho c \frac{\alpha^2}{a^2}$$

As this is the resistance per unit area the total resistance facing a square piston which is 2α on a side will be

$$4\rho c \frac{\alpha^4}{a^2}$$

The maximum area which the square piston can have is when $\alpha=a$. Then the impedance per unit area is of course ρc and the total impedance is $4\rho c a^2$. The ratio of these two impedances is α^4/a^4 . This is exactly the same value which was obtained for the hydraulic transformation as worked out assuming Pascal's law; namely, proportional to the fourth power of the ratio of the linear dimensions or shrinkage ratio.

The character of the reactance term may next be found by observing that below f_c , the expression for the impedance per unit area may be written in terms of frequency, f , as

$$z = \rho c \frac{\alpha^2}{a^2} + j \frac{8a\rho f}{\pi^2} \left\{ \sum_{m=1}^{\infty} \frac{\sin^2 \frac{m\pi\alpha}{a}}{m^2 \sqrt{m - \left(\frac{f}{f_c}\right)^2}} + \frac{a^2}{\alpha^2 \pi^2} \sum_{m,n=1}^{\infty} \frac{\sin^2 \frac{m\pi\alpha}{a} \sin^2 \frac{n\pi\alpha}{a}}{m^2 n^2 \left(m^2 + n^2 - \left(\frac{f}{f_c}\right)^2 \right)} \right\} \quad (8)$$

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For values of f near zero the term

$$\left(\frac{f}{f_c}\right)^2$$

will be negligible and the reactance term will rise linearly with frequency. This term will become appreciable only after

$$\frac{f}{f_c}$$

becomes as large as $\frac{1}{3}$ or $\frac{1}{2}$, after which for larger values of f it begins to rise more rapidly approaching infinity at the value f_c . Thus at the lower frequencies the character of the mechanical impedance presented to the radiation surface is the same as that presented by a mass in series with a mechanical resistance. The electrical analog would be an inductance in series with an electrical resistance as shown in Fig. 4.

A preliminary estimate of the frequency limitation put in by this characteristic is readily obtained by regarding the resistance term as the load on a simple low pass filter with the series inductance regarded as a half series termination. The corresponding cutoff occurs when the resistance equals the reactance and this is indicated on Fig. 3 as f_B . In an actual structure the cutoff will be still lower due to other structure masses which must be added to this one. These masses comprise those of the driven armature and diaphragm described below.

It may be assumed therefore that a good approximation is obtained when

$$\left(\frac{f}{f_c}\right)^2$$

is dropped and the expression for the impedance per unit area becomes

$$z = \frac{\alpha^2}{a^2} \rho c + j\omega \frac{4a\rho}{\pi^3} \left\{ \sum_{m=1}^{\infty} \frac{\sin^2 \frac{m\pi\alpha}{a}}{m^3} + \frac{\alpha^2}{\alpha^2 \pi^2} \sum_{m,n=1}^{\infty} \frac{\sin^2 \frac{m\pi\alpha}{a} \sin^2 \frac{n\pi\alpha}{a}}{m^2 n^2 \sqrt{m^2 + n^2}} \right\} \quad (9)$$

and thus the total impedance facing a single radiator of side 2α will be $4\alpha^2$ times this, or,

$$z_h = 4\rho c \frac{\alpha^4}{a^2} + j\omega \frac{16a\rho\alpha^2}{\pi^3} F\left(\frac{a}{\alpha}\right) \quad (10)$$

in which

$$F\left(\frac{a}{\alpha}\right)$$

represents the infinite series terms within the brackets.

Equation 10 may be interpreted physically as a fluid loading mass, L_H in series with a radiation resistance as shown in Fig. 4. L_H , herein defined as a series mass of the hydraulic transformation.

$$= \frac{16a\rho\alpha^2}{3} F\left(\frac{a}{\alpha}\right)$$

and the radiation resistance

$$R_a = 4 \frac{\alpha^4}{a^2} \rho c$$

This latter agrees with the value derived in the simple check on the hydraulic transformation ratio.

The wave equation solution has thus provided information on the kind of reactance which accompanies a given amount of hydraulic transformation. This reactance can be readily evaluated in terms of analog circuits as to its effect in restricting band width for broad band operation.

The simplest viewpoint is to regard R_a as the terminal load on a filter, with L_H representing a series half coil termination of a low pass filter. Then $2L_H = L_1$, the full coil value used in filter formulas.

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For a low pass filter the upper cut-off frequency

$$f_B = \frac{R_a}{\pi L_1} = \frac{R_a}{2\pi L_H} \quad (11)$$

Hence for the hydraulic transformer as a filter

$$f_B = \frac{\frac{4\alpha^4}{a^2} \rho c}{2\pi \times \frac{16a\rho\alpha^2}{\pi^3} F\left(\frac{a}{\alpha}\right)} = \frac{\alpha^2}{a^2} \frac{\pi^2 c}{8a F\left(\frac{a}{\alpha}\right)} \quad (12)$$

20 Noting that $2a = \lambda_c$ and $c = \lambda_c f_c$

$$f_B = \frac{\alpha^2}{a^2} \cdot \frac{\pi^2 f_c}{4 F\left(\frac{a}{\alpha}\right)} \quad (13)$$

25 This frequency is thus seen to be the point at which the reactance and resistance on Fig. 3 are equal (below f_c). As

$$\frac{\alpha}{a}$$

30 approaches unity

$$F\left(\frac{a}{\alpha}\right)$$

35 goes to zero and f_B goes to infinity and there is no frequency limitation. When

$$\frac{\alpha}{a}$$

is less than unity, then f_B will be less than f_c for any worthwhile amount of impedance transformation. At f_c the piston centers are spaced one wave length apart. Hence the solution for

$$\frac{f_c}{f_B}$$

will give the number of piston centers needed per wave length at the frequency f_B to secure a pass band up to f_B

$$\frac{f_c}{f_B} = \frac{4}{\pi^2} \frac{a^2}{\alpha^2} F\left(\frac{a}{\alpha}\right) \quad (14)$$

50 A quick evaluation of this can be made for the case

$$\frac{a}{\alpha} = 2$$

55 which gives a hydraulic impedance transformation of 16. For this case the even values of m and n make the sines zero in the summation of terms

$$F\left(\frac{a}{\alpha}\right)$$

60 It is then seen that only the terms for $m=n=1$ are significant as the next terms for $m=3, n=3$, will be only 3% of the size of the first terms. Then as

$$\frac{m\pi}{a} = \frac{\pi}{2} \text{ and } \sin \frac{m\pi\alpha}{a} = 1$$

$$F\left(\frac{a}{\alpha}\right) = 1 + \frac{4}{\pi^2 \sqrt{2}}$$

and

$$\frac{f_c}{f_B} = \frac{4}{\pi^2} \times 4 \left(1 + \frac{4}{\pi^2 \sqrt{2}}\right) = 2.1 \text{ centers per wave length}$$

For higher values of

$$\frac{a}{\alpha}, F\left(\frac{a}{\alpha}\right)$$

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becomes more complicated and more terms of the summation must be taken into account.

In an actual structure coupled to an electromagnetic driving element, other masses and compliances, such as those of the diaphragm, will affect the actual design for a given transmission band. However, it will be recognized by those familiar with the art of designing filters that the equivalent circuit of Fig. 4 is in a form which can be perfectly incorporated into standard forms of band pass filters. The detail design then becomes relatively straightforward.

In Figs. 5, 6, and 7 is shown an exemplary embodiment of a transducer array constructed in accordance with the principles set forth above. This array comprises a number such as 37 of equi-distant symmetrically arranged circular radiators 10 located at the centers of a close packed nest of imaginary hexagons (shown in dotted lines) to form a complete hexagonal array 12 having a perimeter at least equal to the wavelength of the lowest frequency of the frequency band for which the array is designed. The individual transducers are fixedly mounted on a rigid skeletal framework 14, 16 which is to be carried or located underwater by any suitable means such as a surface or subsurface vessel.

The transducers shown are of the variable reluctance type and as shown in Fig. 6 comprise an E-shaped core 18 secured by means of potting compound or the like 20 in a casing 22 which is affixed to frame members 16. The outer legs of the core 18 carry a polarizing winding 24 which is energized with a D.-C. current from a source (not shown) while the center leg of each core carries a driving winding 26 to or from which is fed an A.-C. signal either generated for projection by equipment (not shown) on the vessel or generated by relative motion between driven armature 28 and the coil 26 (and core). Armature 28 is fixed to the center of a circular vibratory diaphragm 30 which is peripherally secured to casing 22 by means of an annular plate 32 which may be provided with suitable means such as gaskets for sealing the casing and its contents against the entry of the surrounding water. The transducers or radiators 10 are of identical construction, are arranged with the outer surfaces of diaphragms 30 in the same plane, and are driven with equal amplitude in parallel and in phase when projecting.

In accordance with the principles set forth above impedance division is effected by the use of plural independent transducers operated in parallel and covering a minimum area determined by the wavelength of the lowest frequency of the band to be covered. Hydraulic impedance transformation is effected by reason of the fact that the effective vibratory area of each peripherally clamped diaphragm is less than the ratio of the total area of the array to the number of individual diaphragms (i. e., the area of one imaginary hexagon of Fig. 5) while the frequency of the upper edge of the band to be covered determines the center to center distance of adjacent radiators. This center to center distance must be less than one wavelength at the upper frequency and for a broad band array is preferably less than one half or one third of such wavelength.

In order to provide a rigid baffle in which the vibratory diaphragms 30 are mounted, coplanar therewith, there could be provided a rigid plate 50 (Fig. 8) having a plurality of apertures 52 positioned to each receive one of casings 22. This plate would be rigidly secured in any suitable manner to the casings and skeletal support therefore. This plate might conveniently be formed by extending annular plates 32 to completely cover the inter-casing spaces whereby a single integral plate 32 would be provided coextensive with the area of the array.

The disclosed broadband low frequency array thus has three main characteristics.

First, the perimeter of the array is substantially equal to or greater than one wave length at the lower band edge.

Second, the effective area of each vibratory surface 30 is appreciably smaller than the total area of the array divided by the number of vibratory surfaces whereby the radiation resistance is decreased. This area control provides the characteristic resistance value of the image impedance of each individual transducer (presented at the water contacting side thereof) which is equal to the product of (1) the fourth power of the linear shrinkage ratio (or the ratio of the square of effective area of one transducer to the square of the area of one imaginary hexagonal cell of Fig. 5), (2) the area of such cell, (3) the fluid density, and (4) the velocity of sound in the fluid.

Third, this resistance value of the image impedance in mechanical ohms is at least equal to or greater than the mechanical reactance in ohms, at the frequency of the upper band edge, due to the sum of (1) the mass of armature 28, (2) the effective mass of one imaginary hexagon 30 and (3) the series mass of the hydraulic transformation (defined above) as indicated in Fig. 3 by the intersection of the resistance and reactance curves. It will be readily appreciated that the disclosed array will operate into a favorably low radiation resistance and, at the same time, the radiation reactance is even smaller, since, as indicated in Fig. 3, this array will operate at or below f_b whereby optimum impedance is provided. Thus it is possible with the disclosed array to secure transmission over a band of several octaves with uniform and high efficiency.

While there has been disclosed a specific variable reluctance transducer operable in water it is to be understood that the principles of this invention may be applied to other types of transducer drivers and other fluids of high characteristic impedance.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims the invention may be practiced otherwise than as specifically described.

What is claimed is:

1. A broad band transducer comprising a plurality of independent effective vibratory surface means for transmitting and receiving energy over a predetermined broad band of low frequency in a high impedance fluid and being uniformly spaced over an area having a perimeter substantially equal to one wave length at the lowest frequency of said band, adjacent surface means having a center to center spacing substantially less than one wavelength at the highest frequency of said band, and said surface means having a total area substantially less than said first mentioned area.

2. The structure of claim 1 wherein said surface means are coplanar, and including means for actuating said surface means in like phase.

3. An electroacoustic transducer array for operating with high efficiency into a high impedance fluid over a predetermined band of frequencies comprising a multiplicity of transducers each having a vibratory surface and a driver secured thereto, said transducers being mounted equispaced in a uniform pattern, said array being characterized by (a) an array perimeter which is at least equal to one wavelength at the lowest frequency of said band, (b) the effective area, A_1 , of each of said surfaces is substantially less than an area A_2 , the total area of the array divided by the number of said surfaces, (c) the characteristic resistance value of the image impedance of each of said transducers is equal to the product of (1) A_1^2/A_2^2 , (2) A_2 , (3) the density of said fluid and (4) the velocity of sound in said fluid, and (d) said image impedance resistance value is at least equal to the mechanical reactance in ohms at the highest frequency of said band due to the sum of (1) the mass of one of said drivers, (2) the effective mass of one of said vibratory surfaces and (3) the series mass of the hydraulic impedance transformation due to the mutual action of adjacent vibratory surfaces.

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4. A device for radiating and receiving compressional wave energy within a predetermined band of low frequencies comprising a rigid frame, a plurality of equispaced transducers secured to said frame in a uniform pattern and covering an array area having a perimeter at least equal to one wavelength at the lowest frequency of said low frequency band, each of said transducers including a peripherally fixed vibratory diaphragm having an effective radiating area substantially less than said

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array area divided by the number of said diaphragms, the center to center spacing of said diaphragms being less than one half wavelength at the highest frequency of said low frequency band.

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