Design of Large Variable Resonant Frequency Transducers*

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The transducer design described in this paper employs a mercury column of variable length intimately coupled to an electrically driven piezoelectric element so that a composite vibrating system is formed whose resonant frequency is capable of continuous variation. A large radiating area is realized by combining a number of such composite elements in the form of a matrix. This matrix arrangement is attached to a container which supports the mercury column. One dimension of this column is varied by means of a mechanically driven piston. The entire assembly is enclosed in a steel tank with a sound rubber window to permit its use as an underwater sound transducer.

INTRODUCTION

SINCE the early experimental work of Fox and Rock[1] and Fry, Fry, and Hall,[2] variable resonant frequency transducers have reached a stage in development where such devices, having large radiating areas and high power handling capacities, have become practical acoustic instruments possessing a flexibility in applications not characteristic of fixed resonant frequency transducers. In a previous paper by Welkowitz and Fry[3] results of detailed numerical calculations, based on the usual one-dimensional theory of piezoelectric crystal systems, are presented in graphical form for a variety of variable resonant frequency crystal systems radiating into water. A brief comparison of the theory with experimental results is also given in this previous paper.

In the present paper the design considerations for a large continuously variable resonant frequency transducer, capable of radiating a considerable amount of acoustic power into a water medium, are presented. The transducer is composed of a mercury column of variable length which is intimately coupled to an electrically driven piezoelectric element so that a composite vibrating system is formed whose resonant frequency can be continuously varied by changing the length of the mercury column. The transducer can be operated on the second harmonic over a wide frequency range with only a small variation in the pressure amplitude at a fixed point on the axis of the beam. This paper is concerned with a transducer which has been designed, constructed, and tested. The device performed according to design. Although the piezoelectric element used in the construction of the specific transducer discussed in this paper is cut from the synthetically grown ammonium dihydrogen phosphate (ADP) crystal, it is also possible to apply the same design and construction techniques to a system using

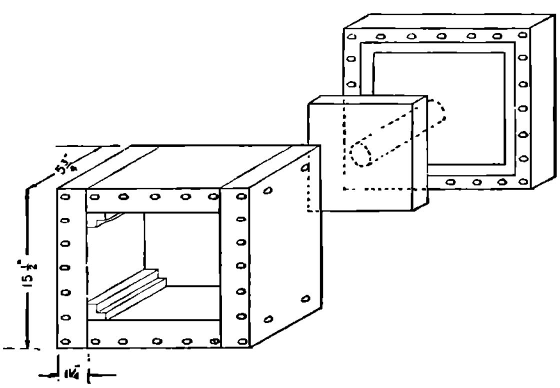

FIG. 1. Exploded view of chamber which supports the mercury.

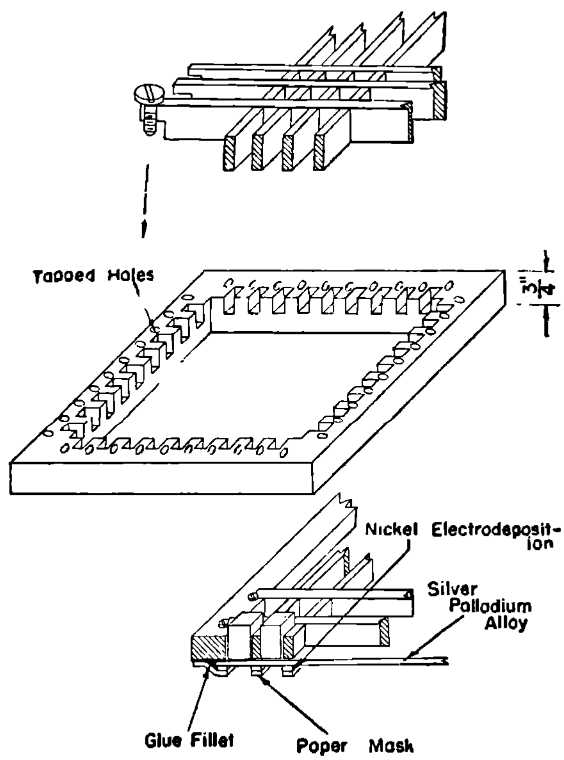

FIG. 2. Construction of the matrix for supporting the electromechanical vibrating elements.

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[1] F. E. Fox and G. D. Rock, Proc. Inst. Radio Engrs. 30, 29 (1942).
[2] Fry, Fry, and Hall, J. Acoust. Soc. Am. 23, 94 (1951).
[3] W. Welkowitz and W. J. Fry, J. Acoust. Soc. Am. 26, 159 (1954).

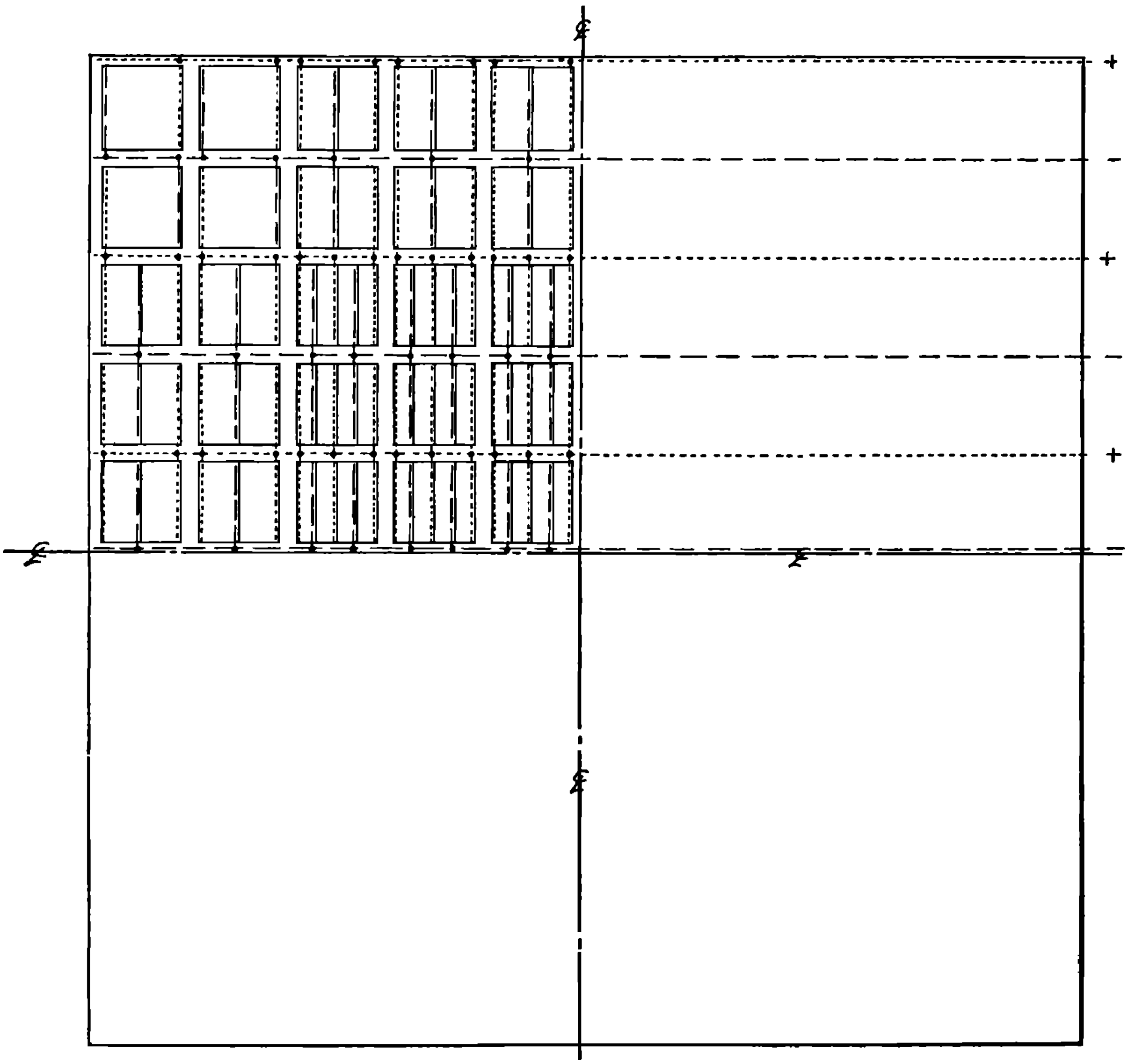

FIG. 3. Arrangement of the electromechanical elements in the matrix.

any electromechanical vibrating element. This includes magnetrostrictive materials as well as ceramics such as barium titanate.

Variable resonant frequency transducers have been realized without a great increase in size over that of fixed resonant frequency transducers of the same radiating area. For a transducer with a plane radiating area, the principal dimensional increase occurs in the direction normal to the radiating surface. This increase in size is a consequence of the method employed to vary the dimensions of the composite resonating system.

Detailed discussion of the principles upon which the construction techniques are based appears in several papers in the literature.[2,4]

[4] W. L. Hall and W. J. Fry, Rev. Sci. Instr. 22, 155 (1951).

DESIGN CONSIDERATIONS

The type of variable resonant frequency system considered consists of: a chamber for housing a mercury column which is continuously variable in one dimension, a drive mechanism for moving the piston which determines the length of the mercury column, an array of electromechanical elements intimately coupled to the mercury column, an over-all housing enabling the system to radiate into a liquid medium such as water, a means for supporting the transducer, and a means for supplying an external driving voltage.

For this transducer, the mercury chamber is square in cross section as shown in Fig. 1. The side walls consist of four pieces of cold rolled steel, ground on all surfaces. These steel sides are painted with an adhesive such as Hysol 6020† in the areas where they will come in contact when bolted and doweled together. The adhesive is applied immediately before the sides are bolted together so that liquid tightness is assured. Using this method of construction, it is possible to realize a chamber with a tolerance of 0.001 inch. Accurately ground cast iron runners are placed in the four corners as supports for the steel piston. A steel plate with a gasket groove serves as a back cover as well as a guide for the piston drive shaft. The piston face is surface ground so that the movable surface of the mercury column is accurately plane. This surface is moved so that it remains parallel to the plane of the crystal array which is bolted to the front face of the square cylinder. To provide acoustic decoupling of the mercury column from the supporting chamber, a pressure release material ($\frac{1}{4}$ inch thick balsa wood in this case) is applied to the walls of the cylinder and to the face of the piston. The balsa wood layer, which is fastened to the face of the piston, is carefully selected for uniformity of thickness and is glued to the steel with a surface ground plate resting on the wood during the setting process.

The surface ground steel matrix, which supports the ADP crystal elements, is bolted to the front face of the mercury chamber, Fig. 1. The crystal elements are glued to a sheet of silver palladium alloy‡ which is supported by the matrix. This alloy is used to provide

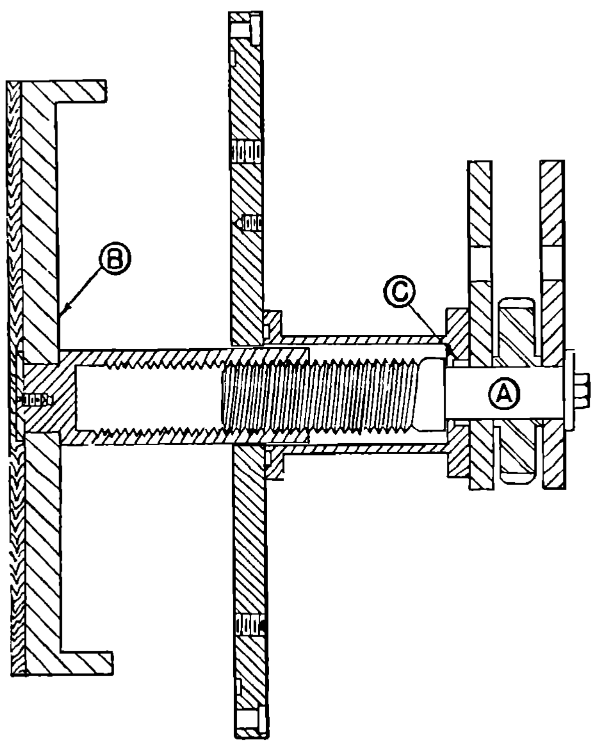

FIG. 4. Essential features of the mechanism for moving the piston.

† Houghton Laboratories, Olean, New York.
‡ 60 percent Ag and 40 percent Pd. This material was fabricated by the American Platinum Works, Newark, New Jersey.

the necessary intimate coupling between the piezoelectric elements and the mercury column. The intimate coupling is obtained by amalgamating the alloy with mercury on the side opposite the glued crystals. The steel matrix is fabricated from a $\frac{3}{4}$ inch thick steel plate 15.5 inches square with its center portion removed, Fig. 2. The appropriate number of slits are made in the plate, in this case nine on each edge spaced $1\frac{3}{16}$ inches on center. The ends of the individual members of an interlaced array of flat ground steel strips are placed in these slits. The ends are held into the peripheral plate by the screw heads shown in Fig. 2. The flat steel stock of the array is $\frac{1}{16}$ inch wide by $\frac{3}{4}$ inch thick. The entire assembled unit is then surface ground on both sides for precision. A sheet of the silver palladium alloy $12\frac{1}{8}$ inches square and 0.010 inch thick is then spot welded to the back of the steel plate and matrix assembly as shown in Fig. 2. This sheet of alloy is specially rolled in order to insure a high degree of flatness. The spot welding is made as continuous as possible on the periphery of the alloy sheet. In the interlaced flat stock region there are a sufficient number of spot welds to produce an extremely well knit structure. There are approximately 2000 spot welds about 1 mm in diameter in the entire unit.

After completing the assembly discussed above, the alloy is thoroughly cleansed in preparation for electroplating a particular area. The area to be electroplated covers the entire alloy and peripheral steel plate on the side opposite the interlaced steel assembly except in the 100 regions 1 inch × 1 inch directly behind each area in which the 1 inch × 1 inch cross section crystal elements will be glued. A thin nickel layer is deposited leaving 100 regions, directly behind the crystal elements, which are amalgamated with mercury. The regions with the nickel coating will not amalgamate, neither does the mercury show any tendency to creep under the nickel layer. An adhesive fillet is provided between the edge of the alloy and the peripheral steel supporting plate as shown in Fig. 2. This fillet insures liquid tightness. A paper mask is then glued to the portion of the alloy sheet on which nickel has been electrodeposited. This paper mask acts as an acoustic decoupling material. The total thickness of the nickel, glue and paper layer is approximately 0.0015 inch. The adhesive used for these glueing operations is Hysol 6020 which is allowed to set at room temperature.

The ADP crystal elements of various plies (for beam shaping[5]) are then glued into the matrix with Hysol 6020 as shown in Fig. 3. During the adhesive setting period, the crystal elements are held in place laterally by balsa wood strips. These strips are removed later. While positioning the crystal element, the adhesive layer is closely observed and worked so that no visible bubbles remain in the adhesive between the crystal and the alloy sheet.

[5] W. Welkowitz, J. Acoust. Soc. Am. 25, 336 (1953).

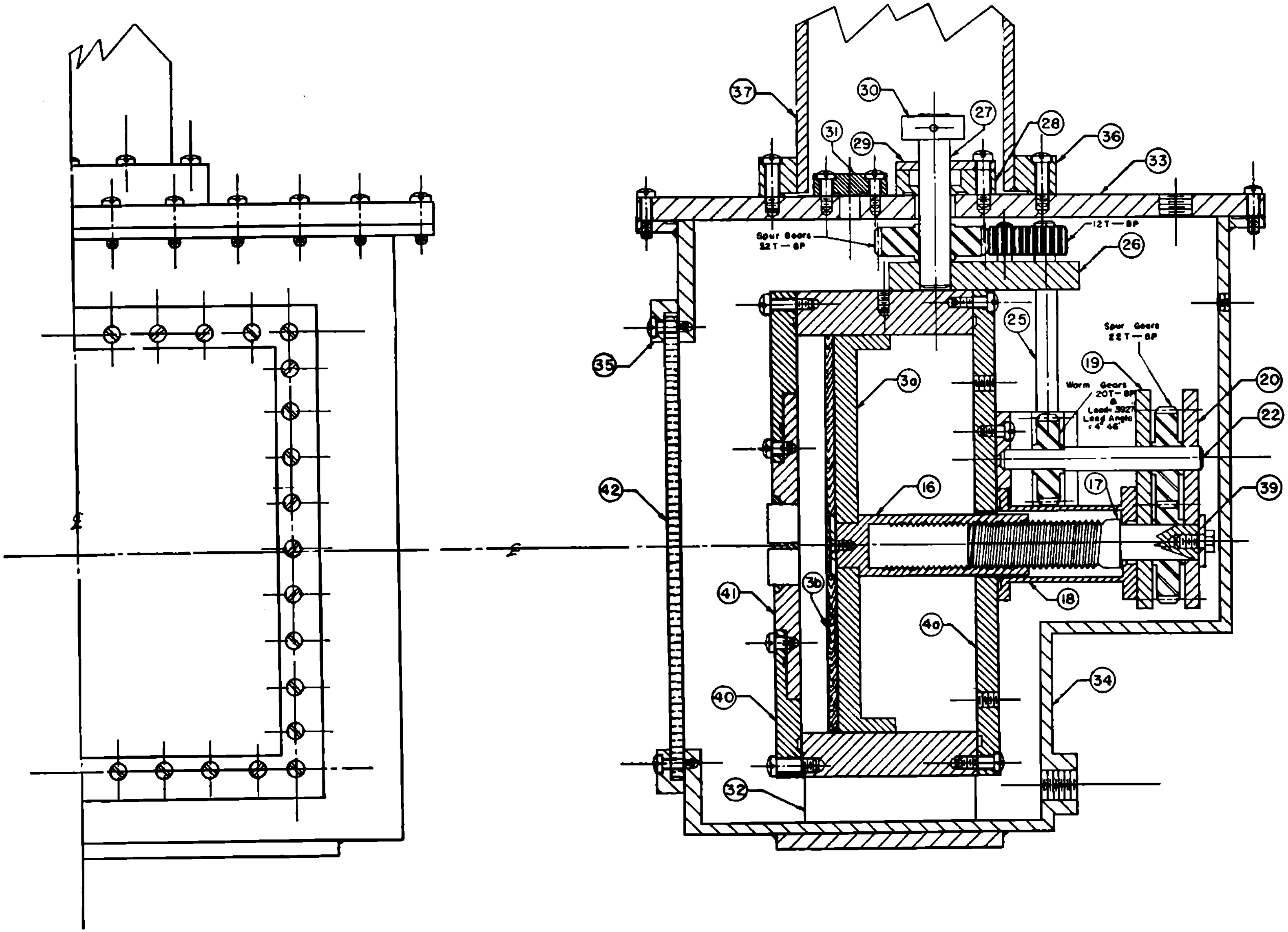

FIG. 5. Assembly drawing of the continuously variable resonant frequency transducer.

The crystal elements§ are provided with gold electrodes and tabs to which silver wires are soldered and connected as shown in Fig. 3. Sheets of Hycar ebonite‖ are placed in the $\frac{1}{16}$ inch wide slots between the crystals and the steel matrix and also in the region between the crystals above the steel matrix. This material serves to acoustically decouple the crystals from the steel matrix and from each other.

When the electrical connections are completed, the alloy surface directly behind the crystal elements is amalgamated with mercury. The amalgamation process is accelerated by the use of a very small quantity of hydrochloric acid, which is wiped on the alloy and then wiped off, and by a slight scraping action of a knife blade moved over the surface. A well amalgamated surface is one such that when a small drop of clean mercury is applied to a small region of the surface, there is an immediate covering of the entire amalgamated area with a bright and reflecting mercury film.

In the completed transducer, the materials which come in contact with the mercury are cold rolled steel, stainless steel, cast iron, balsa wood, Hysol 6020, nickel, the paper mask, the silver palladium alloy, the Neoprene gasket material on the front and back plates and in the piston drive mechanism, and the plastic tubing which connects the interior of the mercury chamber with valves in the external housing (enabling the mercury to be placed in the system after the transducer assembly is completed). Materials such as zinc and aluminum must be avoided because they contaminate the mercury.

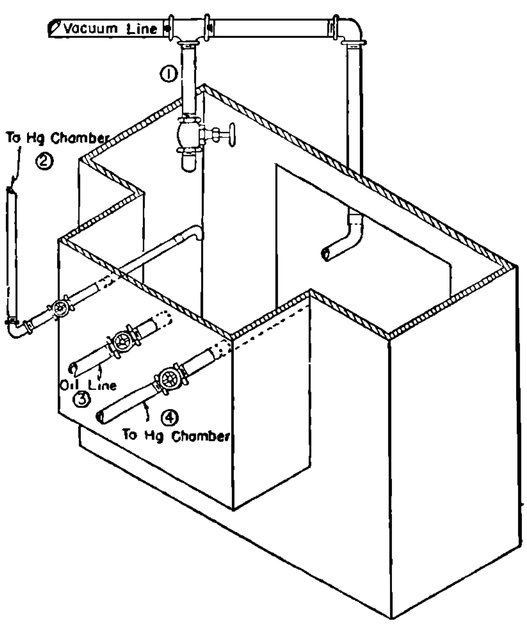

Fig. 6. Arrangement for filling the transducer with castor oil under vacuum conditions.

§ Brush Electronics Company, Cleveland, Ohio.
‖ The Sponge Rubber Products Company, Shelton, Connecticut.

The piston drive shaft which extends through the back of the mercury housing is driven externally by a mechanism which may take many forms. For the specific transducer described here, a relatively slow speed drive is provided which has a total stroke of approximately 4 inches. Figure 4 shows the essential features of this drive mechanism and seal in the mercury chamber. This mechanism is a rotary type, the threaded rotating member *A* screwing into tapped member *B* which is attached to the piston. Seal *C* is a Neoprene member encircling the rotating member *A*. A bellows type seal could be readily incorporated into the design in place of the rotary seal, thus eliminating any possible mercury leakage. By means of appropriate gears and shafts the piston is driven from outside the transducer housing.

The over-all transducer housing encloses the mercury chamber, the crystal array and the drive mechanism. This housing can, of course, take many forms. For this transducer the arrangement is illustrated in Fig. 5 which shows the mercury chamber mounted in a welded steel envelope which is completely filled with degassed castor oil. The sound is transmitted through castor oil to a sound rubber window, $\frac{3}{8}$ inch thick, placed in front of the crystal array. Approximately 15 gallons of castor oil are required to fill the transducer. The piston is externally driven by means of a shaft running through a Neoprene seal. A rubber seal to conduct the necessary electrical leads into the housing is also provided.

The transducer is supported beneath the water for test purposes by a 6 inch IPS steel pipe which is bolted to the transducer lid. This pipe provides passage for the turning rod used to change the piston location and for the electrical leads. The total weight of the transducer is approximately 700 pounds.

In order to fill the transducer with degassed castor oil under optimum conditions, arrangements are incorporated for evacuating the complete transducer so that the oil can be pumped in under vacuum conditions. A steel plate is bolted to the outside of the transducer over the sound rubber window. Vacuum lines then lead to this steel plate, to the transducer housing, and to the mercury chamber which is empty during oil filling. With this technique the hydrostatic pressures on both sides of the sound rubber window are approximately equal. The degassed castor oil is evacuated to the same pressure as the transducer and the oil flows under gravity into the transducer housing. After filling, the entire system is brought simultaneously to atmospheric pressure and the valves leading to the castor oil region are closed. The mercury is then introduced into the mercury chamber through valve 2 shown in Fig. 6. This valve is flexibly connected to the mercury chamber through the transducer housing. Valve 4, which is the air exhaust valve for the mercury chamber when the transducer is being filled with mercury, is similarly connected.

CONCLUSION

A large size continuously variable resonant frequency transducer has been designed and constructed. Such transducers are extremely useful when high acoustic power is desired over a wide frequency range. High intensity irradiation of biological systems over a continuous and wide frequency range and underwater object detection are two applications. For these applications, such a device replaces a number of fixed resonant frequency transducers.

The transducer which has been constructed consists of a plane array of piezoelectric elements (total radiating area one square foot) intimately coupled to a mercury column of variable length. The same principle and design could be used to realize variable resonant frequency transducers using magnetostrictive or ceramic electromechanical elements. The basic principle can be incorporated into many designs dependent on the type of transducer desired and the particular application. Ruggedness of construction and ability to withstand mechanical shock are comparable to that of fixed resonant frequency transducers.

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Survey of Flux-Responsive Magnetic Reproducing Heads*

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A magnetic reproducing head which generates a signal voltage substantially proportional to the magnitude of the intercepted magnetic flux is commonly referred to as a flux-responsive or magnetostatic head.

The fundamental mode of operation, the different approaches to practical solutions, and the characteristic features of this type of head are described. The explanations are illustrated by a number of cases which have been either proposed or practically executed by various organizations and investigators. References are given, including brief abstracts of pertinent patents and other publications.

EVER since the inception of magnetic recording there has been essentially only one method of signal reproduction in practical use. This method consists in moving the magnetic record relative to the reproducing head, thus causing the magnetic flux which leaves the record to induce corresponding signal voltages in the head windings.

Using the same type of magnetic head and the same type of electronic gear—sometimes even physically the same units—the reproducing process is, magnetically, the exact reversal of the recording process. This approach is, indeed, the simplest and most economical one and has, therefore, been almost universally adopted.

This paper will present a review of the exceptions to this rule and of their modes of operation.

A brief look at some fundamental aspects of the conventional playback process will be helpful. A part of the magnetic flux which leaves the surface of the recording medium enters the core structure of the reproducing head and interlinks with the winding on this structure. When there is relative and uniform motion between the head and the recording medium, the interlinking flux will change in accordance with the recorded signal, and an electromotive force proportional to the rate of this change will be induced in the head winding. This electromotive force is the conventional playback voltage.

Whenever the recorded signal shows only very little variation with time, or none at all, the corresponding rate of flux change in the head will result in an either unusuably low or altogether vanishing playback voltage. It is under such conditions that a reproducing head which responds to the magnitude of the signal flux, instead of its rate of change, becomes desirable if not imperative. The need for such flux-responsive, or magnetostatic, heads has been on a steady increase, especially in the fields of low-frequency measurements, industrial control, computers, and other magnetic memory devices.

In this connection it may be of interest to point to somewhat analogous conditions which exist with transducers in fields other than magnetic recording. The best example is probably that of phonograph pickups. There, the so-called velocity type, as represented by the electromagnetic or the electrodynamic systems, corresponds to the conventional magnetic reproducing head; the amplitude, or displacement pickup, represented by piezoelectric or capacitive systems, is the counterpart of the flux-responsive head. Very similar conditions can be found with velocity and displacement types of microphones and many other transducers. The case of optical sound reproduction, on the other hand, represents an amplitude-responsive system which has no velocity-type counterpart.

There is another characteristic feature of flux-responsive heads which must not be overlooked. It is the self-evident fact that the signal reproduced by a

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