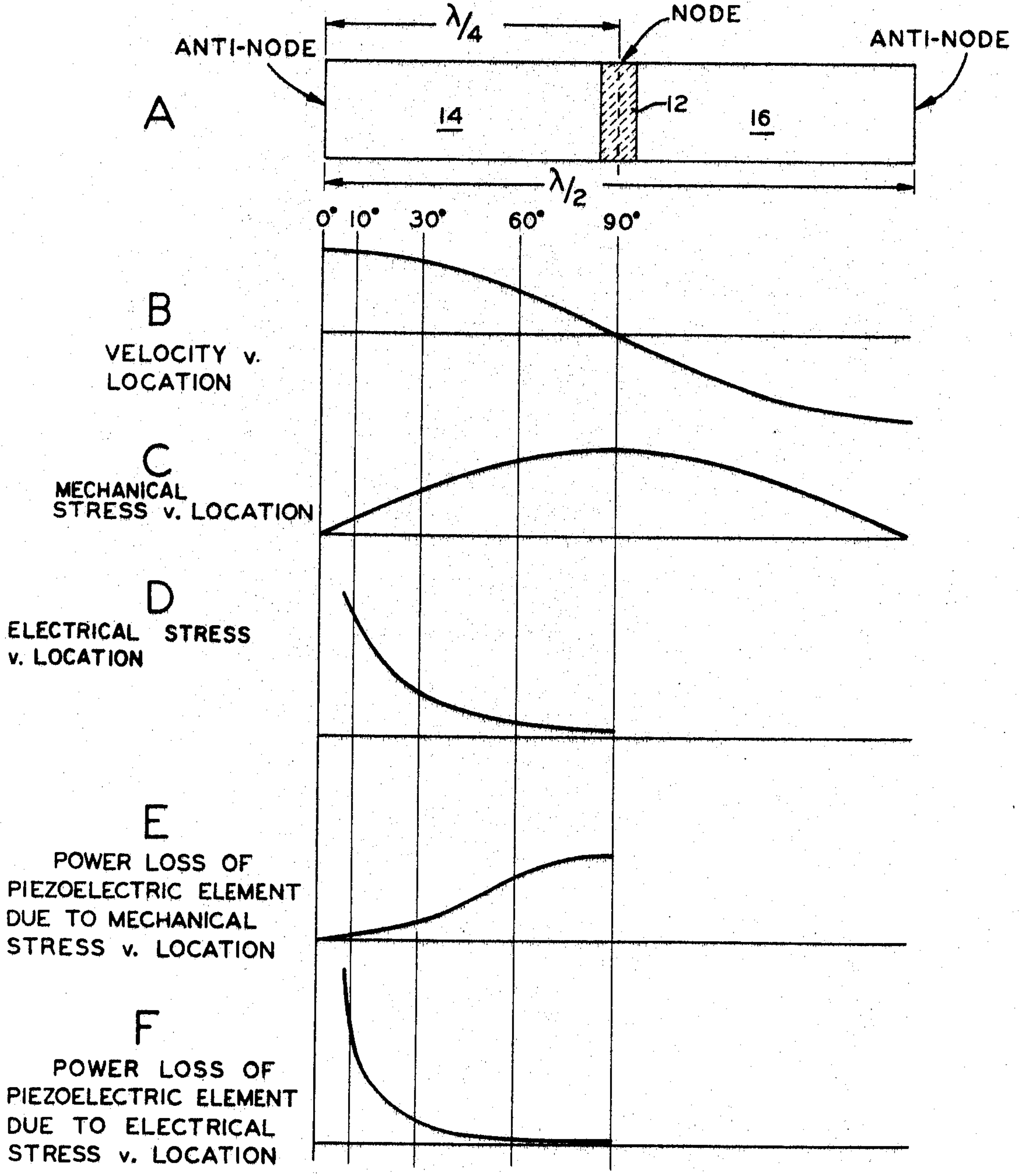
Aug. 11, 1970 A. SHOH **3,524,085**

SONIC TRANSDUCER

Filed May 9, 1968 3 Sheets-Sheet 1

FIG. 1



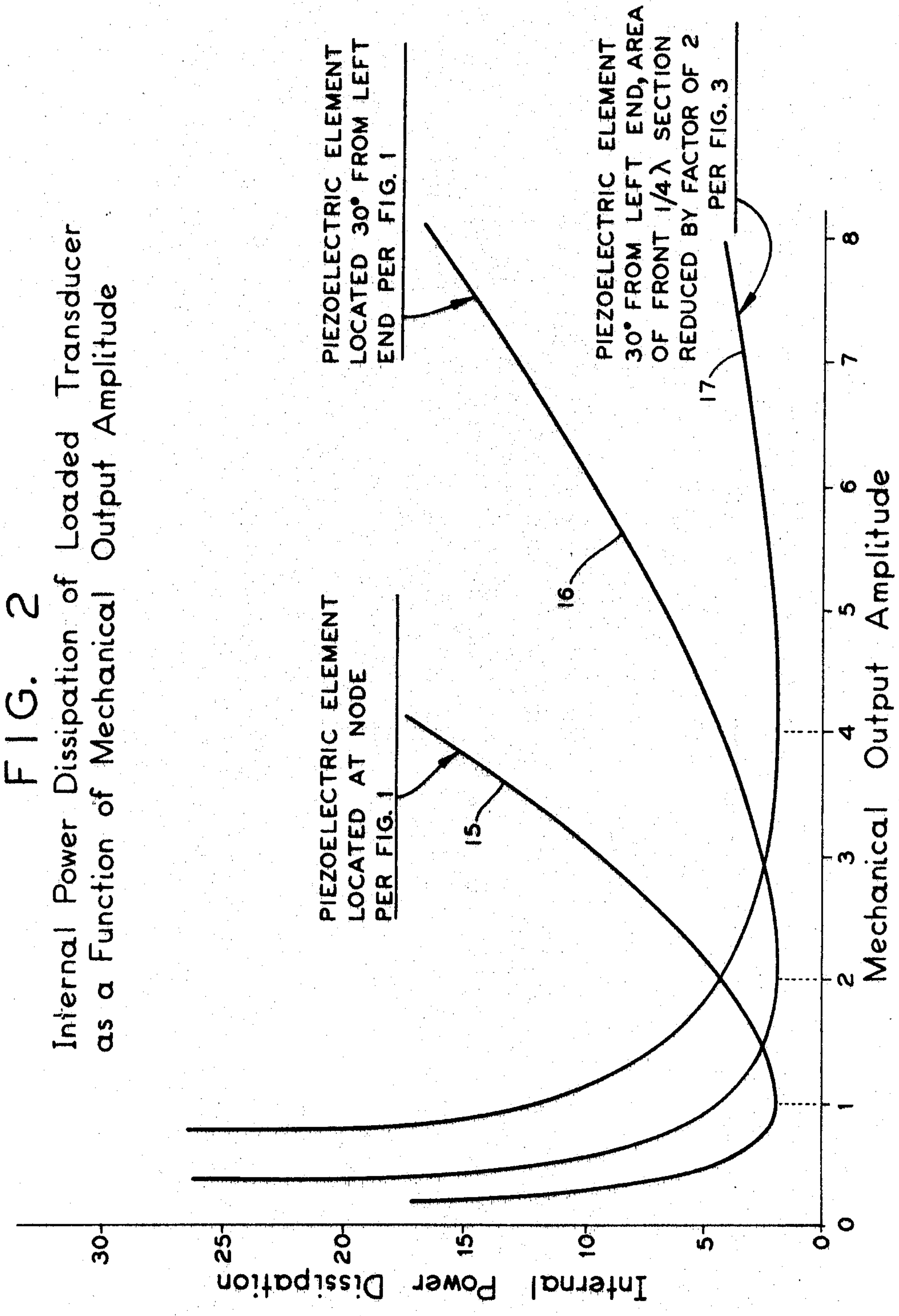
Andrew Shoh
INVENTOR.

BY:

Ervin B. Steinberg

FIG. 2

Internal Power Dissipation of Loaded Transducer as a Function of Mechanical Output Amplitude



Andrew Shoh
INVENTOR.

BY:

Ervin B. Steinberg

FIG. 3

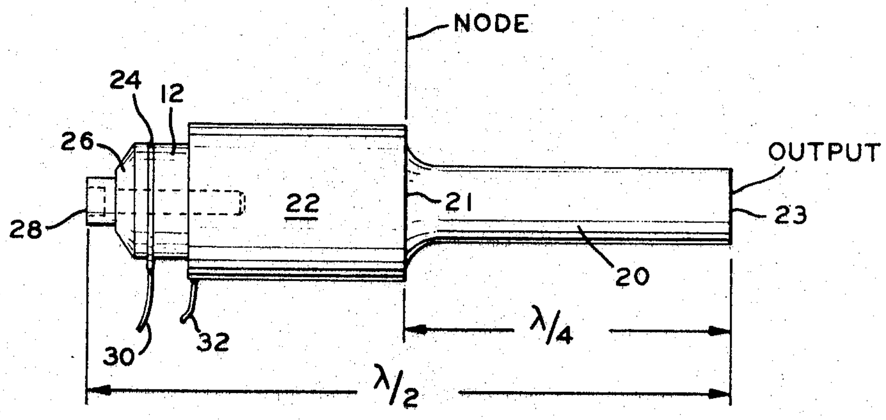
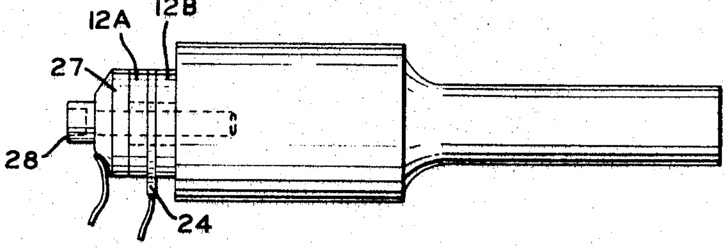


FIG. 4



Andrew Shoh
INVENTOR.

BY:

Erwin B. Steinberg

United States Patent Office

3,524,085

Patented Aug. 11, 1970

3,524,085

SONIC TRANSDUCER

Andrew Shoh, Ridgefield, Conn., assignor to Branson Instruments, Incorporated, Stamford, Conn., a corporation of Delaware

Filed May 9, 1968, Ser. No. 727,905
Int. Cl. H01v *7/00*
U.S. Cl. 310—8.2 6 Claims

ABSTRACT OF THE DISCLOSURE

An improved high performance electromechanical half-wave resonator of the clamped transducer sandwich construction is arranged in such a manner that when the transducer is operated at high motional amplitude the piezoelectric material is placed at a location where the power loss responsive to mechanical stress substantially equals that responsive to electrical stress.

This invention refers generally to a transducer for providing vibrational energy in the sonic or ultrasonic frequency range, and more particularly concerns the design of an electromechanical transducer for providing high intensity sonic vibrations in response to the application of electrical energy. Quite specifically, the invention concerns the design of an electromechanical transducer of the clamped transducer sandwich construction comprising a mass of metal and a piece of piezoelectric material coupled to the mass for causing the mass to resonate, the entire assembly being dimensioned to operate as a half-wave resonator at a sonic, preferably ultrasonic, frequency.

The design of electromechanical transducers for providing concentrated acoustic energy in the sonic or ultrasonic frequency range is well known in the prior art. Particular reference is made to U.S. Pat. No. 3,328,610 issued to Stanley E. Jacke et al., entitled "Sonic Wave Generator," dated June 27, 1967 and to U.S. Pat. No. 3,368,085 entitled "Sonic Transducer" issued to Robert C. McMaster et al., dated Feb. 6, 1968. In each of these patents, there is shown a mass of metal which is provided with a disk of piezoelectric material which, when energized with high frequency electrical energy, causes the mass to resonate as a half-wave resonator. A resonator of this type is characterized by a node and antinodes. At the node the mechanical displacement of the resonator in the longitudinal direction is substantially zero and at the antinodes the longitudinal displacement is a maximum. In the past it has generally been proposed that the piezoelectric material be placed at or near the node since in this region the velocity of longitudinal displacement is a minimum. In order to support the transducer at the node and to assure that the piezoelectric material is always maintained under a state of compression, the piezoelectric disk is generally slightly displaced from the node, but well within the region of low velocity, see FIG. 6 of U.S. Pat. No. 3,368,085 supra.

The maximum motional amplitude which can be obtained from such a transducer at its antinodes is limited essentially by the maximum stress to which the piezoelectric (ceramic) material can be subjected. As is apparent from the physical properties of materials normally used in transducer construction, the permissible stress for the ceramic material is always a great deal lower than the ultimate stress permissible in the adjoining metal, such as steel or aluminum and notably titanium. Hence, the motional amplitude available from a half-wave resonator of the type described could greatly be increased by providing a construction so that the ultimate stress in the metal rather than that in the piezoelectric material becomes the limiting factor.

It is apparent, therefore, that in order to provide a transducer which is characterized by high efficiency and high motional amplitude, and which provides for a better utilization of the piezoelectric material, the piezoelectric material advantageously should be placed away from the node of the electromechanical transducer construction. Quite specifically, it has been discovered that a transducer characterized by a high motional amplitude and improved performance is obtained when the piezoelectric material is placed between the node and the antinode at a location which, when operating at a substantially large motional amplitude, the power loss of the piezoelectric material resulting from the mechanical stress substantially equals that resulting from the electrical stress.

One of the principal objects of this invention, therefore, is the provision of a new and improved electromechanical transducer construction.

Another important object of this invention is the provision of an improved half-wave resonator comprising a mass of metal and a piezoelectric transducer means coupled to the mass for providing sonic energy in response to high frequency electrical energy applied to the transducer means.

Still another important object of this invention is the provision of an electromechanical half-wave resonator using a piezoelectric material which is placed at a location which appears to be optimum for obtaining highly efficient operation of the resonator.

A further object of this invention is the provision of an electromechanical transducer of the clamped sandwich construction using a piezoelectric disk for converting electrical energy to ultrasonic vibrations, the piezoelectric disk being placed at a location at which, when operating the transducer to produce a high motional amplitude, the electrical and mechanical losses of the piezoelectric material are substantially equal.

A still further and other object of this invention is the provision of a sonic transducer which is characterized by improved utilization of the piezoelectric material.

Further and still other objects of this invention will be more clearly apparent by reference to the following description when taken in conjunction with the accompanying drawings, in which:

FIGS. 1A through 1F depict a schematic representation of a typical half-wave sonic transducer per prior art and graphs pertaining thereto;

FIG. 2 is a graph of the internal power dissipation of a half-wave transducer as a function of mechanical output amplitude and as a function of the placement of the piezoelectric element which converts the electrical energy applied to mechanical motion;

FIG. 3 is a view of the improved transducer design in accordance with the teachings of this invention; and

FIG. 4 is a view similar to FIG. 3, but showing a modification.

Referring now to the figures and FIG. 1 in particular, FIG. 1A illustrates a composite piezoelectric transducer comprising a piezoelectric element **12** which is disposed between two one-quarter wave masses **14** and **16**, thereby providing the well known sandwich construction. Coupling between the masses **14** and **16** and the element **12** may be effected through an epoxy bond. Also, the use of a central bolt for maintaining the assembly under compression is well known. The rear mass **14** and the front mass **16**, as shown, are of the same dimension and material, such as steel, aluminum or titanium, and together with the piezoelectric disk form a half-wave resonator. For the purpose of the graphs per FIGS. 1B through 1F, the piezoelectric disk **12** is centered about the node of the resonator. This fairly standard representation of a composite piezoelectric transducer operating as a half-wave resonator, aside from the patent references identified above, is described and explained also in "Ultrasonic Engineering" (book) by Julian R. Frederick, John Wiley & Sons, Inc., New York (1965) Library of Congress Catalog No. 65–14257, pp. 67–74.

The basic weakness of the design shown in FIG. 1A resides in the fact that the piezoelectric (ceramic) material, which has the lowest mechanical stress limitation and the highest mechanical loss per unit stress, is placed at or near the node where the mechanical force is greatest. Consequently, the maximum motion amplitude of such a transducer is limited by the mechanical abuse and the resulting mechanical power loss which the piezoelectric material can take.

The usual center bolt (not shown) which serves the function of keeping the assembly under compression, and which because of its relatively small area is under a high stress, is also located at the area of highest force and, therefore, presents a limitation to the maximum transducer amplitude available.

It is apparent, therefore, that the vibration amplitude of the transducer is limited by the allowable mechanical force on the components in the nodal zone. The mechanical stress, and the power loss resulting from such stress, is amplitude or motion-dependent, and is not appreciably affected by the external mechanical loading of the transducer as long as the transducer amplitude remains unchanged. A direct relationship exists between the mechanical amplitude of the transducer and the real or "motional" component of the electric current supplied to the piezoelectric element.

The power input to the transducer is the product of the voltage across the piezoelectric element and the real component of the current through the piezoelectric element. Thus, for an unloaded transducer, when the power input must only be sufficient to supply the internal losses of the transducer, the voltage across the piezoelectric element is relatively low. As the external loading on the transducer increases, while constant amplitude operation is maintained, the voltage across the piezoelectric element increases and another component of internal transducer dissipation, the load-depedent power loss caused by the electrical stress on the piezoelectric material, becomes significant.

Assuming that the transducer per FIG. 1A resonates at a given or predetermined motional amplitude and is loaded externally such that the required power input to the piezoelectric element is a given predetermined value, and examining then the velocity, the mechanical and electrical stresses on the piezoelectric element as well as the respective power losses resulting from such stresses as a function of the location of the piezoelectric element between the node and the anti-nodes of the transducer, the following curves can be derived:

FIG. 1B depicts the velocity (m./sec.) versus location for the half-wave resonator. The velocity is zero at the node and is a maximum at the anti-node, i.e. the end.

FIG. 1C depicts the mechanical stress applied to the piezoelectric element **12** as a function of location. Since stress (newtons/m.^{2}) equals force per area and inasmuch as the area in the example considered (FIG. 1A) remains constant, the stress is directly related to the force acting on the element **12**.

FIG. 1D shows the electrical stress across the piezoelectric element versus location. For constant thickness of the element **12** the electrical stress in volts/meter is directly related to the voltage appearing across the element.

FIG. 1E shows the power loss (watts/m.^{3}) of the piezoelectric element due to mechanical stress versus location and this loss, to the first approximation, is proportional to the square of the mechanical stress, FIG. 1C.

FIG. 1F depicts the power loss (watts/m.^{3}) of the piezoelectric element **12** due to electrical stress versus location and this loss, to the first approximation, is proportional to the square of the electrical stress, FIG. 1D.

The numerical values of the two piezoelectric loss components depend, of course, on the mechanical transducer amplitude and the degree of loading (power output) selected, as well as on the dimension of the piezoelectric element. However, for a given transducer per FIG. 1A, operated at its predetermined maximum allowable amplitude, the ratio will typically be as shown in FIGS. 1E and 1F, indicating that the piezoelectric element when located at the node is subjected to a much greater mechanical stress than to an electrical stress.

A far more efficient operation at high motional amplitude can be achieved if the piezoelectric element **12** is moved away from the node and, conversely, a still higher motional amplitude can be achieved for the same allowable total power dissipation. This will be clearly apparent by reference to FIG. 2 which shows the internal power dissipation of the piezoelectric element (combined electrical and mechanical heat loss) of the loaded electroacoustic transducer as a function of mechanical output amplitude. The abscissa and ordinate are labeled in arbitrary units, but provide an indication of relative magnitude.

Curve **15** depicts the internal power dissipation of the piezoelectric element as a function of mechanical output amplitude when the piezoelectric element is located at the node as shown in FIG. 1. As is evident, the internal power dissipation decreases to a minimum at a motional amplitude value of "1" and then rapidly rises as the mechanical amplitude of the transducer increases to a higher value. As stated heretofore, the rapid increase in power dissipation in the piezoelectric element limits the motional amplitude which can be obtained from the transducer. Curve **16** shows an improved arrangement wherein the piezoelectric element has been moved to a location between the node and the antinode, see FIG. 1, specifically at a point where the power dissipation responsive to mechanical stress substantially equals the dissipation due to electrical stress, such location being in vicinity of thirty degrees, considering the antinode to be located at 0 degree and the node at 90 degrees. As seen from FIGS. 1E and 1F at this location the mechanical and electrical power loss curves are substantially of the same amplitude. The minimum value of internal power dissipation occurs at an amplitude value of "2," showing that the output amplitude of the transducer has been improved by a factor of two for the same internal dissipation. Curve **17** shows a still further improvement wherein the output end of the transducer has been reduced in diameter, such as is shown in FIG. 3, obtaining mechanical amplification of the motion while maintaining the piezoelectric element in the vicinity of 30°. As is apparent the power dissipation is a minimum at the mechanical amplitude value of "4." If the original transducer design per FIG. 1 were operated at this motional amplitude, it will be seen by reference to curve **15**, the power dissipation of the ceramic material would increase approximately by a factor of eight. Hence, the improved arrangement provides a transducer which is capable of being operated at high motional amplitude while having a comparatively low power dissipation and, therefore, operating under conditions of very high efficiency.

The novel transducer design as calculated per curve **17** in FIG. 2 is illustrated in FIG. 3. The piezoelectric element **12** has been placed at the location where, when operating the transducer under normal conditions, i.e. at or near its rated load capacity and large motional amplitude, the power loss caused by the mechanical stress applied to the piezoelectric element is substantially equal to the power losses resulting from the electrical stress, the location being in the proximity to 30 degrees. The front or output portion **20** of the resonator has been reduced in cross-sectional area so as to decrease the force at the node for a given output amplitude. Removing the piezoelectric element assembly from the node permits the reduction of the cross-sectional area to be made precisely at the node **21** where the effect upon the output amplitude apparent at the frontal surface **23** is most effective. Additionally, this construction allows shaping of the front section directly from the node into a variety of cross-sectional shapes, as required by the desired application.

The rear section **22** of the transducer has been increased in diameter over the diameter of the piezoelectric element to cause a mechanical impedance match between the metal and the piezoelectric element, typically lead zirconate titanate. The piezoelectric element, in most instances, has a higher density than the metal portions **22** and **20**, the latter being most commonly steel, aluminum or titanium.

The piezoelectric element **12** is backed by a thin metallic annular electrode disk **24** and an insulator block **26**, for instance beryllium oxide. The assembly is held under compression by a central bolt **28** threaded into the transducer portion **22**. Conductor leads **30** and **32** apply the electrical excitation across the planar surfaces of the piezoelectric disk **12**.

FIG. 4 shows a slight variation of the construction per FIG. 3. In order to avoid the need for an electrical insulator, two piezoelectric disks **12A** and **12B** are used with a central metallic electrode disk **24** disposed therebetween. The back piece **27** can be electrically conductive material (metal) and is on the same electrical potential as the front transducer portion.

In typical examples, a transducer design per FIG. 4, dimensioned for a frequency of 20 kHz. exhibited an internal heat loss of about 6 watts and could be loaded to power levels in excess of 200 watts providing a motional amplitude of 0.0006 inch, thereby indicating an electro-acoustic efficiency of 97 percent. The metal material used was aluminum, the rear portion **22** being two inch diameter by 1½ inches long, the front portion **20** being 1⅛ inches in diameter by 2½ inches long. A similar transducer made of titanium delivered an output amplitude up to 0.0025 inch, operated with an internal dissipation of about 30 watts and was capable of being loaded in excess of 700 watts, the efficiency being over 95 percent.

It is apparent, therefore, that the above described transducer construction is characterized by high efficiency and constitutes a significant advance in the art. When using the construction disclosed heretofore the losses in the piezoelectric element no longer constitute the limiting factor in obtaining high motional amplitude, but the limiting factor has been moved to the metal which has higher stress limits. In practice, it has been found that, using the construction shown in FIGS. 3 and 4, metal rupture caused by excess stress and fatigue becomes the limiting factor rather than the stress in the ceramic material as experienced previously.

While there has been described and illustrated a preferred embodiment of the novel electro-acoustic transducer construction, it will be apparent to those skilled in the art that various changes and modifications can be made without deviating from the broad principle disclosed heretofore.

What is claimed is:

1. An electromechanical transducer assembly comprising:

a metallic bar;

a piezoelectric disk driving means including means for energizing said driving means with electrical energy;

means for mechanically coupling said driving means to said bar and causing a radial surface of said driving means to be in forced contact with a radial surface of said bar;

said bar, piezoelectric driving means and means for coupling being dimensioned to operate substantially as a half-wave resonator along the longitudinal axis of said bar when said piezoelectric driving means is energized with electrical energy of suitable frequency, and

said piezoelectric driving means being located outside the zone of maximum stress and at a location where the power loss of said piezoelectric means resulting from mechanical stress substantially equals the power loss resulting from electrical stress when said assembly is resonant as a half-wave resonator along its longitudinal axis and operating at a predetermined motional amplitude and power loading.

2. An electromechanical transducer assembly as set forth in claim **1**, said metallic bar including a one-quarter wave resonating output portion which is of reduced cross-sectional area.

3. An electromechanical transducer assembly as set forth in claim **1**, said piezoelectric driving means being of a smaller diameter than the bar surface to which said disk is coupled by said means for coupling.

4. An electromechanical transducer assembly as set forth in claim **1**, said means for coupling comprising a threaded bolt.

5. An electromechanical transducer assembly as set forth in claim **1**, said piezoelectric driving means being located substantially in the vicinity of 30 degrees assuming the node to be located at 90 degrees and the anti-node at zero degrees.

6. An electromechanical transducer assembly as set forth in claim **5**, said piezoelectric driving means comprising two stacked disks having a metallic electrode disposed therebetween for providing electrical connection to one side of each disk.

References Cited

UNITED STATES PATENTS

3,218,488	11/1965	Jacke	310—8.2
3,328,610	6/1967	Jacke et al.	310—8.3
3,368,085	2/1968	McMaster et al.	310—8.3
3,396,285	8/1968	Mincheniko	310—8.7

MILTON O. HIRSHFIELD, Primary Examiner

M. O. BUDD, Assistant Examiner