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Dec. 17, 1963 J. KRITZ 3,114,848

HIGH EFFICIENCY SONIC GENERATOR

Filed March 9, 1960

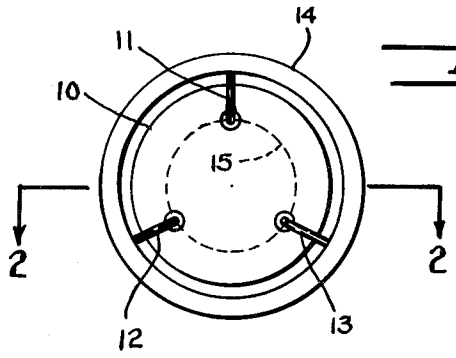


Fig. 1.

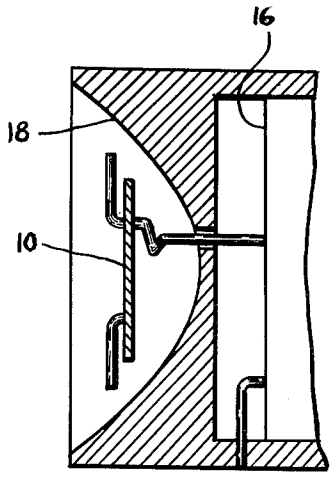


Fig. 3.

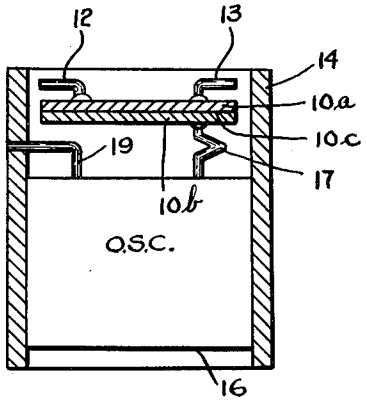


Fig. 2.

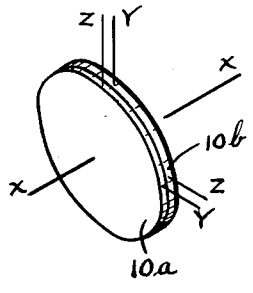


Fig. 4.

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HIGH EFFICIENCY SONIC GENERATOR

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22 Claims. (Cl. 310—9.1)

The present invention relates to sonic vibration transducers and has particular reference to sonic radiators and receivers operating in a narrow band of frequencies. This application is a continuation-in-part of U.S. patent application Serial No. 791,481 filed February 5, 1959.

Many devices have been developed for the conversion of electrical energy into sound vibrations. In every case, difficulty is experienced in producing these sound vibrations with efficiency. Reasonable efficiencies, as high as 90%, within a narrow band can be produced with quartz resonators when working into liquid and solid media. The problem becomes more difficult as the acoustic impedance, product of density and propagation velocity, of the medium is lowered. A severe problem arises when attempting to produce these vibrations into air or gas. Due to the low density of the gas compared to any vibrating solid medium, large deflections must be produced in order to deliver any significant amount of energy to the medium. These large deflections are usually accompanied by large restraining forces built up in the transducing solid or its support structure. In addition, where supersonic vibrations are desired the increase in frequency further aggravates the "lossiness" of the transducing structure, making it extremely difficult to realize efficiencies above 5% in the frequency domain above 20,000 c.p.s. This application describes means for generating sonic vibrations with high efficiency in air, although the invention is suitable for large power, low frequency transduction into air and into other media as well.

In establishing a mode of vibration for a solid transducer, it is necessary to maximize the ratio of energy delivered to air per cycle of vibration to the energy stored per cycle of vibration. In this way, a more favorable condition will exist for any given support structure. This statement can be expressed by stating that the air loaded Q is to be minimized. Here Q is defined as in all vibrating systems by:

$$Q=2\pi \frac{\text{Max. energy stored per cycle}}{\text{Energy dissipated per cycle}}$$

If the air loaded Q is made small enough, reasonably poor mounting structures can be tolerated. In addition, internal losses in the vibrating transducers can then be small compared to the energy delivered to the air.

The conventional thickness mode vibration, e.g.: x cut quartz plate, is a poor choice for this criteria. In order to produce moderate displacement of air, the crystal must expand and contract working against its modulus of elasticity, thus producing large values of stored energy for small displacements of air.

A mode of vibration of a flat plate which is far more favorable is a flexure mode. In causing a plate or a strip of material to flex or bend, large displacements can be obtained for smaller values of internal stored energy. The difficulty here, however, is that for given dimensions the resonant frequency is lower, and in an attempt to raise the frequency to the desired region, thick sections or small sizes must apparently be used. In the first case the flexibility advantage is lost, and in the second case the transducer tends to become too small to preserve plane wave propagation and the air loading is again reduced. However, an optimum configuration does exist where highly efficient transducers may be devised according to the present invention, as will be described.

In accordance with this invention, a thin disk is caused

to flex about a nodal circle at which it is supported, while the dimensions of the thickness and diameter, or radius, are chosen by determining the thickness to diameter ratio which gives optimum efficiency. This ratio is then used to determine the actual dimensions which produce the desired vibration frequency of the disk. The optimum ratio of thickness to diameter is determined, according to this invention, at the point where the operation of the disk changes from non-plane wave radiation to plane-wave radiation as the thickness to diameter ratio is increased. For quartz the optimum ratio has been found to be $\frac{1}{16}$.

It is an object of this invention to produce a sonic transducer employing a disk forced into flexure about a nodal circle.

It is another object of this invention to produce a sonic transducer employing a piezoelectric disk which includes a sandwich of crystalline quartz having particularly oriented axes for obtaining the flexural operation of the disk.

It is a further object of this invention to produce a high efficiency sonic transducer by selective choosing of the thickness to diameter ratio of the disk.

It is another object of this invention to produce a high efficiency piezoelectric sonic transducer using a quartz sandwich in which the thickness to diameter ratio is approximately $\frac{1}{16}$.

These and other objects will be made clear by reference to the following description and accompanying diagrams in which:

FIG. 1 is a plan view of the mounted transducer;

FIG. 2 is a sectional view through line 2—2 of FIG. 1;

FIG. 3 is a modification of FIG. 2; and

FIG. 4 shows a particularly desirable piezoelectric construction.

Before entering into a description of the figures, the concepts underlying the invention will be explained. Consider first the problems with air loading of the transducer.

Due to the very low specific acoustic impedance of the air medium, the development of significant power in this medium immediately implies a large value of generated volume velocity. The implication for the transducer then becomes large displacement and/or large area of the working surface. Unfortunately, both internal and mounting losses also rise significantly with these parameters. A convenient expression for these relationships is embodied in the dimensionless quantity "Q" defined earlier.

In developing a transducer configuration for high efficiency, it is therefore desirable to maximize the Q contributed by mounting and internal losses while simultaneously minimizing the air loaded Q.

An appreciation of the problem can be obtained by the examination of a conventional thickness mode vibrator made of low loss material such as quartz. The air loaded Q for a transducer loaded on both sides is given by:

$$Q=\frac{\pi}{4}\frac{Z\text{ quartz}}{Z\text{ air}}$$ where the Z's are the specific acoustic impedances (1)

The ratio of impedances for quartz and air is 3.67×10^4 thus giving an air loaded Q of 28,800. In addition to presenting an extremely narrow band-width, the maximum possible efficiency from such a device is basically limited. Were such a transducer fabricated of perfectly lossless material with lossless mounting, the high Q of nearly 30,000 would limit its utility considerably. With mounting losses, the efficiency drops drastically. A low loss mounting representing a Q of 5,000 would result in an efficiency of the order of 15%.

However, flexural distortion allows relatively large dis-

placement while minimizing the stored energy. For this reason the present invention utilizes a resonant flexure mode structure as the basis of the sonic air transducer.

An analysis of the behavior of a free edge disk vibrating in its first symmetrical mode, i.e., with only one nodal circle and no nodal diameters, and supported at its nodal circle is extremely complicated and will not be reproduced here. However, the results and some of the background will be helpful to a full understanding of the invention.

The air loaded Q of a flexural vibration free edge disk in general is given by the following expression:

$$Q=k\frac{Z_q}{Z_a}\left(\frac{h}{a}\right)^2 J \qquad (2)$$

where:

k is a constant
Z_q is the acoustic impedance of the transducer material
Z_a is the acoustic impedance of air
h is the thickness of the disk
a is the radius of the disk
J is a factor governing the extent of plane-wave loading dependent on diameter to wavelength ratio.

Examination of the expression above indicates that Q is a function of

$$\left(\frac{h}{a}\right)^2$$

and implies that Q can be decreased to a minimum by choosing an (h/a) ratio small enough. Unfortunately, the resonant frequency drops rapidly with increasing radius, causing the air loading factor J to significantly affect the expression above, to the extent that Q becomes dependent upon the reciprocal of

$$\left(\frac{h}{a}\right)^2$$

There is, therefore, a particular value of h/a which results in the optimum value of Q. Extensive analysis, coupled with justifiable approximations, has led to the following expression for defining the h/a ratio which gives a transducer having the lowest possible Q for the materials used:

$$\frac{h}{a}=\frac{5.4}{\beta\left(\frac{C_b}{C}\right)} \qquad (3)$$

where:

β is a value dependent on Poisson's ratio
C_b is the bulk propagation velocity in the transducer material
C is the propagation velocity in the medium.

β ranges from about 2.4 for Poisson's ratio of zero to about 3.1 for Poisson's ratio of one-half. β for quartz, which has a Poisson's ratio equal to 0.062, is equal to 2.435. The bulk propagation velocity for quartz is 6.04×10^5 cm./sec. while the propagation velocity in air is 3.44×10^4 cm./sec. Substitution of these values in the expression above leads to

$$\frac{h}{a}=.127$$

as the ratio for optimum efficiency of a quartz transducer, or a thickness to diameter ratio of one-half as much, i.e. 0.064 or approximately 1/16.

Poisson's ratio for most transducer materials is in the vicinity of 1/3, for which β is 2.78, and as a result the approximation $h/a=1.94\ c/c_b$ can be used for most materials. The more exact relationship is found by use of Equation 3 with the proper value of β.

With respect to the optimum value of h/a, it has been found that departure from the optimum value by more than 25% to either side of the optimum will result in operation of the transducer in a region where the analysis leading to the Equation 3 does not hold. If

$$\left(\frac{h}{a}\right)$$

is smaller by 25%, the transduction is in the plane wave region and, if

$$\left(\frac{h}{a}\right)$$

is greater by 25%, the transduction is in the non-plane wave region. The high efficiency operation occurs in the region between the well defined plane wave and non-plane regions of operation.

Having obtained the optimum h/a value for the transducer material, the actual dimensions of any transducer can be found from the equation

$$p=\frac{1}{a}\left(\beta\frac{h}{a}\right)C_R \qquad (4)$$

where:

p is the circular frequency $(=2\pi f)$ of the transducer
C_R is the rod propagation velocity of the transducer material

As an example, consider the calculations for a 20 kc. quartz transducer. In Equation 4 substitute the following values and solve for "a";

$$p=2\pi\times20\times10^3;\ \beta=2.435;\ h/a=.127;$$

$$C_R=6\times10^5 \text{ cm./sec.}$$

From this it will be found that "a"=1.49 cm. and h=.186 cm.

The value of the efficiency itself is not pertinent to the present invention and the equations for calculating the efficiency are not given, in order not to mask the essentials of the invention.

The free circular disk vibrating in the first symmetrical mode has a nodal circle which for quartz has a radius equal to 68.2% of the disk radius, and for other materials is not significantly different therefrom. The existence of the nodal circle provides a circular locus on the active transducer on which fastening devices may be attached to support the disk.

The principles of the invention are carried out in the apparatus shown in FIGS. 1, 2, 3 and 4.

Referring now to FIGS. 1 and 2, a typical embodiment of a sonic transducer using the present invention is illustrated. A disk **10** is supported by three supporting members **11, 12, 13** which extend between a frame **14** and the disk **10**. The supports **11, 12, 13** are equidistantly spaced on the surface of the disk **10** and are attached to the nodal circle **15** of the disk **10**, i.e. at points 68.2% from the center to the edge. The supporting members **11, 12, 13** are preferably proportioned so as to have a resonant frequency equal to that of the disk **10** whereby the effects of errors in the placement of supports on the disk **10** are minimized. One or all of the supporting members **11, 12, 13** are electrically connected to one terminal of an exciting oscillator power supply **16**, which may be conveniently located in the frame **14** behind disk **10**. The electrical connection may be made by means of the frame **14** to which the oscillator **16**, FIG. 2, is grounded by lead **19** and to which the leads **11, 12, 13** are attached. The other terminal of oscillator **16** is connected to the disk **10** through the connector **17**, which may also be mechanically resonant at the resonant frequency of the supports **11, 12, 13** and is attached to the opposite side of disk **10** on a nodal circle. FIG. 3 shows a reflector **18** behind the disk, but is otherwise similar to FIG. 2.

The disk **10** is preferably a piezoelectric transducer prepared by bonding a pair of circular x-cut crystalline quartz plates **10***a*, **10***b* with like polarity faces in contact as the junction plane **10***c*. The bonding may be by soldering, plastic resins, or other suitable media. The axes of the quartz plates **10***a*, **10***b* are preferably arranged as shown

in FIG. 4 with the X axes of each plate directed in opposite directions, the Y axis of one plate **10***a* located adjacent the Z axis of the other plate **10***b*, and the Z axis of the first plate **10***a* located adjacent the Y axis of the second plate **10***b*. This arrangement will provide the forces necessary to produce flexural vibration of the disk upon application of an electrical field between the faces of the disk. Although other axial arrangements will work, the arrangement described has been found to give the best results.

Other types of flexure transducer plates may be employed if desired, as for example, Y-cut quartz plates adapted for vibration in shear. Although at this time, quartz appears to be the preferred piezoelectric transducer material, the invention is not to be limited to the use thereof but any suitable piezoelectric material can be used, if desired. The desired mode of flexure vibration is the first symmetrical mode which, for the disk **10**, is that mode in which only one nodal circle is found on disk **10**. This symmetrical mode is obtained by forcing the disk into vibration at the proper frequency as, for example, by designing the oscillator **16** to include the disk **10** as the frequency-controlling element. The supports **11, 12, 13** being on the nodal circles, assist in insuring that the desired mode of vibration is obtained.

Now in carrying out the invention disclosed herein, the calculation of the transducer dimensions proceeds as outlined earlier. The actual frequency of the device designed according to this process may depart somewhat from that to be designed, due to the frequency shift caused by the air loading. However, this effect is quite small and can be neglected in most cases. In order to tailor the manufactured transducer to the exact operating condition required, the thickness and radius of the disk can be trimmed as desired.

It should be pointed out that the invention is not limited to the use of piezoelectric drives for the sonic transducer disks, although it appears to be most convenient at this time. It is contemplated that future developments might make other types of drives such, for example, as electromagnetic or electrostatic means, more attractive. The invention herein broadly is the use of a circular vibrating free edge disk supported at its nodal circle, having a thickness to radius ratio substantially equal to

$$5.4/\beta\left(\frac{c_b}{c}\right)$$

or approximations thereof.

I claim:

1. In a sonic transducer, a free-edge flexure mode thin circular plate, means for driving said plate in vibration in the first symmetrical mode, and means for supporting said plate at its nodal circle.

2. In a sonic transducer, a free-edge flexure mode thin circular plate including a sandwich made of two plates of quartz having the X axis in the thickness direction, with the Y axis of one plate aligned with the Z axis of the other plate bonded together, and means for supporting said plate at its nodal circle.

3. In a sonic transducer for producing sonic vibrations in an adjacent medium a free-edge flexure mode circular piezoelectric plate having a nodal circle, a support for said plate, said plate being suspended from said support by supporting members attached to said plate at the nodal circle, said supporting members consisting of low loss wires.

4. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular piezoelectric plate having a nodal circle, a support for said plate, said plate being suspended from said support by supporting members attached to said plate at the nodal circle and said members having a resonant frequency substantially the same as the resonant frequency of said plate.

5. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular piezoelectric plate having a nodal circle, a support for said plate, said plate being suspended from said support by supporting members attached to said plate at the nodal circle and having a resonant frequency substantially the same as the resonant frequency of said plate, the ratio of thickness of the plate to the radius of the plate being approximately

$$\frac{h}{a}=\frac{5.4}{\beta\left(\frac{C_b}{C}\right)}$$

wherein h is the thickness of said plate, a is the radius of said plate, β is a constant dependent on Poisson's ratio and having a value between 2.4 and about 3.1, C_b is the bulk propagation velocity in the material of said plate, and C is the propagation velocity in said adjacent medium.

6. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular piezoelectric plate having a nodal circle, a support for said plate, said plate being suspended at the nodal circle, the ratio of the thickness of the plate to the radius of the plate being approximately.

$$\frac{h}{a}=\frac{5.4}{\beta\left(\frac{C_b}{C}\right)}$$

wherein h is the thickness of said plate, a is the radius of said plate, β is a constant dependent on Poisson's ratio and having a value between 2.4 and about 3.1, C_b is the bulk propagation velocity in the material of said plate, and C is the propagation velocity in said adjacent medium.

7. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular piezoelectric plate having a nodal circle, a support for said plate being suspended at the nodal circle, the ratio of the thickness of the plate to the radius of the plate being approximately $h/a=1.94c/c_b$ wherein h is the thickness of said plate, a is the radius of said plate, c_b is the bulk propagation velocity in the material of said plate, and c is the propagation velocity in said adjacent medium.

8. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular piezoelectric plate having a nodal circle, a support for said plate, said plate being suspended from said support by supporting members attached to said plate at the nodal circle and having a resonant frequency substantially the same as the resonant frequency of said plate, the ratio of the thickness of the plate to the radius of the plate being approximately $h/a=1.94c/c_b$ wherein h is the thickness of said plate, a is the radius of said plate, c_b is the bulk propagation velocity in the material of said plate, and c is the propagation velocity in said adjacent medium.

9. In a sonic transducer for producing sonic vibrations in an adjacent medium a free-edge flexure mode circular piezoelectric plate having a nodal circle, a support for said plate, said plate being suspended from said support by supporting members attached to said plate at the nodal circle.

10. In a sonic transducer for producing sonic vibrations in an adjacent medium a free-edge flexure mode circular piezoelectric plate having a nodal circle, a support for said plate, said plate being suspended at the nodal circle, the ratio of the thickness of the plate to the radius of the plate not deviating by more than twenty-five percent from $h/a=1.94c/c_b$ wherein h is the thickness of said plate, a is the radius of said plate, c_b is the bulk propagation velocity in the material of said plate, and c is the propagation velocity in said adjacent medium.

11. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular

piezoelectric plate having a nodal circle, a support for said plate, said plate being suspended at the nodal circle, the ratio of the thickness of the plate to the radius of the plate not deviating by more than twenty-five percent from

$$\frac{h}{a}=\frac{5.4}{\beta\left(\frac{C_b}{C}\right)}$$

wherein h is the thickness of said plate, a is the radius of said plate, β is a constant dependent on Poisson's ratio and having a value between 2.4 and about 3.1, C_b is the bulk propagation velocity in the material of said plate, and C is the propagation velocity in said adjacent medium.

12. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular crystalline quartz plate having a nodal circle, a support for said plate, said plate being suspended at the nodal circle, the ratio of the thickness of the plate to the diameter of the plate being approximately one-sixteenth.

13. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular crystalline quartz plate having a nodal circle, a support for said plate, said plate being suspended at the nodal circle, the ratio of the thickness of the plate to the diameter of the plate being approximately within the range of one-tenth to one-twentieth.

14. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular plate having a nodal circle, a support for said plate, said plate being suspended from said support by supporting members attached to said plate at the nodal circle, said supporting members consisting of low loss wires.

15. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular plate having a nodal circle, a support for said plate, said plate being suspended from said support by supporting members attached to said plate at the nodal circle and said members having a resonant frequency substantially the same as the resonant frequency of said plate.

16. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular plate having a nodal circle, a support for said plate, said plate being suspended from said support by supporting members attached to said plate at the nodal circle and having a resonant frequency substantially the same as the resonant frequency of said plate, the ratio of the thickness of the plate to the radius of the plate being approximately

$$\frac{h}{a}=\frac{5.4}{\beta\left(\frac{C_b}{C}\right)}$$

wherein h is the thickness of said plate, a is the radius of said plate, β is a constant dependent on Poisson's ratio and having a value between 2.4 and about 3.1, C_b is the bulk propagation velocity in the material of said plate, and C is the propagation velocity in said adjacent medium.

17. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular plate having a nodal circle, a support for said plate, said plate being suspended at the nodal circle, the ratio of the thickness of the plate to the radius of the plate being approximately

$$\frac{h}{a}=\frac{5.4}{\beta\left(\frac{C_b}{C}\right)}$$

wherein h is the thickness of said plate, a is the radius of said plate, β is a constant dependent on Poisson's ratio

and having a value between 2.4 and about 3.1, C_b is the bulk propagation velocity in the material of said plate, and C is the propagation velocity in said adjacent medium.

18. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular plate having a nodal circle, a support for said plate, said plate being suspended at the nodal circle, the ratio of the thickness of the plate to the radius of the plate being approximately $h/a=1.94c/c_b$ wherein h is the thickness of said plate, a is the radius of said plate, c_b is the bulk propagation velocity in the material of said plate, and c is the propagation velocity in said adjacent medium.

19. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular plate having a nodal circle, a support for said plate, said plate being suspended from said support by supporting members attached to said plate at the nodal circle and having a resonant frequency substantially the same as the resonant frequency of said plate, the ratio of the thickness of the plate to the radius of the plate being approximately $h/a=1.94c/c_b$ wherein h is the thickness of said plate, a is the radius of said plate, c_b is the bulk propagation velocity in the material of said plate, and c is the propagation velocity in said adjacent medium.

20. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular plate having a nodal circle, a support for said plate, said plate being suspended from said support by supporting members attached to said plate at the nodal circle.

21. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular plate having a nodal circle, a support for said plate, said plate being suspended at the nodal circle, the ratio of the thickness of the plate to the radius of the plate not deviating by more than twenty-five percent from $h/a=1.94c/c_b$ wherein h is the thickness of said plate, a is the radius of said plate, c_b is the bulk propagation velocity in the material of said plate, and c is the propagation velocity in said adjacent medium.

22. In a sonic transducer for producing sonic vibrations in an adjacent medium, a free-edge flexure mode circular plate having a nodal circle, a support for said plate, said plate being suspended at the nodal circle, the ratio of the thickness of the plate to the radius of the plate not deviating by more than twenty-five percent from

$$\frac{h}{a}=\frac{5.4}{\beta\left(\frac{C_b}{C}\right)}$$

wherein h is the thickness of said plate, a is the radius of said plate, β is a constant dependent on Poisson's ratio and having a value between 2.4 and about 3.1, C_b is the bulk propagation velocity in the material of said plate, and C is the propagation velocity in said adjacent medium.

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