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**P. B. FLANDERS**

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## MECHANICAL IMPEDANCE DEVICE

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**FIG. 1.**

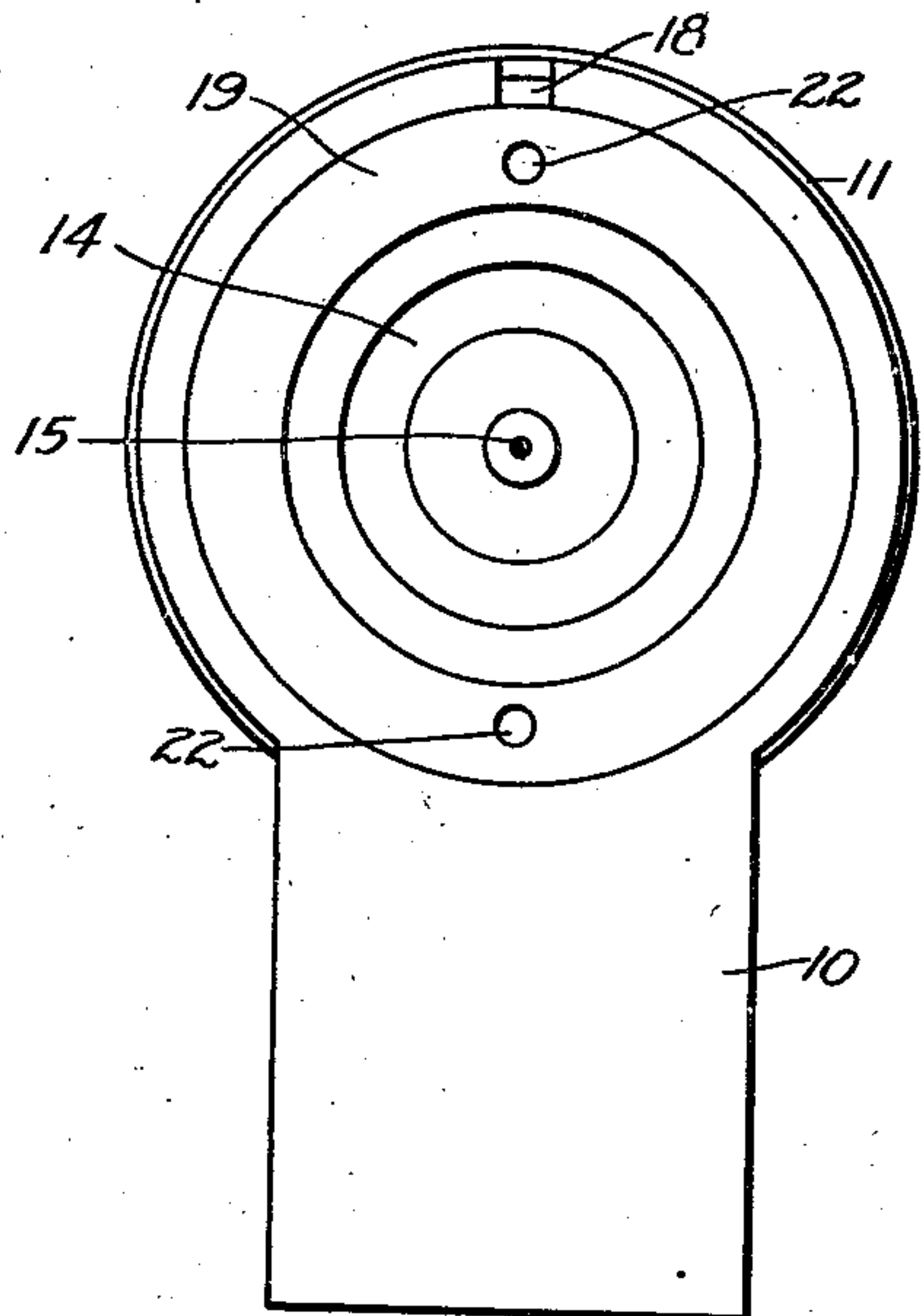
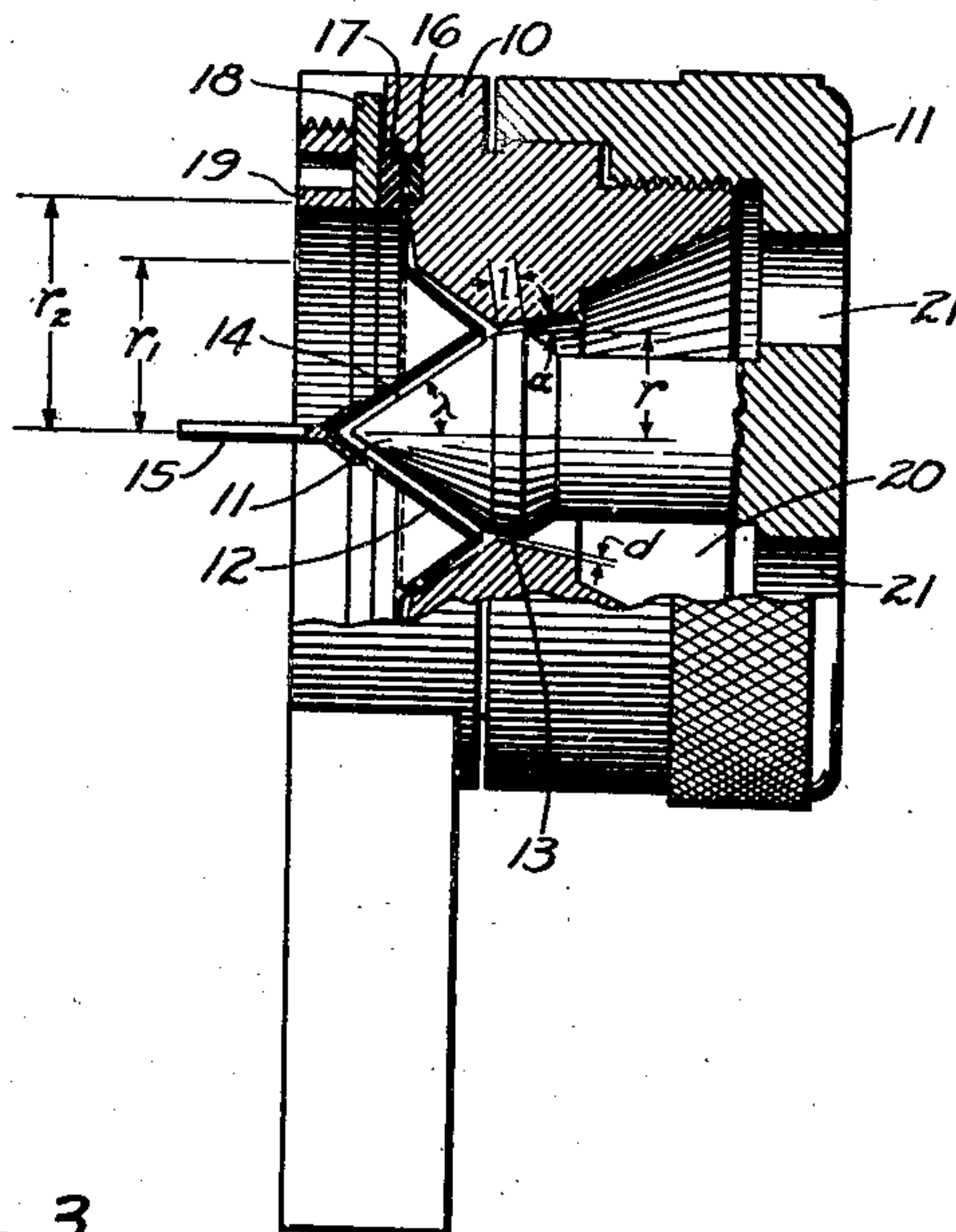
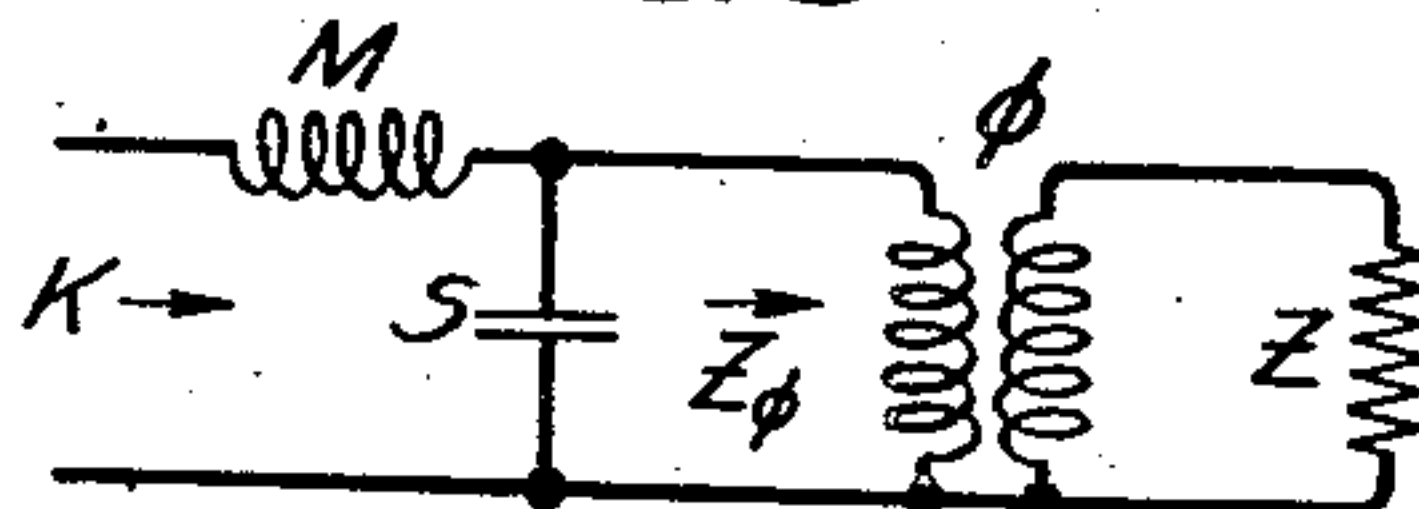


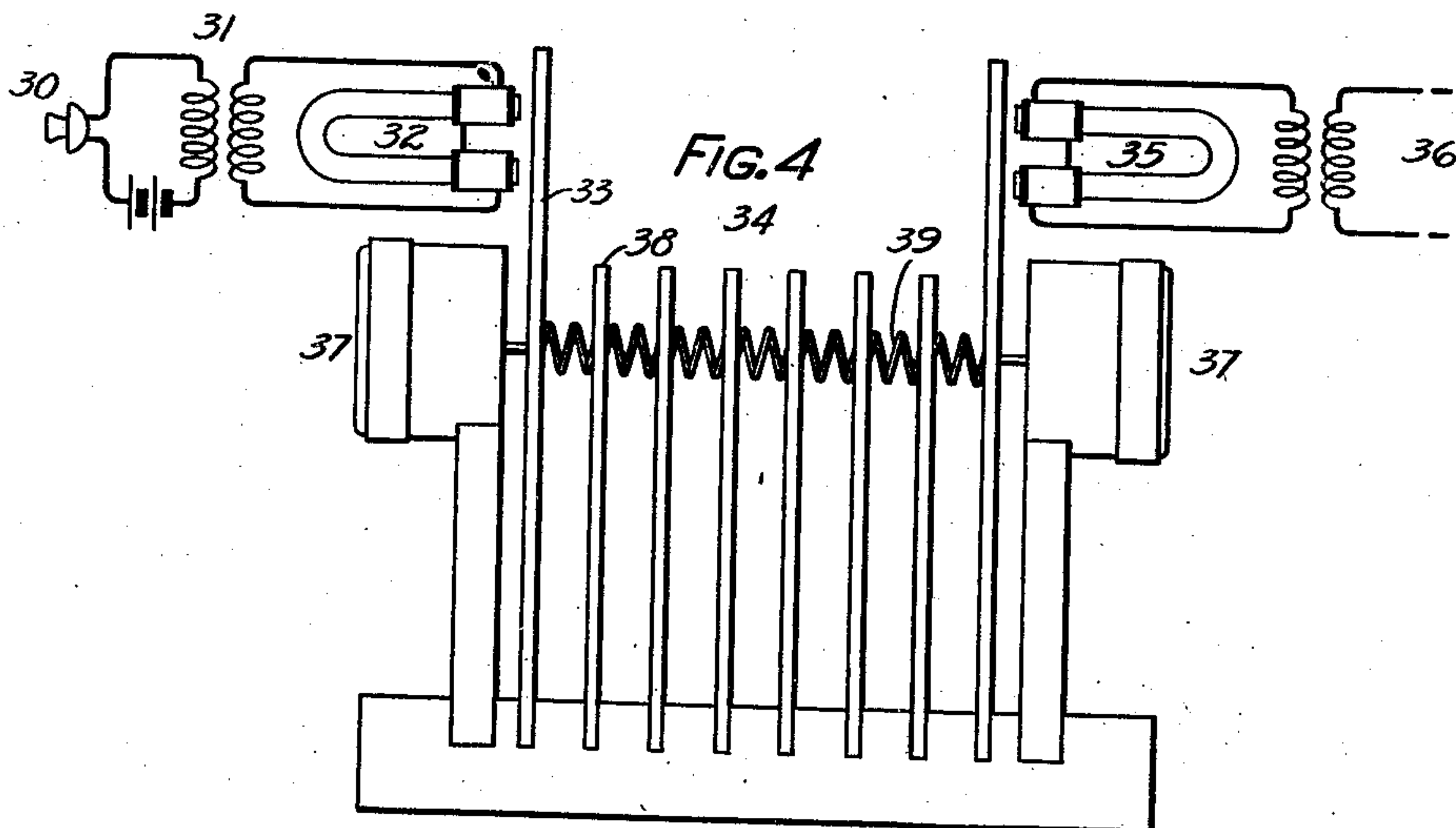
FIG. 2.



**FIG. 3**



**FIG. 4**



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## MECHANICAL IMPEDANCE DEVICE

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This invention relates to impedance devices and more particularly to mechanical devices adapted to oppose to vibratory forces an impedance which is substantially constant and resistive.

Mechanical wave transmission lines, such as filters and delay devices, have been designed for use in speech transmission systems, for example, as mechanical links between two parts of an electrical line. They may be incorporated into telephone systems by means of a mechanical-electrical translating device, such as a magnetic type of telephone receiver. In general, the mechanical impedance of a receiver is not the same as the characteristic impedance of a mechanical line, and hence wave reflections occur at the junction points. These reflections give rise to irregularities in speech transmission which it is desirable to avoid. The proper operation of such a combination requires that the mechanical line should receive wave energy from, and should deliver energy to, mechanical impedances equal to its characteristic impedance. This invention provides an adjustable mechanical impedance element which can be made to have an impedance equal to the characteristic impedance of a mechanical line, and so is well adapted for the termination of mechanical wave transmission systems. The device consists essentially of an air chamber closed at one end by a diaphragm and connected with the atmosphere at the other end through a narrow slot of air. The slot has the nature of a mechanical resistance, while the diaphragm and air chamber are essentially a mass and elastance, respectively. The linear dimensions of the slot and of the diaphragm, and the mass and elastance of the diaphragm and air chamber, are so proportioned with respect to each other and to a preassigned resistance that the device has an impedance substantially constant over a wide range of frequencies. A feature of the invention is that the width of the slot is adjustable so that it can be made to have any impedance within its range of adjustability.

The invention will be understood from the following detailed description and by refer-

ence to the accompanying drawing of which Figs. 1 and 2 illustrate the invention; Fig. 3 shows the equivalent electrical circuit of the device; and Fig. 4 illustrates an application of the invention in a mechanical vibratory system.

Fig. 1 shows a front view of the invention, and Fig. 2 is a side view in section showing the essential parts of the invention in its preferred form. The member, 10, is the base of the device on which the other parts are assembled. The member, 11, comprises a threaded flange for screwing on the base, 10, and has integral with it a shaft with a conical end concentric with an aperture in the part, 10, into which it extends. These parts may be made of any workable material such as steel. A diaphragm, 12, is held in place between two rings, 16 and 17, of a soft substance such as gum rubber which in turn are held in recesses in the base piece by a metallic washer, 18, and an end piece, 19, which is threaded to screw into the base piece and which may conveniently have a pair of holes, 22, for applying a tool to aid in screwing into place. The diaphragm, which may be made of any light rigid metal, such as duralumin, has a rod, 15, attached at its center for connecting with the mechanical wave transmission line. The diaphragm is so shaped that its surface closely conforms to those of the parts, 10 and 11, with which it is associated so that an air chamber, 14, is formed containing a layer of air of approximately uniform thickness and having the shape of the diaphragm. The air chamber is connected to the outer chamber, 20, through a very narrow annular slot, 13, with parallel walls between the inner surface of the aperture in the base piece, 10, and the conical surface of the member, 11. The width of the slot can be adjusted by screwing the flanged piece, 11, into or out of the base piece, 10. The outer chamber, 20, is in turn connected with the atmosphere by means of concentrically centered holes, 21, in the piece, 11.

The operation of the device can most readily be understood from a study of its electrical analogue, which is illustrated in Fig. 3. The diaphragm consists essentially of the



dimension of mass and is depicted as a series inductance,  $M$ . The air chamber, 14, consists of the element of stiffness and is shown as a shunt condenser,  $S$ . Due to the fact that the effective areas of the diaphragm and of the annular slot, 13, are different, there is an impedance transformation,

$$\Phi = \left( \frac{A_2}{A_1} \right)^2,$$

where  $A_2$  is the effective diaphragm area and  $A_1$  the transverse area of the slot. This is represented by the transformed,  $\Phi$ . The last element in the circuit is the impedance of the slot, 13, which due to the extremely small space between its walls, is a resistance almost free from reactance as will be shown later, and is designed  $Z$ .

Fig. 4 is an illustration of the use of the present invention as terminating elements for a mechanical line incorporated into a telephone system. A transmitter, 30, is shown connected through a transformer, 31, to a receiver, 32, the armature, 33, of which is rigidly fastened to the terminating element of a mechanical line, 34. At the other end of the line is connected another translating device, 35, similar to the receiver, 32, for the purpose of transforming the mechanical vibrations into electrical energy to send out on the electrical line, 36. Each end of the mechanical line, 34, is connected to a terminating resistance unit, 37, of the form of this invention. The receiver and resistance unit are effectively in series and since receivers of the type shown, in general, have impedances small in comparison with that of mechanical lines, the actual impedance terminating the line, 34, is approximately that of the terminating resistance unit; so no serious wave reflections occur, inasmuch as the terminating unit is made to have a resistance equal to the characteristic impedance of the mechanical line.

It remains to show how a terminating element embodying this invention can be designed in accordance with a given resistance value. The impedance of a parallel-sided slot, such as the slot, 13, is given by the equation,

$$Z = \left( \frac{12\mu}{d^3} + \frac{j6\omega\rho}{5} \right) bdl \quad (1)$$

in which,

$\mu$  is the coefficient of viscosity,

$\rho$  the air density,

$d$  the width of the slot between the walls,

$b$  the length of the slot transverse to the direction of flow, and

$l$  the length in the direction of flow.

The dimensions of  $Z$  when c. g. s. units are used, are

$$\frac{\text{dyne seconds}}{\text{centimeters}}$$

The impedance  $Z$  is the mechanical impedance, defined as the ratio of the total pressure force (pressure difference  $\times$  slot area) to the average linear velocity. The reactance component may be made relatively very small by decreasing the separation  $d$ . If it is desired that the reactance be less than 10% of the resistance at all frequencies up to an assigned limiting frequency,  $\omega_0 \div 2\pi$ , the separation should be at least as small as that given by

$$d = \sqrt{\frac{\mu}{\omega_0 \rho}} \quad (2)$$

If  $d$  be approximately .001" the impedance will be substantially free from reactance throughout the range of speech frequencies. The effect of viscosity in producing a sliding or shearing motion of the adjacent layers of air with respect to each other, is discussed in Appendix A of "Theory of Vibrating Systems and Sound" by Irving Crandall, published by D. Van Nostrand Co., Incorporated, in which it is pointed out that the shear velocity is propagated normally from the walls with a wave length,

$$\lambda = 2\pi \sqrt{\frac{2\mu}{\omega \rho}} \quad (3)$$

From this it follows that the separation defined by Equation (2) is approximately one-ninth of the shear velocity wave, or "diffusion wave", corresponding to the highest frequency to be considered. In calculating the effect of inserting a resistance device into any given sound conduit, it is necessary to take into account the transformer effect due to the difference between the cross-sectional areas of the air paths in the element and in the conduit. A more detailed discussion of impedance transformations involved when air chambers of different cross-sectional areas are joined, is given in a paper by H. C. Harrison and J. P. Maxfield entitled "Methods of high quality recording and reproducing of music and speech based on telephone research" in the American Institute of Electrical Engineers Journal, February, 1926, pages 334-348. In Fig. 2 the annular air slot, 13, is a resistance element substantially free from reactance because the width,  $d$ , between the walls is very narrow. Its length,  $l$ , is as shown in the figure. The length of the passage transverse to the direction of air flow,  $b$ , is approximately  $2\pi r$ , where  $r$  is the mean radius of the slot, and its area,  $A_1$ , transverse to the direction of flow is approximately  $2\pi r d$ . The diaphragm illustrated is the plunger type in which the central part out to the radius  $r$ , is rigid and the portion between the radii  $r_1$  and  $r_2$  is flexible. The radii  $r_1$  and  $r_2$  are shown in the figure. The



effective area for the present purpose of this type of diaphragm is given by the equation, and S are the mass and stiffness of a half section, the cut-off frequency  $f_c$ , is given by,

$$A_2 = \pi r_2^2 \frac{l + n + n^2}{3} \quad (4)$$

where

$$n = \frac{r_1}{r_2}$$

The impedance of the slot, 13, as seen from the air chamber, 14, is

$$Z_\Phi = \left( \frac{A_2}{A_1} \right)^2 Z, \quad (5)$$

and should be made equal to the characteristic impedance of the mechanical line. The mass of the diaphragm, M, and the stiffness of the air chamber, S, constitute a portion of low pass filter and consequently must be so proportioned with respect to  $Z_\Phi$  that the characteristic impedance is the same. Furthermore, there will be a cut-off frequency above which attenuation occurs, and which must be so located, that the desired band of frequencies is transmitted. In Fig. 4 the mechanical line consists of masses, 38, effectively in series and springs or elastances, 39, effectively in shunt, and hence is a low pass filter. The mass, M, and stiffness, S, of the terminal device should preferably be proportioned to effectively constitute part of the filter. Then the terminating mass of the filter with the diaphragm mass, M, together constitute a full section mass. Likewise, the stiffness, S, should preferably be twice that of each spring of the mechanical filter so that the filter will be effectively mid-shunt terminated in accordance with the theory of filter design. For a treatment of this theory reference is made to Chapters XVI and XVII of "Transmission Circuits for Telephonic Communication" by K. S. Johnson, published by D. Van Nostrand Co., Incorporated. It is not essential, however, that M and S be treated as a component part of the line with which the device is used. Satisfactory operation is obtained so long as the cut-off frequency of M and S considered as a half section of low pass filter, is situated substantially above the range of frequencies being transmitted. The above reference to K. S. Johnson treats of the theory of half sections of filters. In taking into account the mass of the diaphragm, an effective mass must be used which for the corrugated plunger type diaphragm shown in the drawing is expressed by,

$$M = M_w \frac{1 + 2n + 3n^2}{6}, \quad (6)$$

where  $M_w$  is the weighed mass. When M

$$f_c = \frac{1}{2\pi} \sqrt{\frac{S}{M}}, \quad (7)$$

and the characteristic impedance is,

$$K = \sqrt{MS} = Z_\Phi = Z \left( \frac{A_2}{A_1} \right)^2 \quad (8)$$

where

$$S = \frac{kA_2}{V},$$

$k$  = coefficient of elasticity of air =  $1.4 \times 10^6$  c. g. s. units,

$V$  = volume of air chamber in c. g. s. units.

In c. g. s. units M is measured in grams, S in dynes per centimeter and K in dyne seconds per centimeter.

In designing a resistance unit in accordance with the invention, it is preferable to start by assigning convenient values to the diameter and length of the annular air slot. Its impedance can then be adjusted by means of the variable width,  $d$ , in accordance with Equation (1). The effective area of the diaphragm,  $A_2$ , may then be established so that  $Z_\Phi$ , according to Equation (5), has the value pre-assigned to the device. This is done by assigning proper values to the radii  $r_1$  and  $r_2$  as shown by Equation 4. By the choice of a material and thickness for the diaphragm, its weight is determined, from which its effective mass is ascertained from Formula (6). It is necessary then, to fix the air chamber volume, V, so that the proper value of elasticity, S, is obtained to make the characteristic impedance, K, equal to  $Z_\Phi$  by Equation (8). If it should be found that this elasticity, when applied to Formula 7, gives too low a value for the cut-off frequency, the diaphragm may be made thinner, which will result in a smaller mass, M, and necessitate a larger elastance, S. When the impedance,  $Z_\Phi$ , is varied by regulating the width of the annular slot, the characteristic impedance, K, should vary equally. This will follow if the slot width,  $d$ , is proportional to the square of the air chamber volume, V, as the member, 11, is moved in and out of the base piece, 10. This condition holds approximately when the following dimensions are employed or when their same proportions are adhered to:

$$r = 1/4''$$

$$r_1 = 3/8''$$

$$r_2 = 1/2''$$

$$\lambda = 34^\circ$$

$$\alpha = 2^\circ$$

Although the diaphragm in the preferred embodiment is corrugated and the narrow slot is annular in shape, the invention is not restricted to these features, but only in accordance with the appended claims. The



form disclosed is advantageous, however, because of the added rigidity of the corrugated type diaphragm and because the resultant shape of the air chamber allows the flow of air to occur through the annular slot without excessive eddies of air currents.

The resistance device is of use in conjunction with apparatus other than telephone receivers. It may conveniently be used with the stylus of a speech recorder.

What is claimed is:

1. A mechanical resistance unit comprising a diaphragm for receiving energy from a vibratory system, an air chamber, and means defining slot through which occurs a flow of air between said chamber and the atmosphere due to vibrations of said diaphragm, said slot being narrow in a direction transverse to that of the air flow and having an appreciable length in the direction of flow, whereby it offers an impedance to the air flow which is substantially a resistance free from reactance.

2. A mechanical resistance unit for damping vibratory waves, said unit comprising a corrugated diaphragm, an air chamber, and means defining an annular slot the diameter of which is approximately equal to and coincident with that of a ridge of said diaphragm, the motion of said diaphragm being damped by forcing air into and out of said air chamber through said slot, said slot being narrow and having an appreciable length in the direction of air flow whereby it offers to the flow of air an impedance which is substantially a resistance free from reactance.

3. A mechanical resistance unit for damping mechanical vibrations comprising a base piece, a member extending through an aperture in said base piece, there being a very narrow space between the surfaces of said member and of said aperture, and a diaphragm having a shape conforming to the inner surfaces of said base piece and of said member and held in proximity thereto.

4. A mechanical resistance unit comprising a diaphragm, air chamber, and means defining a slot through which air is forced into and out of said air chamber by vibration of said diaphragm, said slot being narrow in a direction transverse to that of air flow and having an appreciable length in the direction of flow whereby it offers a resistive impedance substantially free from reactance to the air flow; the width of said slot being adjustable.

5. A mechanical resistance unit comprising a base piece having an aperture with a conical surface, a member with a conical surface protruding through said aperture, leaving a narrow annular space between said surfaces, and a diaphragm having a corrugated area closely conforming in shape with the inner areas of said base piece and conical

member and fastened in such a manner that it encloses an air chamber, said conical member being movable inward and outward through said aperture so that the width of said annular space and the volume of said air chamber may be varied.

6. A mechanical resistance unit in accordance with claim 5 in which the movement of the conical member causes the width of the narrow annular slot to vary proportionally to the square of the air chamber volume.

In witness whereof, I hereunto subscribe my name this 22nd day of August, 1928.

PAUL B. FLANDERS.