

May 25, 1937.

S. J. A. M. BAGNO

2,081,572

ATTENUATOR

Filed Oct. 1, 1934

3 Sheets-Sheet 1

Fig. 1.

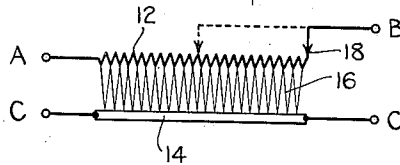


Fig. 2.

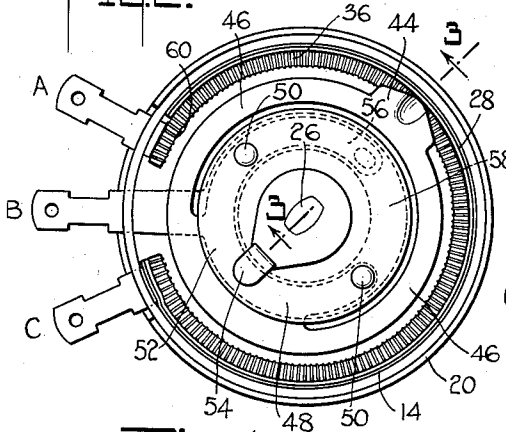


Fig. 3.

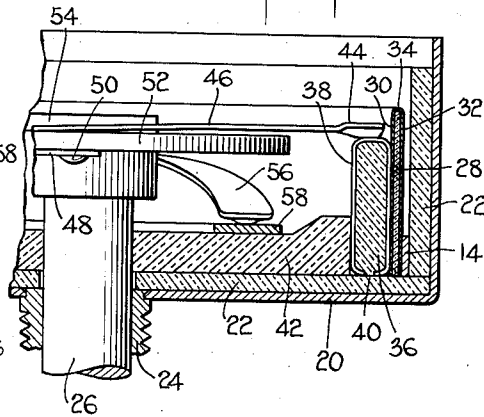


Fig. 4.

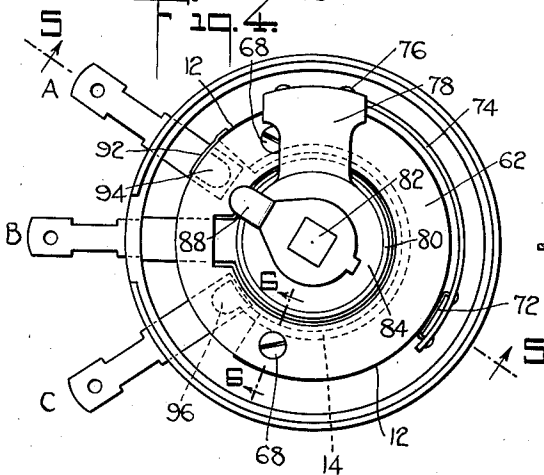


Fig. 5.

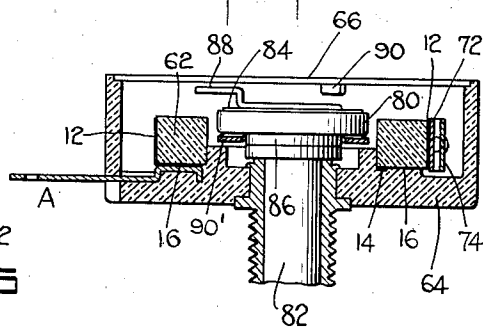
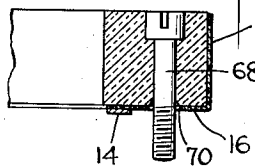


Fig. 6.



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3 Sheets-Sheet 3

Fig. 9.

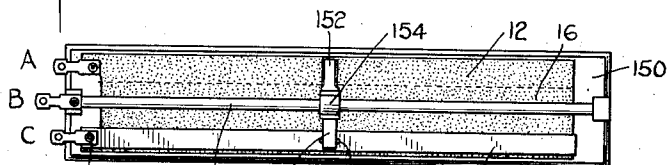


Fig. 10.

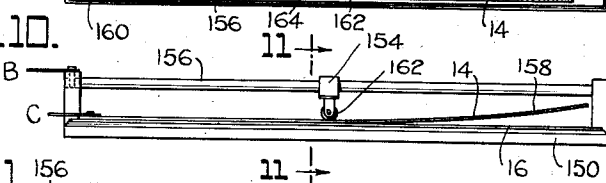


Fig. 11.

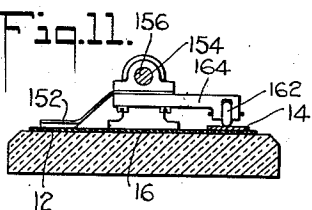


Fig. 12.

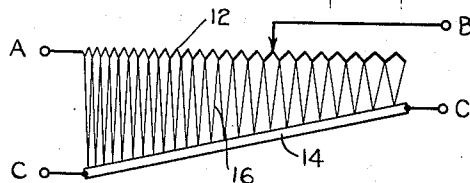


Fig. 13.

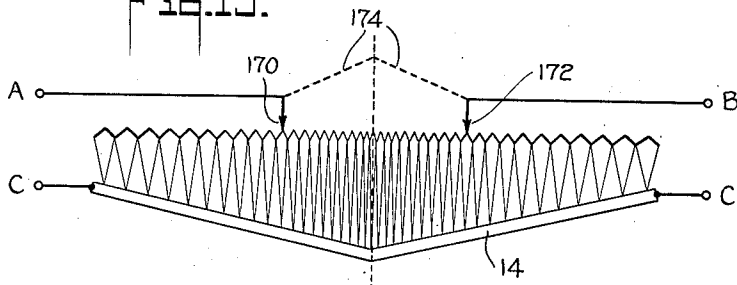
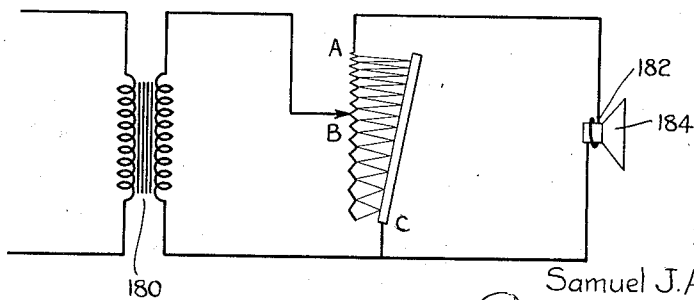


Fig. 14.



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UNITED STATES PATENT OFFICE

2,081,572

ATTENUATOR

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by mesne assignments, to Electrad, Inc.

Application October 1, 1934, Serial No. 746,316

23 Claims. (Cl. 178—44)

This invention relates to attenuators.

The object of my invention is to generally improve attenuators. A more particular object resides in the provision of an attenuator so arranged that the attenuation obtained may be divorced from the impedance of the attenuator, so that special requirements as to attenuation and impedance may be fulfilled largely independently of one another, all while using only a single unit.

One special case of great commercial importance is the provision of logarithmic attenuation. This is valuable for volume control of sound producing apparatus such as radio receivers because it is a well-known physiological law that equal steps of attenuation on a logarithmic scale sound approximately like equal loudness steps, and logarithmic attenuation therefore acts as an apparently uniform control of volume. In accordance with an important object and feature of my invention, I provide logarithmic attenuation, while utilizing uniform resistance elements of simple form, whereby the attenuator may be manufactured under quantity production conditions at minimum cost.

Another special case of frequent importance is the provision of constant or approximately constant input and output impedance during variation of the attenuator. It should be kept in mind that with a conventional unit, for example a potentiometer, the output impedance varies from zero to the actual maximum resistance of the unit, which is an infinity percentage variation. In accordance with my invention, however, the impedance may be kept within a range of say two to one, and this result is obtained while dealing with a unit of extremely simple and inexpensive construction. As will later appear, by a very slight complication of the apparatus, I may obtain nearly perfect constancy of impedance both for input and output. In accordance with a further object of my invention, I provide both logarithmic attenuation and approximately constant impedance in a single unit of simple and inexpensive construction.

Still further objects of my invention reside in the provision of an attenuator which may be given a high range of attenuation if desired; which may be, and preferably ordinarily is, arranged to provide continuous variation over the entire range; and which is purely resistive in character, it being non-inductive.

Further specialized objects of my invention reside in the provision of an attenuator particularly well adapted for use in oscillators for laboratory purposes and test sets; the further pro-

vision of an attenuator particularly suitable for volume control in radio receivers; and the further provision, when desired, of a volume and tone control combined in a single unit. Still another object of my invention resides in the provision of advantageous structural embodiments of the attenuator, which embodiments are practical, compact and susceptible of manufacture at a cost but little if at all higher than the cost of an equivalent simple variable resistance or potentiometer.

To the accomplishment of the foregoing and such other objects as may hereinafter appear, my invention consists in the attenuator elements and their relation one to the other, as hereinafter are more particularly described in the specification and sought to be defined in the claims.

The specification is accompanied by drawings, in which:

Fig. 1 is a diagram explanatory of my invention;

Fig. 2 shows the interior of a practical unit with the back plate removed;

Fig. 3 is an enlarged section taken on the plane of the line 3—3 of Fig. 2;

Fig. 4 shows the interior of a different type of practical unit with the back plate removed;

Fig. 5 is a section taken on the plane of the line 5—5 of Fig. 4;

Fig. 6 is an enlarged section taken on the plane of the line 6—6 of Fig. 4;

Fig. 7 shows one mode of application of my attenuator to an audio frequency, radio frequency oscillator or test set;

Fig. 8 illustrates one way in which the attenuator of my invention may be applied for controlling the volume in an amplifier;

Fig. 9 is a plan view of an attenuator modified to maintain nearly perfect constancy of impedance;

Fig. 10 is a side elevation thereof;

Fig. 11 is a section taken on the plane of the line 11—11 of Fig. 10;

Fig. 12 is a schematic diagram of a modified attenuator having non-uniform resistance elements;

Fig. 13 is a schematic diagram of a tapered double unit with tapered resistance elements arranged to maintain nearly constant impedance; and

Fig. 14 shows a combined tone and volume control, and one manner in which the same may be connected in circuit.

The attenuator of my invention may be described as somewhat analogous to a long line with leakage, for example a telegraph line. Such a

line has series resistance along the line and leakage or shunt resistance to ground. These characteristics are accidental and undesirable. In my invention, compact resistances are intentionally provided for intentional and variable control of attenuation. Referring to Fig. 1, the attenuator of my invention comprises a series resistance 12, a highly conductive bus 14 extending along but spaced from said series resistance 12, and a shunt resistance 16 extending between and continuously connecting the series resistance 12 to bus 14. A terminal A is connected to one end of series resistance 12. A second terminal B is connected to a contact or shoe 18 which is movable along resistance 12 in order to vary the effective length of the attenuator. A third terminal C is connected to bus 14. Terminals A and C may be used as the input or output respectively of the attenuator. One important feature of my invention resides in the fact that the resistances 12 and 16 may be continuous, thus affording continuous variation of attenuation. The resistance may be a film, or solid, or even wire-wound, although I prefer the use of a film as being the most convenient. The resistances 12 and 16 may also be uniform and in fact, when these resistances are uniform, the attenuation obtained is logarithmic in character. This simplifies and cheapens manufacture, for it is indeed a simple matter to provide a uniform resistance film. Furthermore, by appropriately spacing bus 14 from series resistance 12, it is possible to make shunt resistance 16 exactly like series resistance 12 in resistivity, or in other words, it is possible to provide a single film of resistance made of one resistance paint uniformly applied with a uniform thickness for both the series resistance 12 and the shunt resistance 16, thus further simplifying manufacture of the attenuator.

If we assume the simple case of uniform series resistance and uniform shunt resistance, and further assume that the unit is closed by or connected to a load which properly matches the surge resistance of the attenuator, or what is equivalent to the last assumption, if we assume that the total available attenuation is large, (analogous to a very long line) the attenuator may be designed by utilizing the following formulae. The mathematical derivation of these is given near the end of the specification in order not to disturb the continuity and readability of the disclosure. The designer is ordinarily given the impedance and the total attenuation. The total attenuation is α^2 , where α is the attenuation per unit length and equals

$$e^{-\sqrt{RG}}$$

in which R is the resistance per unit length, and G is the leakage conductance per unit length, which in turn is the reciprocal of the leakage resistance or shunt resistance per unit length, and α is the length. The surge resistance R_0 is equal to the

$$\sqrt{\frac{R}{G}}$$

From these two equations, the designer may solve for R and for G, thus defining the necessary resistance elements.

In Figs. 2 and 3, I show a practical structural form in which the attenuator may be embodied. Referring to these figures, the unit comprises a dish or relatively flat, cylindrical sheet metal

casing 20 lined by appropriate insulation 22. Casing 20 is provided on its forward face with a conventional threaded bushing 24 through which there passes the usual oscillatable control shaft 26. The casing is closed by a back plate which is not shown in the drawings.

A strip of insulation 28 is coated on both faces 30 and 32 and on one edge 34 with a resistance film. The coated strip 28 is bent to arcuate form and placed within the casing as is clearly shown in the drawings. Another insulation strip 36 is wound with fine wire 38 and the windings are interrupted, severed or open-circuited as is shown at 40 in Fig. 3. Wire-wound strip 36 is also bent into arcuate form and placed within strip 28 and contacting directly with the inner resistance film 30. The highly conductive strip of metal or bus 14 is bent to arcuate form and placed within the casing in contact with the lower portion of the outer film 32. Bus 14, coated strip 28, and wire-wound element 36 are pressed into intimate contact between the wall of the casing and a central disc 42 which is pressed within wire-wound element 36.

The wire-wound element is slidably engaged by a contact arm 44 connected by arcuate arms 46 to a disc 48 riveted by rivets 50 to a disc of insulation 52 which in turn is secured to the end of the control shaft 26. A stop arm 54 is riveted in place together with disc 52 and cooperates with an appropriate stop lug on the back plate of the case, thereby limiting the movement of the contact arm. A brush 56 is bent downwardly from disc 48 and bears against and rides upon a metallic ring 58 which in turn is connected with and preferably formed integrally with, the soldering lug or terminal B. Contact 44, arcuate arms 46, disc 48 and depending brush 56 are also preferably formed from a single piece of metal. Another soldering lug or terminal A is connected with the end portion 60 of wire-wound element 36 and it will be understood that the windings at the end portion 60 are not severed, and accordingly, provide contact with the end of the inside resistance film 30. A third terminal or soldering lug C bears against and is connected directly to one end of the highly conductive bus 14.

The operation of this unit will be understood by direct analogy to the schematic diagram shown in Fig. 1. Terminal A connects with one end of that part of inside film 30 which corresponds in width to the height of wire-wound element 36. The said portion of inside film 30 which is engaged by wire-wound element 36 corresponds to series resistance 12 in Fig. 1. The bus 14 corresponds of course to bus 14 in Fig. 1. The remaining resistance film, i. e., the uppermost part of inside film 30, the edge film 34 and the outer film 32 down to bus 14, corresponds to shunt resistance 16 in Fig. 1. Contact arm 44 corresponds to sliding contact 18 in Fig. 1, and is likewise connected to terminal B.

It will be understood that an important advantage of the present type of unit resides in the fact that a high resistance is obtainable by the use of a resistance film, while sliding contact is obtained between metallic surfaces, i. e., contact 44 and wire element 36, thereby eliminating any tendency to wear away or change the resistance value of the resistance film.

As an instance of quantitative values, I may refer to a unit like that shown in Figs. 2 and 3, except that coated strip 28 is reduced in width to the width of wire-wound element 36 so that inside film 30 corresponds directly to series re-

istance 12, while outside film 32 corresponds directly to shunt resistance 16. An attenuator designed for 80 db. attenuation employs a coated strip about three inches long and having a series resistance on one side of the strip totalling 2000 ohms. This resistance is conveniently measured before painting the edge 34. The edge and outer side of the strip are then painted like the inner side of the strip. The shunt resistance is given a total value of 20 ohms. This is readily tested by placing a copper plate under the series resistance, applying a copper bus at the lower edge of the shunt resistance, and then moving the copper bus upwardly slightly until the total shunt resistance reaches the desired value. The unit proportioned as aforesaid provides 80 db. attenuation in accordance with a logarithmic characteristic; and provides approximately constant impedance. By approximately constant impedance I mean a variation of the order of say two to one, for example from 50 to 100 ohms. This may be considered approximately constant for ordinary volume control or attenuation purposes, because it is to be contrasted with the infinity ratio of impedance variation obtained with conventional volume control units such as the ordinary potentiometer.

To measure a constructed unit in order to test its resistance to check the same against design values, the shunt resistance is readily determined as previously mentioned by covering the series resistance with a metallic plate and measuring the total shunt resistance for the entire shunt band. The reciprocal of this value is the leakage conductance of the band, and that divided by the length of the band gives the leakage conductance per unit length or G. Similarly, the total series resistance may be divided by the length to obtain the resistance per unit length or R. When the shunt resistance is high, it is not essential to disconnect the shunt resistance from the series resistance when measuring the value of the series resistance, and a fairly close reading may be obtained by simply measuring the resistance between terminals A and B. For more accurate work, of course, the shunt resistance is preferably disconnected from the series resistance during the measurement. For measuring the surge resistance of the physical unit, it is merely necessary to apply Ohm's law, introducing a test potential and test current on the terminals of the unit. During this measurement, it is necessary for strict accuracy, to close the unit or connect the same to a resistance equal to the surge resistance, or in other words, to match the impedance of the unit. However, I find that for units with a substantial range of attenuation, say more than 30 db., the unit may be considered analogous to a very long or infinite line and no appreciable error results even if the precaution of matching the impedance of the unit is neglected.

Another practical form in which the attenuator may be embodied for volume control and like purposes is illustrated in Figs. 4, 5, and 6. This unit differs from that heretofore described primarily in dispensing with the use of the wire-wound element and instead providing sliding contact directly with the surface of the series resistance film. Referring to the drawings, the resistance elements are provided upon an insulation ring 62 which is preferably rectangular in cross-section. The outer periphery is coated with a resistance film 12, while the forward face is coated with a resistance film 16. A highly

conductive metallic bus 14 is provided at the inner peripheral edge of shunt resistance 16.

Ring 62 is placed within an insulation case 64 and rests against the front wall thereof. Case 64 is in the form of a flat cylinder and is closed by a metallic back plate 66, which has been removed in Fig. 4, but is shown in Fig. 5. Ring 62 is held against the front wall of the case by screws 68 and the holes receiving said screws are preferably counterbored slightly as shown at 70 in Fig. 6 in order to prevent contact between shunt resistance 16. Series resistance 12 is engaged by a wiper or contact shoe 72 carried at one end of an arcuate resilient arm 74 which in turn is riveted at 76 to an oscillatable arm 78. This is downwardly dishd to form a hub 80 which is insulatively secured to control shaft 82 between insulation washers 84 and 86. A stop arm 88 is preferably also riveted to control shaft 82, the said arm cooperating with a stop lug 90 struck inwardly from back plate 66. Metallic hub 80 is engaged by an upwardly bowed resilient ring 90' (Fig. 5) which is connected to and preferably formed integrally with soldering lug B (Fig. 4). Another terminal or soldering lug A extends through the wall of the casing and is clamped between ring 62 and the casing. A layer of metallic paint is extended from one end of series resistance 12 along the periphery of the ring as is indicated at 92 and thence around the lower face of the ring as indicated at 94, thereby providing direct contact with soldering lug A. The conductive bus 14 may be stamped from thin metal or may be applied to the unit in the form of metallic paint, and in either case, is preferably enlarged at 96 where it contacts directly with the inner end of a third terminal or soldering lug C.

The operation of this unit will be readily understood by analogy to the schematic diagram of Fig. 1. Terminal A is connected to one end of series resistance 12 located on the periphery of ring 62. This resistance is varied over its entire width by wiper shoe 72 which may rock on arm 74, and which arm is yieldable, thus providing self-adjusting seating of the contact on the film. Contact 72 is of course connected through arm 74, arm 78, hub 80 and bowed ring 90' to the terminal or lug B. Shunt resistance 16 extends between and is continuously connected to series resistance 12 and bus 14, and the latter is in turn connected directly to terminal C. With this unit, as with that previously described, logarithmic attenuation is obtained with simple uniform resistance films. Films 12 and 16 may be made different in thickness for a specific resistance, or when desired, may conveniently be made the same in thickness, in which case the desired value of leakage conductance is obtained by appropriately adjusting the radial dimension of the film.

In Fig. 7 I show a test set oscillator suitable for use by radio repair men and for laboratory purposes. This oscillator comprises a tube 100 having a tuned radio frequency oscillatory circuit 102 connected between its cathode and control electrode. The radio frequency is controlled by an appropriate calibrated variable condenser 104 while a change in range of frequency is obtained by an inductance switch 106. The feed-back coil 108 is connected in the plate circuit of tube 100 and is regeneratively coupled to the inductance 110 of tuned circuit 102.

Audio frequency energy is generated with the aid of a tube 112 having a tuned circuit 114 connected between the cathode 116 and control elec-

trode 118. The audio frequency is adjusted by means of variable condenser 120. Coil 122 is connected in the circuit of anode 124 and is regeneratively coupled to the coil 126 of tuned circuit 114. The radio and audio frequency energies are combined or modulated by tube 112 which acts also as a mixer tube, the radio frequency energy being applied to another control electrode 128 of the tube. In practice, I prefer to use a multiple grid tube and the extra grids, in this case three, are all connected to anode 124. I find this desirable when using a low potential, say 22½ volts on the anode, which in turn is convenient so that a relatively small B battery 130 may be used to energize the oscillator. This, of course, makes for portability. The cathodes are heated by a 4½ volt battery 132, the circuit of which is controlled by a switch 134.

The modulated energy is supplied to the load or receiver being tested, through terminals 136. My attenuator 138 is preferably connected in circuit between the oscillator and terminals 136 in the manner shown, the terminals AC acting as input terminals and the terminals BC acting as output terminals. If it is desired to obtain audio frequency energy rather than modulated radio frequency energy, connection may be made to terminals 140.

The use of my attenuator for the present purpose is characterized by a number of advantages, including the facts that it does not detune the antenna circuit; that a large range of attenuation is wanted and is obtainable; the impedance is kept below the capacity leakage of the load or set being tested and therefore the calibration of the test set is not upset; the percentage of accuracy of the calibrated attenuator is constant regardless of the attenuation; and the attenuator is non-inductive.

In Fig. 8, I illustrate the application of the attenuator to a cascade amplifier including vacuum tubes 142 and 144 coupled in cascade by a transformer 146 having its primary connected to the output circuit of tube 142 and its secondary connected to the input circuit of tube 144 in conventional fashion. In the present case, the attenuator is connected between tube 142 and the primary of transformer 146. Terminals AC act as the input and the terminals BC act as the output.

It should be appreciated that the attenuator may, if desired, be connected between the secondary of transformer 146 and tube 144. Furthermore, assuming the amplifier to form a part of a radio receiver, it is possible to insert the attenuator between the antenna and the receiver as well as between tubes of the receiver. It may be used in the radio frequency portion or in the audio frequency portion of the receiver. It may also be used between the receiver and the speaker coil, as is later illustrated in connection with Fig. 14. In Fig. 8, the resistance elements are assumed to be constant thereby producing logarithmic attenuation. It may be remarked that in such case, there is no tone control effect because the impedance is substantially constant.

It is possible both theoretically and practically to provide constant input and output impedance for the attenuator, and a device for this purpose is illustrated in Figs. 9 through 11. Such departure from constant impedance as takes place across terminals AC in the units heretofore described is due to the variable shunting effect of the load, or from another viewpoint, is due to the effect of the unused part of the attenuator following the movable tap. In other words, if the

attenuator were variable in length, the unused part following the tap being disconnected at all times, there would be perfect maintenance of constant impedance both for input and output. Such a result may be obtained for all practical purposes by open-circuiting or making ineffective the highly conductive bus for the unused part of the attenuator.

Referring to the drawings, Figs. 9 through 11, the attenuator comprises an insulation base 150 provided with a series resistance film 12, a highly conductive bus 14 and a shunt resistance film 16. Terminal A is connected to one end of series resistance 12. The series resistance is slidably engaged by a contact shoe 152 mounted on a metallic support 154 slidable on a conductive rod 156 to which terminal B is connected. Bus 14 is in this case made of a strip of resilient metal so shaped that it tends at all times to lift from the resistance film as is indicated by the raised portion 158 in Fig. 10. Terminal C is connected to the fixed end 160 which is secured to base 150. The resilient strip is forced downwardly by a roller 162 carried on an insulation arm 164 mounted on support 154. It will be manifest that as the slider is moved along the unit the bus 14 is made effective only for the useful part of the attenuator, i. e., only for the distance between terminal A and the contact 152. The remaining or free end portion of the bus is elevated, thus eliminating the shunting of energy across the unused part of the attenuator to the bus.

With this arrangement a very nearly or practically constant impedance is obtained, by which I mean a constancy as near perfect as is ordinarily obtainable or expected with practical working apparatus. There is a slight departure from absolute perfection because of the slight leakage in the resistance film itself even though not grounded by a conductive bus.

It is possible to use tapered rather than uniform resistance elements and such arrangement is schematically illustrated in Fig. 12, in which the series resistance element 12 tapers from a high resistance at terminal A to a low resistance at its opposite end. The shunt resistance 16 likewise tapers from a high resistance to a low resistance in the same direction as series resistance 12. This arrangement has the advantage of minimizing the effect of the unused portion of the attenuator for the reason that this effect is significant only at the low attenuation or high volume end of the unit when the unused part of the unit comprises nearly all of the unit. With a tapered unit such as is shown in Fig. 12, when the slider is moved near to terminal A for low attenuation, the resistance values are high and but little loss takes place.

However, with this arrangement the impedance across terminals BC is variable although the impedance across terminals AC may remain approximately constant.

I may provide constant output as well as constant input impedance by utilizing in effect, two tapered units, and such an arrangement is shown in Fig. 13. In this arrangement, the series resistance tapers from the center towards its ends and the same applies to the shunt resistance. The series resistance is provided with a pair of sliders 170 and 172, which are preferably simultaneously and oppositely moved by appropriate mechanical link mechanism schematically shown by the dotted lines 174. Terminal A is connected to one of the sliders and terminal B to the other. In practice, the units

may of course be arranged side by side instead of end to end, this facilitating simultaneous movement of sliders 170 and 172. Such a unit is characterized by equal and constant input and output impedances, the constancy obtained being nearly as good as that obtained in the unit of Fig. 9. The connections of the bus 14 are, of course, permanent. The unit of Fig. 13 may therefore be thought of as a wholly different approach to the problem of obtaining constant input and output impedance, for in the unit of Fig. 9 a mechanical change is introduced for varying the bus connection, whereas in Fig. 13, the change is an electrical one by tapering the resistance values.

Reverting now to Fig. 12, the variation of impedance is sometimes permissible and even desirable. One example is the case of a conventional L-type resistance unit which, however, requires two variable resistances, whereas the unit of Fig. 12 requires only one variable resistance. Incidentally, I may point out that it is possible to obtain logarithmic attenuation even when using tapered instead of uniform resistance values, provided that the resistance values are properly adjusted. It is, of course, also possible to obtain different desired rates of attenuation by appropriate tapering of the resistance values. As an extreme case, I may mention the possibility of obtaining uniform attenuation by utilizing logarithmically tapering resistances.

Another application or use for a tapered unit such as shown in Fig. 12, is for a combined tone control and volume control for a radio receiver. The logarithmic attenuation of a uniform resistance unit such as is shown in Fig. 1, is highly desirable and is sufficient when dealing with a single frequency because, as has been already mentioned, the relation between sensation level and intensity of a sound is approximately logarithmic. However, in a radio receiver, we deal with a wide band of frequencies, and the requirements become somewhat different when we wish to obtain an attenuation vs. frequency characteristic resulting in an apparently uniform pitch-intensity level relationship. The response of the ear is such that it is desirable to increase the relative loudness of low frequencies at a low volume level and vice versa at a high volume level. Complicated multiple units have heretofore been designed in an effort to obtain this result. With my invention, the requirements may be satisfied by a simple tapered unit and such an arrangement is illustrated in Fig. 14.

The attenuator is there shown connected between output transformer 180 of the audio frequency amplifier and the movable or voice coil 182 of an electrodynamic speaker 184. The conventional field coil is omitted from the drawings. By utilizing a tapered unit such as is shown in Fig. 14, at maximum volume, the shunt resistance is at maximum and there is accordingly best response for high frequencies. At minimum volume the shunt resistance is at minimum and there is best response for low frequencies, the high frequency energy being dissipated to a larger extent in the shunt resistance; also, a larger proportionate drop occurring across the leakage reactance of the transformer for the higher frequencies. The unit may be proportioned to obtain logarithmic attenuation together with a beneficial tone control effect. It will be understood that the attenuator is not itself a tone control but acts as such only in co-operation with the associated external circuit.

Considered broadly, the attenuator is a combined attenuator control and variable impedance passive transducer, so arranged that the latter property of impedance change is used to vary the frequency-gain characteristic.

Mathematical treatment

The following mathematical treatment resembles that heretofore developed in connection with telegraph lines, but so far as I am aware, it is wholly new to apply the same for purposeful attenuation in a volume control or like compact structure which does not involve a long line and which is intentionally provided with shunt leakage resistance. In the following treatment it is assumed that inductance and capacitance are ignorable.

At a distance of x millimeters from the beginning of the attenuator, let the steady potential to the low resistance return or conductive bus be "E" volts, and let the steady current along the series resistance element be "I" amperes. Let "R" be the series resistance per unit length, in which case the resistance of an element dx will be Rdx ohms. Let "G" be the leakage conductance across the shunt resistance in ohms per millimeter, in which case the leakage conductance in the element dx is Gdx . The drop in potential in the element is $IRdx$ volts, while the drop of current in the element is $EGdx$ amperes.

This may be expressed:

$$(1) \quad \frac{dE}{dx} = -IR \text{ volts per millimeter}$$

$$(2) \quad \frac{dI}{dx} = -EG \text{ amperes per millimeter}$$

Differentiating (1) with respect to "x", we obtain:

$$(3) \quad \frac{d^2E}{dx^2} = -R \frac{dI}{dx}$$

But inserting (2) in (3), we obtain:

$$(4) \quad \frac{d^2E}{dx^2} = GRE$$

Differentiating (2) with respect to "x", we obtain:

$$(5) \quad \frac{d^2I}{dx^2} = -G \frac{dE}{dx}$$

Substituting (1) in (5), we obtain:

$$(6) \quad \frac{d^2I}{dx^2} = GRI$$

Equations (4) and (6) are simple linear differential equations of the second order and may be solved either exponentially or in terms of hyperbolic functions. Equation (4) may be solved exponentially as follows:

$$\text{Let } E = e^{mx}$$

Then

$$\frac{dE}{dx} = me^{mx}$$

And

$$\frac{d^2E}{dx^2} = m^2e^{mx}$$

Substituting this in (4), we get:

$$m^2e^{mx} = ERG = e^{mx}RG$$

Therefore,

$$m^2 = RG$$

And

$$m = + \text{ or } - \sqrt{RG}$$

The solution of Equation (4) is therefore:

$$(7) \quad E = Ae^{\sqrt{RG}x} + Be^{-\sqrt{RG}x}$$

wherein A and B are arbitrary constants of integration.

Students of differential equations will recognize (7) as a solution of (4) directly. From (7) it follows that when $x=0$, the maximum or input potential is

$$(8) \quad E_0 = A + B$$

Since we desire logarithmic attenuation, it follows that when

$x=1$, $E_1 = \alpha E_0$, where α is the attenuation per unit length, and when

$$x=n, E_n = \alpha^n E_0$$

Therefore, using (7),

$$(9) \quad \alpha^n E_0 = E = Ae^{\sqrt{RG}n} + Be^{-\sqrt{RG}n}$$

And,

$$(10) \quad \alpha^{n-1} E_0 = Ae^{\sqrt{RG}(n-1)} + Be^{-\sqrt{RG}(n-1)}$$

Assume,

$$\alpha = e^{-\sqrt{RG}}$$

To test the validity of this assumption divide (9) by (10)

$$(11) \quad \frac{\alpha^n}{\alpha^{n-1}} = \alpha = \frac{Ae^{\sqrt{RG}n} + Be^{-\sqrt{RG}n}}{Ae^{\sqrt{RG}(n-1)} + Be^{-\sqrt{RG}(n-1)}}$$

from which

$$Ae^{\sqrt{RG}n} = Ae^{\sqrt{RG}(n-2)}$$

This is true only if A is zero. Taking Equation (7),

$$E = Ae^{\sqrt{RG}x} + Be^{-\sqrt{RG}x}$$

Assume an infinitely long attenuator, then since the first term

$$(Ae^{\sqrt{RG}x})$$

increases with "x", it is evident physically that if x increases without limit, the voltage cannot rise without limit, whence the constant A must be zero.

$$(11) \quad A = 0$$

Which justifies the assumption that:

$$(12) \quad \alpha = e^{-\sqrt{RG}}$$

This defines the attenuation per unit length, and is one of the equations referred to in the first part of the specification.

From (8) and (11), it follows that

$$B = E_0$$

Rewriting (7), we obtain:

$$(13) \quad E = E_0 e^{-\sqrt{RG}x}$$

Differentiating (13) and substituting the same in (1), we obtain:

$$(14) \quad I = \frac{-1}{R} \frac{dE}{dx} = \frac{-1}{R} (-E_0 \sqrt{RG} e^{-\sqrt{RG}x})$$

Which may be simplified as:

$$(14) \quad I = E_0 \sqrt{\frac{G}{R}} e^{-\sqrt{RG}x}$$

This equation defines the current at any point along the attenuator.

Now, assuming that the attenuator is properly matched in impedance, or in other words, con-

nected to or closed by a resistance equal to the surge resistance, the surge resistance at any point along the attenuator may be expressed by:

$$(15) \quad R_0 = \frac{E}{I}$$

Substituting (13) and (14) in (15), we obtain:

$$R_0 = \frac{E}{I} = \frac{1}{\sqrt{\frac{G}{R}}} = \sqrt{\frac{R}{G}}$$

From which we conclude that the surge resistance is

$$(16) \quad R_0 = \sqrt{\frac{R}{G}}$$

which is another value used in the first part of the specification.

The solution in terms of hyperbolic functions may be made more general. The solutions of (4) and (6) are respectively as follows:

$$(17) \quad E = A \cosh(\sqrt{GR}x) + B \sinh(\sqrt{GR}x) \text{ volts}$$

And

$$(18) \quad I = C \cosh(\sqrt{GR}x) + D \sinh(\sqrt{GR}x) \text{ amperes}$$

The values in the parentheses above are hyperbolic angles, while the constants are dependent on the connecting or shunting circuit between the resistance and its return path.

Differentiating (18) and inserting the same in (2), we obtain:

$$(19) \quad E = -\frac{\sqrt{GR}}{G} [C \sinh(\sqrt{GR}x) + D \cosh(\sqrt{GR}x)]$$

If one source of electromotive force supplies current to the device and this source be located at the start of this device, then

$$x = 0$$

and we may call the current and voltage at this point I_0 and E_0 , respectively. Since $\cosh(0) = 1$, and $\sinh(0) = 0$, it follows that:

$$E_0 = \frac{\sqrt{GR}}{G} D$$

$$(20) \quad D = -E_0 \frac{G}{\sqrt{GR}}$$

and

$$I_0 = C(1) + 0$$

$$(21) \quad I_0 = C$$

Substituting these values in Equation (18), we get:

$$(22) \quad I = I_0 \cosh(\sqrt{GR}x) - \frac{G}{\sqrt{GR}} E_0 \sinh(\sqrt{GR}x) \text{ amperes}$$

This equation defines the current at any point x along the attenuator.

Substituting the values of (20) and (21) in (19), we obtain:

$$(23) \quad E = -\frac{\sqrt{GR}}{G} I_0 \sinh(\sqrt{GR}x) + E_0 \cosh(\sqrt{GR}x)$$

These equations define the potential at any point along the attenuator.

Equations (22) and (23) are general in all respects, except the assumption of uniform resistance and leakage conductance, and the assumption that the capacitance and inductance are ignorable.

General Equations (22) and (23) may be sim-

plified if we assume the attenuator connected to a properly matched surge resistance so that

$$R_0 = \sqrt{\frac{R}{G}} \quad (\text{Equation 16})$$

and

$$\alpha = \sqrt{GR}$$

where " α " is the attenuation constant or exponent (not the attenuation per unit length α which is defined by Equation 12).

Equation (23) may then be rewritten as follows:

$$(24) \quad E = E_0 \cosh \alpha x - I_0 R_0 \sinh \alpha x \quad \dots \text{volts}$$

Equation (22) may be rewritten as follows:

$$(25) \quad I = I_0 \cosh \alpha x - \frac{E_0}{R_0} \sinh \alpha x \quad \dots \dots \text{amperes}$$

These Equations (24) and (25) define the potential and current at any point along the line, with matched impedance.

Equation (24) which is in terms of hyperbolic functions may be converted to exponential form as follows, thus showing the correctness of Equation (13) above.

In Equation (24), $I_0 R_0$ may be replaced by E_0 , giving:

$$E = E_0 (\cosh \alpha x - \sinh \alpha x)$$

But

$$\cosh \alpha x - \sinh \alpha x = e^{-\alpha x} = e^{-\sqrt{RG}x}$$

Whence we obtain:

$$(13) \quad E = E_0 e^{-\sqrt{RG}x}$$

In connection with the non-uniform or tapered resistance units, it will be understood that the mathematical treatment is to be modified by recognizing in Equations (1) and (2), that R and G instead of being constant, are variables which are themselves a function of the distance along the device, x .

Advantages

It is believed that the mode of practicing as well as the many advantages of my invention, will be apparent from the foregoing detailed description thereof. The attenuator opens up a new field of development in that the attenuation is separated or divorced from the impedance so that particular requirements for each may be fulfilled. Attenuators may be conveniently and inexpensively constructed, which provide constant impedance, with the attendant advantage to the circuits in which the attenuator is used. Attenuators are also readily constructed which provide logarithmic attenuation and particularly convenient is the obtention of logarithmic attenuation with simple uniform resistance elements. The variation obtainable is continuous and may be made of high range. The unit is non-inductive. Attenuators of my invention are particularly suitable for use in oscillators and in amplifiers and radio receivers, and in the latter case, a combined volume control and tone control of simple form is made available. A constant impedance attenuator is available for use following the output transformer of a push-pull circuit. With my invention, a constant impedance attenuator is made possible by a unit having only a single control. Logarithmic attenuation is obtainable together with constant impedance and both of these are further obtainable by means of only a single control. In all of these cases, a continuous variation is available in contrast with the stepped

adjustment necessary with ladder or other lumped resistance networks.

It will be understood that while I have illustrated attenuators which employ resistance elements of the film type it is also possible to use various other forms of resistance elements. When dealing with resistance elements of the film type I have illustrated the series and shunt resistances as having equal thickness, but it will be understood that whenever it proves more convenient so to do, these resistances may differ in thickness. When they differ in thickness, it is desirable to form the same by first coating the entire area for the series and shunt resistances with a high resistance paint; and to thereafter additionally coat one of the resistance areas with another coat of paint to obtain the desired value. I may further mention that when dealing with very high frequency work, it is desirable to shield the unit, or more specifically, to take appropriate precautions to prevent a capacitance transfer of energy across the unit itself.

It will also be apparent that while I have shown and described my invention in preferred forms, many changes and modifications may be made in the structures disclosed without departing from the spirit of the invention, defined in the following claims.

I claim:

1. An attenuator comprising a continuous series resistance, a contact movably related thereto, a highly conductive bus, and a continuous shunt resistance extending between and continuously connected to said series resistance and said bus.

2. A substantially constant impedance attenuator comprising a uniform continuous series resistance, a contact movably related thereto, a highly conductive bus extending parallel to and spaced from said series resistance, and a uniform continuous shunt resistance extending between and continuously connected to said series resistance and said bus.

3. A substantially constant impedance attenuator comprising a uniform continuous series resistance film, a contact slidably related thereto, a highly conductive bus extending parallel to and spaced from said series resistance film, and a uniform continuous shunt resistance film extending between and connected to said series resistance film and said bus.

4. A substantially constant impedance attenuator comprising a uniform continuous series resistance film, a contact slidably related thereto, a highly conductive bus extending parallel to and spaced from said series resistance film, and a uniform continuous shunt resistance film extending between and connected to said series resistance film and said bus, said series and shunt films being made of the same material and constituting structurally a single film.

5. An attenuator comprising an elongated continuous resistance element having substantial width, a short movable contact slidable longitudinally relative to and making electrical contact solely with one longitudinal edge portion of said element, and a highly conductive fixed bus extending along and making fixed continuous contact solely with the opposite longitudinal edge portion of said element.

6. An attenuator comprising an insulation base coated with an elongated continuous resistance film, a movable contact longitudinally slidable relative to and making electrical contact solely with a longitudinal strip of said resistance film lying near one edge of said film, a highly conduc-

tive fixed bus bearing against and making fixed continuous contact solely with the opposite longitudinal edge portion of said film, a terminal connected to one end of the first-mentioned portion of the film, a terminal connected to said slidable contact, and a terminal connected to said bus.

7. A substantially constant impedance attenuator comprising an insulation base coated with a uniform, elongated continuous resistance film, a movable contact slidable longitudinally relative to and making electrical contact solely with a strip of said resistance film lying near one longitudinal edge of said film, a highly conductive fixed bus bearing against and making fixed continuous contact solely with the opposite longitudinal edge portion of said film, a terminal connected to one end of the first-mentioned portion of the film, a terminal connected to said slidable contact, and a terminal connected to said bus.

8. An attenuator comprising an insulation ring of rectangular cross-section, a continuous resistance film coated on the outer periphery and on one face of said ring to form connected peripheral and face films, a control shaft, a wiper arm mounted on said shaft and slidably engaging one of said films, and a highly conductive bus extending along and engaging the free edge of the other film.

9. An attenuator comprising a flat cylindrical casing, an insulation ring of rectangular cross-section mounted therein, a continuous resistance film coated on the outer periphery and on one face of said ring, a control shaft in said casing, a wiper arm mounted on said shaft and slidably engaging the peripheral resistance film, a highly conductive bus engaging the face film at the inner periphery thereof, a first terminal connected to one end of the peripheral film, a second terminal connected to the wiper arm, and a third terminal connected to the bus.

10. A compact substantially constant impedance attenuator comprising a flat cylindrical casing, an insulation ring of rectangular cross-section mounted therein, a continuous uniform resistance film coated on the outer periphery and on one face of said ring, a control shaft centrally mounted in said casing, a wiper arm mounted on said shaft and slidably engaging the peripheral resistance film, a highly conductive bus engaging the face film at the inner periphery thereof, a first terminal connected to one end of the peripheral film, a second terminal connected to the wiper arm, and a third terminal connected to the bus.

11. An attenuator comprising a series resistance, means to vary the same, a shunt resistance continuously connected on one side to said series resistance, and means mechanically associated with the means to vary the series resistance for continuously short-circuiting the opposite side of the shunt resistance to an extent dependent upon the position of the slider.

12. An attenuator comprising a continuous series resistance, a contact slidable relative thereto, a shunt resistance having one edge continuously connected to said series resistance, a short-circuiting bus adapted to be continuously connected to the opposite edge of said shunt resistance, and means mechanically associated with the slider for making a part of said short-circuiting bus effective and the remainder ineffective dependent upon the position of the slider.

13. An attenuator comprising a continuous series resistance, a contact slidable relative thereto, a shunt resistance having one edge continu-

ously connected to said series resistance, and highly conductive means mechanically associated with the slider for bearing against the opposite edge of the shunt resistance an amount dependent upon the position of the slider.

14. An attenuator comprising a continuous series resistance film, a contact slidable thereover, a terminal at one end of said film, a highly conductive bus collateral to but spaced from said series resistance film, a continuous shunt resistance film connected to and extending from said series resistance film to and underlying said bus, said bus being resilient and so shaped as to tend normally to move away from said shunt film, and means mechanically associated with the slider for bearing against said bus and forcing the same against said shunt film only as far as the slider has been moved from the terminal, whereby said bus is ineffective over the unused portion of the attenuator.

15. An attenuator comprising a uniform continuous series resistance film, a contact slidable thereover, a terminal at one end of said film, a highly conductive bus extending parallel to and spaced from said series resistance film, a uniform continuous shunt resistance film connected to and extending from said series resistance film to and underlying said bus, said series and shunt films being of the same material and constituting structurally a single film, said bus being resilient and so shaped as to tend normally to move away from said shunt film, and means mechanically associated with the slider for bearing against said bus and forcing the same against said shunt film only as far as the slider has been moved from the terminal, whereby said bus is ineffective at the unused portion of the attenuator.

16. An attenuator comprising a continuous series resistance which tapers in resistance from one end to the other, a slider movable thereover, a highly conductive bus arranged collaterally to said series resistance, and a continuous shunt resistance connected at all points between the series resistance and the bus, said shunt resistance tapering in resistance in the same direction as the series resistance.

17. A combined volume control and tone control device for a radio receiver, said control comprising a continuous series resistance which tapers in resistance from one end to the other, a slider movable thereover, a highly conductive bus arranged collaterally to said series resistance, a continuous shunt resistance connected at all points between the series resistance and the bus, said shunt resistance tapering in resistance in the same direction as the series resistance, the slider and the bus constituting one pair of terminals of the control and the high resistance end of the series resistance and the bus constituting the other terminals of the control.

18. An attenuator comprising a resistance element made up of a single continuous body of resistance material, a slider longitudinally movable over only a longitudinal edge part of said element, a fixed metallic bus making fixed continuous contact with only the opposite longitudinal edge part of said element, an additional fixed connection to one end only of the first part of said element, said connection, slider, and element being so arranged and proportioned as to provide substantially constant impedance attenuation.

19. An attenuator comprising a resistance ele-

ment made up of a single continuous body of resistance material, a slider longitudinally movable over only a longitudinal edge part of said element, a fixed metallic bus making fixed continuous contact with only the opposite longitudinal edge part of said element, an additional fixed connection to one end only of the first part of said element, said connection, slider, and element being so arranged and proportioned as to provide logarithmic attenuation by continuous variation with substantially constant impedance solely by movement of the slider.

20. An attenuator comprising two resistance elements in edge to edge conductive contact, a longitudinally movable slider movably contacting one only of said elements, a fixed metallic bus making fixed continuous contact longitudinally along the other only of said elements, and an additional fixed connection to one end only of the first of said elements, said resistances, slider, and connection being so arranged and proportioned as to provide substantially constant impedance attenuation.

21. An attenuator comprising two continuous resistance elements in edge to edge conductive contact, a longitudinally movable slider mov-

ably contacting with one only of said elements, a single control to move the same, a fixed metallic bus making fixed continuous contact longitudinally along the other only of said elements, and an additional fixed connection to one end only of the first of said elements, said resistances, slider, and connection being so arranged and proportioned as to provide continuous logarithmic attenuation with substantially constant impedance by means of said single control.

22. A resistance net work comprising a compact continuous resistance, a continuous conductor, and a second compact continuous resistance connected between the first resistance and the conductor, said connection being continuously distributed along both the first resistance and the conductor.

23. An attenuator comprising a uniform continuous series resistance, a contact movably related thereto, a highly conductive bus extending collaterally with and spaced from said series resistance, and a continuous shunt resistance extending between and continuously connected to said series resistance and said bus.

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