

May 23, 1933.

R. B. BOURNE
ACOUSTIC WAVE FILTER
Filed May 13, 1932

1,910,672

2 Sheets-Sheet 1

Fig. 1.

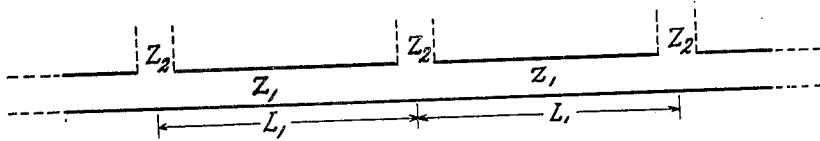


Fig. 2.

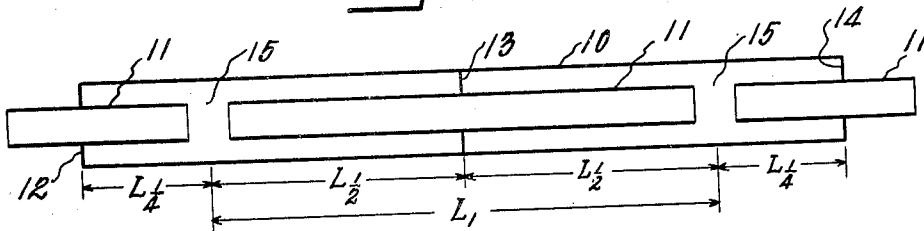


Fig. 3.

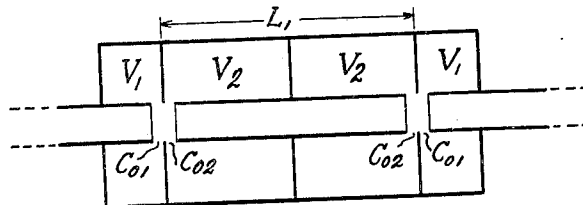
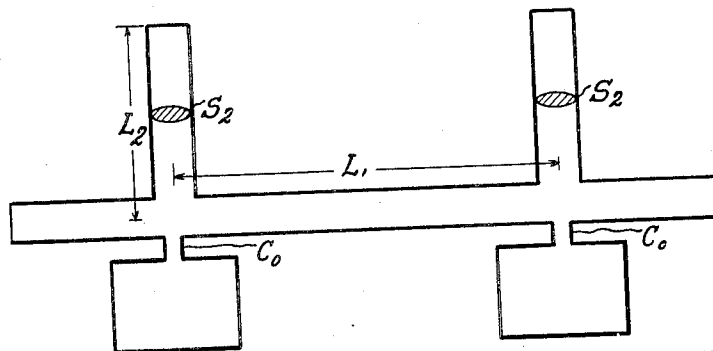


Fig. 4.



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Fig. 5.

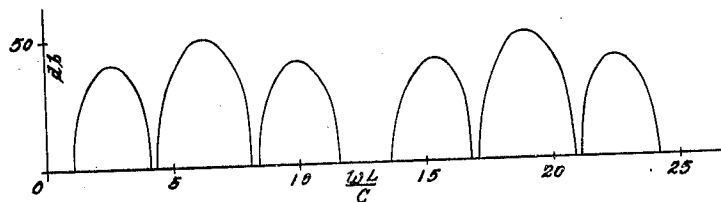


Fig. 6.

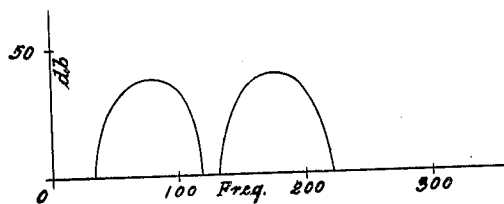


Fig. 7.

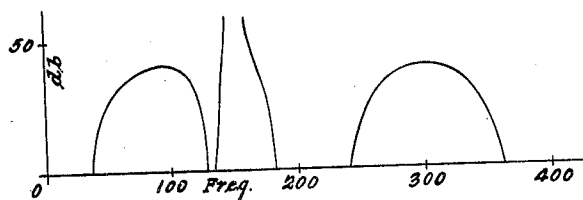
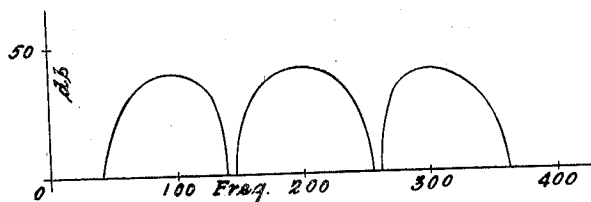


Fig. 8.



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ACOUSTIC WAVE FILTER

Application filed May 13, 1932. Serial No. 611,060.

The present invention relates to devices of the wave filter type, particularly to those structures wherein the acoustic properties of mass and elasticity are uniformly distributed; that is, to structures having physical dimensions such that wave motion or change of phase takes place within the various discreet parts thereof. An example of an acoustic structure having uniformly distributed constants of mass and elasticity is the organ pipe.

The advantages of employing structures of the wave filter type for attenuating certain sound frequencies known to exist in the exhaust conduits of internal combustion engines, and the like, are evident when it is considered that straight, smooth, unobstructed conduits may be employed for the passage of the exhaust gases, that high degrees of attenuation are obtainable, that wide bands of sound frequencies may be made to suffer attenuation, that the physical construction may be made extremely simple and cheap to manufacture and that no small holes, fine interstices or complicated baffles and passageways which might in time become clogged with carbon, etc. are necessary.

The prior art teaches how to construct certain acoustic wave filters. In the past, stress has been laid on structures having a series of relatively narrow attenuation bands with correspondingly wide passbands and upon structures having but a single attenuation band, which in practice turns out to be none too wide, where the main object is to offer attenuation, especially over a wide frequency range.

The main object of this invention is to provide an acoustic wave filter having, in its attenuation vs. frequency characteristic, a series of wide attenuation bands separated by extremely narrow passbands.

Another object of the invention is to provide an acoustic wave filter having a series of harmonically related, narrow passbands.

A further object of the invention is to provide a structure, having predictable acoustic attenuation characteristics, said structure

being extremely simple to design and fabricate on a commercial scale.

To assist in a more complete understanding of the invention, reference is now made to the drawings wherein—

Fig. 1 shows a generalized recurrent ladder-type structure involving both series and shunt impedances;

Figs. 2, 3, and 4 show various embodiments of acoustic wave filters;

Figs. 5, 6, 7, and 8 show the attenuation-frequency characteristics of various embodiments of the invention.

For the purposes of this invention, structures having distributed impedance constants of mass and elasticity are constructed of tubes or conduits which are an appreciable fraction, or greater, of a wavelength long and in which, therefore, wave motion or progressive change of phase takes place along the length thereof. Structures in which no appreciable wave motion or change of phase, as a function of length, takes place, are considered as having lumped impedance constants of mass and elasticity and may be represented by a closed volume together with a communicating orifice or neck, short in comparison to a wavelength.

Since the invention embodies structures employing both kinds of impedance elements as sidebranches, it is desirable to give a fundamental equation which will represent the attenuation-frequency characteristic of all the embodiments shown. For structures employing tubular main line or series conduits of uniform cross-sectional area, it can be shown that

$$\cosh P = \cos \frac{\omega L_1}{C} + \frac{i Z_1}{2 Z_2} \sin \frac{\omega L_1}{C} \quad (1)$$

L_1 = length of the main channel between sidebranches

C = velocity of sound in the medium

Z_1 = impedance of the main channel

Z_2 = impedance of each of the shunt branches

P = propagation constant of the structure

The symbols i and ω have, of course, their conventional meanings of $\sqrt{-1}$ and 2π times the frequency respectively.

It will be seen that $\cosh P$ is, in general, a complex quantity, having both real and imaginary components. Since, in the structures embodying this invention, acoustic resistance may be kept to a low value, it is permissible to neglect the effects of acoustic resistance and frictional dissipation and to consider the impedance elements as pure reactances. From this it follows that the propagation constant P is either a real quantity or else an imaginary one. Since $\cosh P$ cannot be less than plus one nor greater than minus one, it follows that P is real for all values of $\cosh P$ lying outside the above limits, in which case P represents the attenuation per section of the structure in nepers. To convert nepers to the more common decibel unit of attenuation it is only necessary to multiply the result by 8.686. When the value of the right-hand side of Equation (1) falls between plus one and minus one, it represents the phase change per section of the filter, the attenuation constant, for these values, being zero. Such values indicate a passband and the cut-off frequencies occur when $\cosh P$ equals plus or minus one.

Considering Equation (1), it is evident that if appropriate values for Z_1 and Z_2 are chosen and substituted therein, the equation governing specific structures embodying the foregoing principles will at once be obtained. In all the cases pertinent to this invention, the value of Z_1 is taken equal to

$$\frac{\rho C}{S_1},$$

where ρ is the density of the medium and S_1 the cross-sectional area of the main conduit. This is obtainable directly from the fundamental equation showing the velocity of sound in a gaseous medium. This quantity is in the nature of a resistance since it does not involve a consideration of frequency. The value of Z_2 will depend upon the nature of the shunt branch used. Since the invention is largely concerned with exhaust discharges from internal combustion engines and the like, it is evident that sidebranches open to the atmosphere cannot be used and the choice of sidebranches to give desired effects rests among those sidebranches which are closed.

The simplest sidebranch meeting this requirement is a tubular member coupled to the main channel and closed at its remote end. Such a tube is a quarter of a wavelength long for the fundamental resonant frequency. It is also resonant at odd harmonics of the fundamental frequency. Placed in shunt to an infinitely long conduit, it offers zero impedance, looking into it from the main conduit, to its resonant frequencies and relatively high but diminishing attenuation to adjacent frequencies.

The width or broadness of the band depends upon the relative areas of the sidebranch and main conduit, being broader as the area of the sidebranch is increased with respect to that of the main conduit. When now a plurality of similar closed sidebranches are connected in shunt to the main conduit at equal intervals along its length, the series and shunt impedance functions conspire to give not only attenuation bands, but also pass bands, wherein negligible attenuation occurs. In this kind of a structure, the sections of the main conduit are of equal length and are terminated in the same manner; consequently, they may for convenience be considered to behave as if resonant to those frequencies for which the distance between successive sidebranches is one-half wavelength and all the harmonics thereof, both even and odd. If now, the lengths of the sidebranches and distance between them be so chosen that resonance occurs in both for the same frequency, the impedance functions conspire to limit the amount of attenuation at resonance to a finite value and to broaden the band of frequencies over which attenuation occurs. Since a filter structure having inherently narrow attenuation bands is commercially impracticable, however great the attenuation therein may be, due to unknown variations in the velocity of sound in the medium (hot exhaust gas, in many cases), commercial requirements dictate the use of structures offering the widest possible attenuation bands.

As pointed out above, the value of Z_1 , the impedance of the main channel, is given by the relation

$$Z_1 = \frac{\rho C}{S_1} \quad (2)$$

A corresponding relation for a sidebranch tube closed at its far end is derived in works on acoustics in the form

$$Z_2 = -\frac{i\rho C}{S_2} \cot \frac{\omega L_2}{C} \quad (3)$$

in which, in addition to the symbols defined above S_2 is the area of the sidebranch and L_2 its length. Substituting these values in Equation (1) we have

$$\cosh P = \cos \frac{\omega L_1}{C} - \frac{S_2}{2S_1} \sin \frac{\omega L_1}{C} \tan \frac{\omega L_2}{C} \quad (4)$$

Considering now a filter wherein the shunt branches are closed tubes of equal length coupled to the main conduit at intervals along the length thereof equal to twice the length of the sidebranch tubes, Equation (4) becomes

$$\cosh P = \cos \frac{\omega L_1}{C} - \frac{S_2}{2S_1} \sin \frac{\omega L_1}{C} \tan \frac{\omega L_2}{2C} \quad (5)$$

A consideration of the sine and tangent functions, above, shows that whenever the tangent is infinity the sine is zero; and further, since the sine is changing twice as fast as the tangent, an alternate series of values makes both the sine and tangent zero simultaneously. This gives rise to an harmonically related series of broad attenuation bands which are, however, separated by pass bands of substantially the same width. Since an important object of the invention is to provide attenuation over as wide a range of frequencies as possible, it is necessary, in order to secure a commercially practicable device, to fill in as many of these undesirable passbands as possible, with attenuation bands. This may be accomplished mathematically by adding another tangent function to the Equation (5), said function changing one-quarter as fast as the sine function; physically, this is accomplished by adding another closed tubular sidebranch in parallel at each junction point along the length of the conduit, the additional sidebranches being one-quarter as long as the distance between sidebranches along the main channel.

By making the proper substitution in Equation (5) it is evident that

$$\cosh P = \cos \frac{\omega L_1}{C} - \frac{S_2}{2S_1} \sin \frac{\omega L_1}{C} \left[\tan \frac{\omega L_1}{2C} + \tan \frac{\omega L_1}{4C} \right] \quad (6)$$

This equation holds for the condition that the areas of both paralleled sidebranches are equal.

A plot of this equation is shown in Fig. 5, the large portion of the frequency spectrum consumed by attenuation bands being evident. The commercial embodiment of the invention operating under Equation (6) is shown in Fig. 2. In this embodiment, the filter is of two sections, the minimum permissible under the theory. The area of the sidebranch conduits are equal and may be made much larger than the area of the main conduit, due to the concentric construction. The construction of this device is so simple as to be self-evident from the figure, involving as it does two concentric tubular members 10 and 11 and three headers 12, 13, and 14 positioned as shown. The openings 15 in the main conduit, giving in to the annular side conduits are not critical in design, it being only necessary to make the length of the slot-like opening of the order of the diameter of the main channel.

Considering further the plot shown in Fig. 5, the ordinates are plotted in decibels for two sections. The passbands, while of two different sets of widths, occur in sub-

stantially harmonic relation to each other and at values of

$$\frac{\omega L_1}{C} = n \frac{4\pi}{3},$$

where n is any integer or zero. One method of using the several broad attenuation bands obtained is to arbitrarily place the seventh harmonic of the fundamental frequency to be attenuated at

$$\frac{\omega L_1}{C} = 4\pi.$$

This procedure place the first six harmonics of the fundamental frequency well within the attenuation bands. Commercially speaking, harmonics above the sixth are of little importance, although it may be pointed out that with the exception of the seventh, the first thirteen harmonics all fall inside attenuation bands.

It is now apparent that, in order to design a filter of this type to attenuate greatly a sound wave of known frequency and having considerable harmonic content, it is only necessary, once the cross-sectional area of the main conduit is fixed, to substitute the proper values in the equation

$$\frac{2\pi FL_1}{C} = \frac{4\pi}{7} \quad (7)$$

and solve for the value of L_1 , the other dimensions being apparent by inspection.

A further important use of the filter is as a bandpass filter, where it is desired to permit transmission of a very narrow band of frequencies and all their harmonics. Selecting a value of

$$\frac{\omega L_1}{C} = \frac{4\pi}{3}$$

for the desired frequency, there is obtained immediately the design data for a filter possessing extremely selective properties. The use of such a filter as an audio frequency selective device is at once apparent.

Since these filters embody principles involving recurring functions, they extend their calculable characteristics well up in the frequency spectrum. This is of great advantage in the case of a complex noise, all frequencies of which must be attenuated, in that the burden of attenuating relatively high frequency sounds is greatly removed from the realm of those devices which depend upon acoustic resistance for attenuation, thus permitting much more efficient and economical constructions.

Another example of two unlike impedances in parallel as a side branch is shown in Fig. 3. Here, the main channel of length L_1 and area S_1 has coupled to it the lumped impedances represented by the volumes V_1 and V_2 together with the cou-

pling orifices or "conductivities" C_{01} and C_{02} , respectively. By substituting the proper values for a structure of this kind in Equation (1), there results

$$\cosh P = \cos \frac{\omega L_1}{C} + \sin \frac{\omega L_1}{C} \cdot \frac{C}{2S_1} \left[\frac{1}{\frac{\omega}{C_{01}} - \frac{C^2}{V_1 \omega}} + \frac{1}{\frac{\omega}{C_{02}} - \frac{C^2}{V_2 \omega}} \right] \quad (8)$$

A plot of Equation (8) is shown in Fig. 6, attenuation being plotted against frequency in this case. A unique feature of this filter is found in the fact that the distance between sidebranch junction points along the main channel is one-half wave length for the resonant frequency of the larger of the two paralleled sidebranches and a full wave length for the smaller of the two. The broadening effect of the correlation described above between the spacing of the junction points along the main channel and the resonant frequency of the sidebranches is again noted. The plot of Equation (8) is not carried beyond the upper cut-off frequency of the second attenuation band, since with the construction shown in Fig. 3, the exact behavior of the sidebranches for the higher frequencies is not readily determined mathematically.

Fig. 4 shows an acoustic wave filter in which the main channel has coupled to it the unlike parallel impedances represented respectively by the linear sidebranch $L_2 S_2$ and the volumetric sidebranch $C_0 V$. The equation for a filter of this type is

$$\cosh P = \cos \frac{\omega L_1}{C} + \sin \frac{\omega L_1}{C} \cdot \frac{C}{2S_1} \left[\frac{1}{\frac{\omega}{C_0} - \frac{C^2}{V \omega}} - \frac{S_2 \tan \frac{\omega L_2}{C}}{C} \right] \quad (9)$$

A plot of this equation is shown in Fig. 7. This particular filter has the frequencies of maximum attenuation placed at 100 cycles and 150 cycles for the linear and volumetric sidebranches respectively. The distance between junction points along the main channel is, in the particular case chosen for illustration, a half wave length for 100 cycles but not for 150 cycles. The first three attenuation bands only are plotted, the resulting shapes being clearly shown. Another variation of this type filter is obtained by placing the fundamental frequency of the volumetric system at twice the fundamental frequency of the tubular sidebranch. The normally infinite attenuation at particular frequencies due to a sidebranch is reduced to a finite quantity, and at the same time the attenuation bands are widened, by spacing the junction points along the main channel equal to a multiple of a half wave

length of the frequency for which the sidebranch is resonant. Fig. 7 shows this clearly for the attenuation bands due to the tubular sidebranch. In Fig. 8 this effect is extended to the volumetric sidebranch. The plot, shown in Fig. 8 is similar to that shown in Fig. 5 for the first three attenuation bands, although the passbands may not necessarily be harmonic, depending upon the design of the volumetric sidebranch. The effect of increasing the "conductivity" of the volumetric sidebranch, for a given frequency, is to broaden the attenuation band, thus displacing slightly the adjoining bands.

It is obvious that three or more parallel sidebranches might be used, giving various characteristics. In general, it may be stated that increasing the number of paralleled sidebranches results in increasing the number of pass and, therefore, attenuation bands. The choice of a particular filter resolves into a knowledge of the conditions to be met.

In all acoustic wave filters, the theory assumes either an infinite number of sections or a finite number terminated in a structure having an impedance equal to the characteristic impedance of the filter. In practice, this is not altogether realizable, but a sufficient approximation for commercially satisfactory results may be obtained by use of straight conduits of proper length.

I claim:

1. An acoustic wave filter comprising a main sound conduit of uniform cross-sectional area, said conduit having, at equally spaced intervals along the length thereof, a plurality of equal acoustic impedances disposed in shunt with and acoustically coupled to said main conduit, said acoustic impedances each comprising two or more unlike closed acoustic sidebranches in parallel.

2. An acoustic wave filter in accordance with claim 1 in which the sidebranch impedances comprise two or more closed tubes of uniform cross-sectional area and of unequal length, in parallel.

3. An acoustic wave filter in accordance with claim 1 in which the sidebranch impedances comprise two closed tubes of uniform cross-sectional area in parallel, one of which is half as long as the distance between sidebranches along the main conduit and the other of which is one-quarter of said distance.

4. An acoustic wave filter in accordance with claim 1, in which the sidebranch impedances comprise two closed chambers of different volume, in parallel, communicating with said main sound conduit through orifices therein.

5. An acoustic wave filter in accordance with claim 1 in which the sidebranch impedances comprise two closed chambers in parallel communicating with said main

sound conduit through orifices therein, the lumped impedance system comprising one of said volumes, together with its communicating orifice, resonating to a frequency for which the distance along said main sound conduit between said sidebranch impedances is one-half wave length, and the system comprising the other of said volumes, together with its communicating orifice, resonating to twice that frequency.

6. An acoustic wave filter in accordance with claim 1 in which the sidebranch impedances comprise, respectively, a uniform tubular conduit, closed at its remote end, in parallel with a closed chamber coupled to said main sound conduit through orifices.

7. An acoustic wave filter in accordance with claim 1 in which the sidebranch impedances comprise, respectively, a uniform tubular conduit, closed at its remote end, in parallel with a closed chamber coupled to said main sound conduit through orifices, whereby the lumped acoustic system comprising said chamber and orifices resonates to a frequency equal to twice the fundamental frequency of said tubular member.

8. An acoustic wave filter comprising a uniform, tubular, main sound conducting channel having two openings therein in spaced relation along the length of said channel, each of said openings communicating with a uniform, tubular, laterally disposed conduit, closed at both ends, at a point distant from one end thereof equal to one-third its total length.

9. An acoustic wave filter comprising two concentric uniform tubular members radially spaced one from the other, end closures extending between the members, and an intermediate partition also extending therebetween, whereby are formed a central tubular conduit and two equal annular chambers surrounding it, said annular chambers being long in proportion to the wave lengths to be attenuated so that appreciable acoustic wave motion takes place therein, and openings from the central conduit into the annular chambers in spaced relation along the length of the central conduit and asymmetrically located with respect to the length of each annular chamber whereby the central conduit is acoustically coupled to the two annular chambers.

10. An acoustic wave filter comprising two eccentric uniform tubular members radially spaced one from the other, end closures extending between said members, and an intermediate partition also extending therebetween, whereby are formed a central tubular conduit and two equal annular chambers surrounding it, said annular chambers being long in proportion to the wave lengths to be attenuated so that appreciable acoustic wave motion takes place therein, and openings from the central conduit into

the annular chambers at points one-third the distance from each end closure to the intermediate partition whereby the central conduit is acoustically coupled to the two annular conduits.

11. An acoustic wave filter comprising a main conducting channel, openings therein in spaced relation along the length thereof, and a pair of closed, annular, tubular sidebranches of unequal length communicating in parallel with each of said openings.

12. An acoustic wave filter comprising a main conducting channel, openings therein in spaced relation along the length thereof, and a pair of closed, annular, tubular sidebranches of unequal length communicating in parallel with each of said openings, one of each pair of sidebranches being twice as long as the other of the pair.

13. An acoustic wave filter comprising a main conducting channel, openings therein in spaced relation along the length thereof, and a pair of closed, annular, tubular sidebranches of unequal length communicating in parallel with each of said openings, the cross-sectional area of said sidebranches being large compared to that of the main conducting channel.

14. An acoustic wave filter comprising a central conduit having circumferential slots spaced along its length, an external casing, headers closing the space between the conduit and the casing at the ends of the casing, a partition joining the conduit and the casing intermediate the slots, and annular partitions extending from the casing towards the conduit with their free edges in adjacency with the slots.

15. An acoustic wave filter comprising a central conduit, an external casing, headers closing the space between the conduit and the casing at the ends of the casing, a partition joining the conduit and the casing at the longitudinal midpoint of the casing, the conduit being formed with circumferential slots located one-third of the distance between each header and the central partition, and annular partitions extending from the casing towards the conduit with their free edges in adjacency with the slots.

16. An acoustic wave filter comprising a main acoustic conduit having acoustic junctions spaced along its length, and a plurality of closed acoustic sidebranches arranged in groups at each of the several acoustic junctions, the sidebranches forming the group at each junction having different fundamental resonant frequencies related one to another in the ratio of small integers and having a common acoustic coupling to the main acoustic conduit at said junction.

17. An acoustic wave filter comprising a main acoustic conduit having acoustic junctions spaced along its length, and a plurality of closed acoustic sidebranches arranged in

groups at each of the several acoustic junctions, the sidebranches forming the group at each junction having different fundamental resonant frequencies related one to another
5 as integral multiples and having a common acoustic coupling to the main acoustic conduit at said junction.

18. An acoustic wave filter comprising a main acoustic conduit having acoustic junctions spaced along its length at intervals
10 equal to the wave length of one frequency to be attenuated, and a plurality of closed acoustic sidebranches arranged in groups at each of the several acoustic junctions, the
15 sidebranches forming the group at each junction having different fundamental resonant frequencies of which one corresponds to said frequency to be attenuated and another is an integral multiple thereof, and having
20 a common acoustic coupling to the main acoustic conduit at said junction.

19. An acoustic wave filter comprising a main sound conduit of uniform cross-sectional area, and a plurality of equal acoustic
25 impedances disposed in shunt with and acoustically coupled to the main conduit at intervals along its length equal to two-sevenths the velocity of sound in the medium divided by the major frequency to be attenuated, each of said impedances comprising
30 a pair of closed tubes of uniform cross-sectional area, one of which is half as long as the interval between the side branches and the other is one-quarter of that interval.
35 In testimony whereof I have affixed my signature.

ROLAND B. BOURNE.

40

CERTIFICATE OF CORRECTION.

Patent No. 1,910,672.

May 23, 1933.

ROLAND B. BOURNE.

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction as follows: Page 3, line 79, for "place" read "places"; page 5, line 55, claim 10, for "eccentric" read "concentric"; and that the said Letters Patent should be read with these corrections therein that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 25th day of July, A. D. 1933.

M. J. Moore.

(Seal)

Acting Commissioner of Patents.