Jan. 19, 1943. W. P. MASON 2,308,886

ACOUSTIC WAVE FILTER

Filed Nov. 29, 1940

FIG. 1

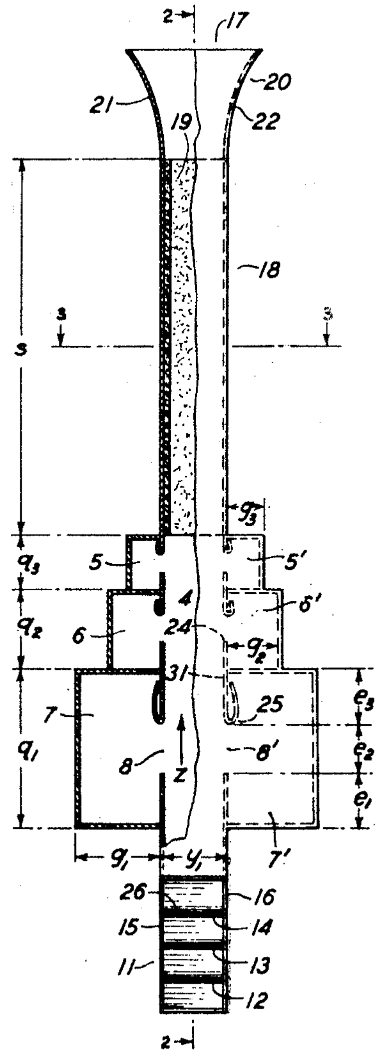


FIG. 2

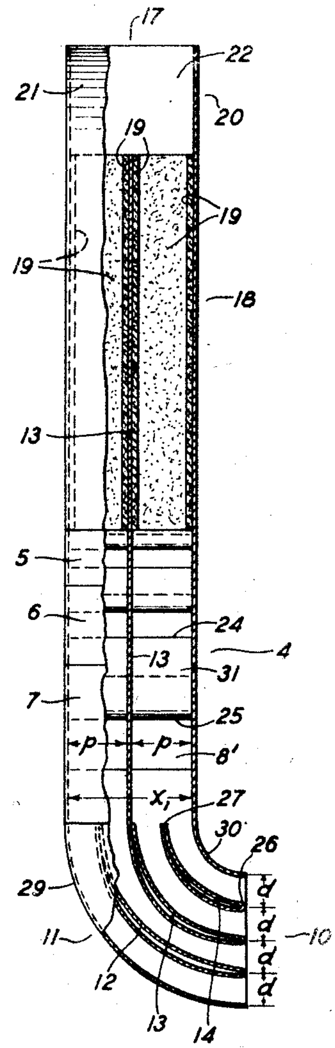
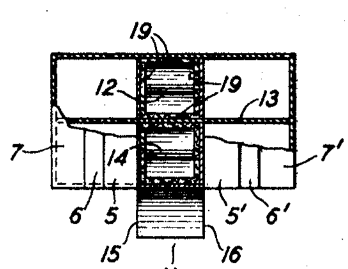


FIG. 3



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ACOUSTIC WAVE FILTER

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18 Claims. (Cl. 181—48)

This invention relates to acoustic wave filters and more particularly to filters of the suppression type adapted to handle a large volume of air.

The principal object of the invention is to suppress a band of objectionable frequencies while permitting the free flow of a large volume of air.

An air conditioning installation usually includes a blower to provide a forced circulation of air in the room to be conditioned. The blower may be arranged either to force air into the room or to withdraw air from the room. In either case it is desirable to introduce an acoustic wave filter between the blower and the air duct communicating with the room in order to suppress the objectionable audible frequencies set up by the blower. If a large room is being conditioned the filter must be capable of effectively suppressing the noise while permitting the substantially unrestricted flow of a large volume of air per unit of time.

The acoustic wave filter of the present invention is a simple and efficient device suitable for the purpose indicated. The filter comprises a main conduit, preferably of rectangular cross-section, and one or more pairs of side branches arranged to form a symmetrical structure about a central longitudinal plane. For proper functioning of the filter only plane waves of the frequencies to be suppressed are permitted to reach the openings into the side branches. To accomplish this the width dimension of the main conduit is limited to a wave-length λ_0 corresponding to the highest frequency f_0 to be suppressed in the sections of the filter with which the side branches are associated. For the same reason the main conduit is divided in the direction of its depth by one or more partitions which are parallel to the width dimension and are spaced apart by a distance not exceeding λ_0. These partitions are preferably extended into and all the way across the side branches.

If the air entering the filter has an unsymmetrical particle velocity, as may be the case when the filter is fed by a blower, the cross-partitions at the input end of the main conduit preferably have a spacing which does not exceed a half wave-length, that is, $\frac{1}{2}\lambda_0$. The half-wave spacing of the partitions may also be advantageously employed in any curved sections of the main conduit. The partitions are given the same curvature as the sides of the conduit and are placed parallel to them. Furthermore, if the filter is unbalanced in structure, that is, if one side branch of each pair is omitted, the cross-partitions should have the half-wave spacing throughout the entire length of the main conduit, and also, preferably, in the side branches.

The different pairs of side branches preferably have different lengths so that they will have different frequencies of resonance. These resonances determine the frequencies of maximum attenuation for the filter sections and they are so chosen that they all fall below f_0 and are spaced for maximum sustained attenuation in the band to be suppressed.

The spacing between the successive openings into the side branches and the longitudinal dimensions of the side branches determine the lower cut-off of the filter, that is, the lowest frequency which will be attenuated. For the most efficient use of space the side branches occupy the full length of the main conduit, that is, a preceding branch abuts against the next succeeding one.

All of the partitions in the filter parallel to the direction of the air flow are preferably made rounded on the ends toward the flow and sharp on the ends from which the air leaves. For some of the partitions, especially those serving as guides in curved sections of the main conduit, the streamlining may advantageously be carried further. For most efficient results the openings into the side branches preferably constitute approximately one-third of the cross-sectional area of the side branch. To improve the suppression of undesired frequencies higher than f_0 the main conduit may be extended at one end and lined with sound absorbing material such, for example, as felt or glass wool. To provide an impedance match between the filter and its load the discharge end of the main conduit may be flared by curving one or both pairs of sides outwardly.

The nature of the invention will be more fully understood from the following detailed description and by reference to the accompanying drawings, in which like reference characters represent like or similar parts and in which:

Fig. 1 is an elevation, partly in section, of an acoustic wave filter in accordance with the invention;

Fig. 2 is a plan view of the filter of Fig. 1, partly in section, along the line 2—2; and

Fig. 3 is a sectional view along the line 3—3 of Fig. 1, with parts of the side branches broken away.

As shown in the views of Figs. 1, 2 and 3 the acoustic wave filter of the invention comprises a main conduit 4 of rectangular cross-section extending from one end to the other and a number of pairs of side branches 5, 5′, 6, 6′ and 7, 7′. The two branches of each pair are arranged opposite to each other to form a balanced structure. The side branches are closed chambers communicating with the main conduit 4 by means of openings such as 8 and 8′.

At the intake end 10 of the filter the main conduit 4 is extended in the form of a curved section 11 which describes a 90 degree angle. The section 11 has a number of partitions 12, 13 and 14 which extend from one side 15 to the other side 16 and are parallel to the curved sides 29 and 30.

At the discharge end 17 the main conduit 4 is extended in a section 18 lined internally with a layer of sound absorbing material 19 to increase the suppression of the higher frequencies. The section 18 terminates in an end portion 20 which has flaring sides 21 and 22 designed to match the impedance of the filter to that of the load. The partition 13 is extended through the main conduit 4, including the section 18, and all the way across the side branches 5, 5′, 6, 6′, 7 and 7′. Each side of the partition 13 within the section 18 is also covered with a layer of sound absorbing material 19. The layer 19 may, for example, be felt, glass wool or other suitable material and may have a thickness of perhaps one inch. The walls and partitions of the filter may be made of any suitable metal and may be welded, soldered or otherwise secured at the joints.

Some design considerations to be observed in dimensioning the filter will now be taken up. It is known that the side branches of an acoustic filter will function properly only when a plane wave alone is propagated down the main conduit. The conditions necessary to insure only a plane wave in a conducting tube of rectangular cross-section will now be considered. The first case of interest is the one in which the air has an unsymmetrical particle velocity.

The equation of motion for any type of sinusoidal air waves passing through a conduit of rectangular cross-section is

$$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}+\frac{\partial^2\phi}{\partial z^2}+\frac{\omega^2\phi}{c^2}=0 \qquad (1)$$

where ϕ is the velocity potential, ω is 2π times the frequency f, c is the velocity of sound in air and x, y and z are the rectangular coordinates. It is assumed that the sides of the channel are closed in the x and y directions and that the x dimension is equal to $2a$ and the y dimension to $2b$. For waves to be propagated along the z direction the necessary conditions are that the particle velocities at the side walls along the x and y directions be zero. As expressed mathematically

$$\dot{x}=-\frac{\partial\phi}{\partial x}=0 \text{ when } x=\pm a \qquad (2)$$

$$\dot{y}=-\frac{\partial\phi}{\partial y}=0 \text{ when } y=\pm b \qquad (3)$$

A solution of Equation 1 which satisfies Equations 2 and 3 is

$$\phi=\left[\sum_{n=0}^{\infty}\sum_{m=0}^{\infty}A_{m,n}\cos\sqrt{\frac{\omega^2}{c^2}-\frac{\pi^2}{4}\left(\frac{n^2}{a^2}+\frac{m^2}{b^2}\right)}\,z+\sum_{n=0}^{\infty}\sum_{m=0}^{\infty}B_{m,n}\sin\sqrt{\frac{\omega^2}{c^2}-\frac{\pi^2}{4}\left(\frac{n^2}{a^2}+\frac{m^2}{b^2}\right)}\,z\right]\cos\frac{n\pi(x+a)}{2a}\cos\frac{m\pi(y+b)}{2b} \qquad (4)$$

The fact that this equation satisfies Equations 1, 2 and 3 may be verified by differentiation.

For the plane wave case, when $A_{m,n}=B_{m,n}=0$ if m and n are not zero,

$$\phi=A_{o,o}\cos\frac{\omega}{c}z+B_{o,o}\sin\frac{\omega}{c}z \qquad (5)$$

Such a wave will be transmitted along the conduit without attenuation.

For the next simplest case, when $m=1$ and $n=0$.

$$\phi=A_{1,0}\cos\sqrt{\frac{\omega^2}{c^2}-\frac{\pi^2}{4b^2}}\,z+B_{1,0}\sin\sqrt{\frac{\omega^2}{c^2}-\frac{\pi^2}{4b^2}}\,z \qquad (6)$$

In Equation 6 it is apparent that if

$$\frac{\omega}{c}<\frac{\pi}{2b} \qquad (7)$$

the value of the expression under each of the radicals is negative and therefore the square root is imaginary. This represents a wave which is attenuated as it is propagated through the conduit. The other values of m and n represent more complicated wave forms which will be attenuated to a higher frequency in the conduit.

In expression (7) if y_1, the width of the conduit in the y direction, is substituted for $2b$ and $2\pi f_0$ is substituted for ω there is obtained

$$y_1<\frac{c}{2f_0}=\tfrac{1}{2}\lambda_0 \qquad (8)$$

where λ_0 is the wave-length corresponding to the frequency f_0. The rule to be deduced from expression (8) is that, for the unsymmetrical case, if the width y_1 of the main conduit is kept less than $\tfrac{1}{2}\lambda_0$ then all waves of frequency f_0 or lower permitted to pass through the conduit will be plane waves. Since plane waves only are properly attenuated by the side branches of the filter it follows that f_0 is the highest frequency which can be successfully suppressed by the filter in the sections including the side branches.

An unsymmetrical case would be presented if half of the side branches, for example branches 5, 6 and 7, were omitted. In this case the dimension y_1 should be half a wave-length. Another unsymmetrical case occurs where the direction of the air flow is changed, as in section 11. Here the partitions 12, 13 and 14 are spaced apart a distance d equal to $\tfrac{1}{2}\lambda_0$.

The symmetrical case will now be considered. The filter as shown represents such a case, since the side branches occur in oppositely disposed pairs. The half-wave spacing of the partitions 12, 13 and 14 assures only plane waves leaving the section 11. The side branches, however, set up particle velocities in the y direction, for the pressure wave causes air to flow into the side branches. However, due to the balanced construction of the side branches, the direction of flow has a plane of symmetry down the center and therefore any parasitic wave set up by the side branch must have an opposite flow on the two sides.

The waves involving $m=1$ will have a particle velocity in the y direction given by

$$\dot{y}=-\frac{\partial\phi}{\partial y}=k\frac{\sin\pi(y+b)}{2b} \qquad (9)$$

and therefore between the limits $y=-b$ and $y=+b$ the flow will be all in one direction and will not reverse. The lowest order term with the zero velocity in the center is $m=2$. For this case,

$$\dot{y}=-\frac{\partial\phi}{\partial y}=k\frac{\sin 2\pi(y+b)}{2b} \qquad (10)$$

which represents a wave with opposite particle velocities on the two sides. The symmetrical flow into the side branches will tend to set up such a wave in the main branch which will not be attenuated by other side branches. However, from an equation similar to (6) it may be shown that this wave will be attenuated rapidly as it passes along the main branch provided the dimension y_1 is less than a wave-length for the frequency f_0, that is,

$$y_1 < \frac{c}{f_0} = \lambda_0 \tag{11}$$

A comparison of expressions (8) and (11) shows that for the symmetrical case the dimensioning may be twice that for the unsymmetrical case.

The depth or x dimension of the main conduit may have any value and in practice is chosen to permit the passage of the required volume of air through the filter. However, if the dimension x_1, as shown in Fig. 2, exceeds a wave-length λ_0 it is advisable to insert one or more partitions, such as **13**, running the full length of the main conduit and preferably extending into the side branches. These partitions are spaced apart a distance p which does not exceed a wave-length λ_0. In the example shown,

$$x_1 = 2p = 2\lambda_0 \tag{12}$$

However, it is to be understood that in general

$$x_1 = h\lambda_0 \tag{13}$$

where h is any integer, in which case there will be $(h-1)$ partitions required.

The opening into the main branch, such as **8'** for the side branch **7'**, preferably extends for approximately one-third of the width of the branch and is centrally located. Thus, as shown in Fig. 1, the dimensions e_1, e_2 and e_3 are all equal. If the opening is smaller than this the air encounters too high a resistance in flowing into and out of the side branch, and if the opening is larger the pressure is not sufficiently uniform over the opening. In either case the efficiency of the filter is impaired. The portions, such as **31**, of the main conduit forming the openings into the side branches are preferably made comparatively sharp on the side nearer the discharge end of the filter, as shown in Fig. 2 at **24**, and rounded on the side nearer the intake end, as shown at **25**.

In order to impede the air flow as little as possible the guides **12**, **13** and **14** are preferably streamlined to a certain extent. As shown in Fig. 2 the outer end **26** is made rounded and the inner end **27** is comparatively thin. Each guide may be made from a single sheet of metal doubled back upon itself and formed in the shape shown.

If a number of pairs of side branches are used, as shown in Fig. 1, each pair is preferably given a different length from the other pairs so that the various pairs will have different frequencies of resonance, all falling below f_0. For example, the branch **7** may have a length g_1 and a resonance at f_1, branch **6** a length g_2 and a resonance at f_2 and branch **5** a length g_3 and a resonance at f_3. The frequences f_1, f_2 and f_3 are chosen to provide the maximum sustained attenuation over the frequency range below f_0 which is to be suppressed. Since the side branches occupy all available space along the sides of the main conduit **4** the distances q_1, q_2 and q_3 which the branches **7**, **6** and **5**, respectively, extend along the main conduit **4** determine the lowest frequency which will be suppressed by the filter. The longer these dimensions are made the lower will be the lower cut-off of the filter. The branches **5'**, **6'** and **7'** are similar, respectively, to the branches **5**, **6** and **7**. The principles to be followed in designing the side branches are more fully discussed in Patent 1,692,317 to G. W. Stewart issued November 20, 1928, and in my prior Patent 1,874,326 issued August 30, 1932.

The frequencies above f_0 will not be attenuated by the sections of the filter which include the side branches but they will be attenuated to a considerable extent in the extension **18** of the main conduit which is divided by the partition **13** and lined throughout with a layer of sound absorbing material **19** as already mentioned. The longer the dimension s is made the greater will be the suppression of the frequencies above f_0.

As a specific example suitable dimensioning for a filter meet a certain set of requirements will be given. It is assumed that the filter is to carry 3430 cubic feet of air per minute and that the principal attenuation band is to extend from 200 to 1760 cycles per second. The velocity of sound in air is taken as 1100 feet per second. The width dimension y_1 of the main conduit **4** is equal to one wave-length at the frequency $f_0=1760$, and from expression (11) is found to be

$$y_1 = \lambda_0 = \frac{c}{f_0} = \frac{1100 \times 12}{1760} = 7.5 \text{ inches}$$

The depth dimension x_1 of the main conduit is chosen as two wave-lengths and therefore

$$x_1 = 2\lambda_0 = 15 \text{ inches}$$

The spacing p between the central partition **13** and each of the side walls of the main conduit **4** is equal to a wave-length and therefore

$$p = \lambda_0 = 7.5 \text{ inches}$$

In accordance with expression (8) the guides **12**, **13** and **14** in section **11** have a half wave-length spacing, and therefore

$$d = \tfrac{1}{2}\lambda_0 = 3.75 \text{ inches}$$

The frequencies of resonance for the side branches **7**, **6** and **5** are chosen, respectively, as

$$f_1 = 250 \text{ cycles per second}$$
$$f_2 = 360 \text{ cycles per second}$$
$$f_3 = 455 \text{ cycles per second}$$

giving the following lengths for the side branches:

$$g_1 = 10 \text{ inches}$$
$$g_2 = 6 \text{ inches}$$
$$g_3 = 4 \text{ inches}$$

Since the lowest frequency to be attenuated is 200 cycles per second the following are suitable longitudinal dimensions for the side branches:

$$q_1 = 18 \text{ inches}$$
$$q_2 = 9 \text{ inches}$$
$$q_3 = 6 \text{ inches}$$

The side branch **7'** has an opening **8'** equal to one-third of its longitudinal dimension q_1 and therefore

$$e_1 = e_2 = e_3 = \tfrac{1}{3}q_1 = 6 \text{ inches}$$

A suitable length s for the high frequency section **18** of the main conduit is 42 inches.

Although the sections of the filter which include the side branches are designed to provide an attenuation band extending only from 200 to

1760 cycles per second, the high frequency section 18 will furnish enough attenuation at frequencies above 1760 cycles so that all frequencies between 200 and 8000 cycles are effectively suppressed by the filter structure as a whole.

If a filter with greater air carrying capacity is required it is only necessary to extend the depth dimension x_1 in increments equal to p and to provide the required number of partitions such as 13 with a spacing not exceeding p. It is to be understood that, in practice, any one or all of the dimensions may vary somewhat from those given. Also, if a different frequency band is to be suppressed, the dimensions should be changed accordingly. The dimensions given for y_1, p and d are the maximum permissible for the conditions assumed, and provide the most efficient use of material. These dimensions may, of course, be smaller and the filter will still function to suppress the required band, but the air capacity will be correspondingly reduced.

What is claimed is:

1. An acoustic wave filter for suppressing a band of frequencies comprising a main conduit of rectangular cross-section and a pair of oppositely disposed side branches connected to said main conduit, said side branches having a frequency of resonance which falls within the band of frequencies to be suppressed, the depth of said main conduit being greater than λ_0, said main conduit being divided by longitudinal partitions parallel to the width dimension and the spacing of said partitions not exceeding λ_0.

2. An acoustic wave filter for suppressing a band of frequencies comprising a main conduit of rectangular cross-section and a pair of oppositely disposed side branches connected to said main conduit, said side branches having a frequency of resonance which falls within the band of frequencies to be suppressed, said main conduit having a curved section which includes therein guide partitions disposed parallel to the curved sides of said section and the spacing of said partitions not exceeding ½ λ_0.

3. An acoustic wave filter for suppressing a band of frequencies comprising a main conduit of rectangular cross-section and a pair of oppositely disposed side branches connected to said main conduit, said side branches having a frequency of resonance which falls within the band of frequencies to be suppressed, and a portion of said main conduit being lined with a layer of sound absorbing material.

4. An acoustic wave filter for suppressing a band of frequencies comprising a main conduit of rectangular cross-section and a pair of oppositely disposed side branches connected to said main conduit, said side branches having a frequency of resonance which falls within the band of frequencies to be suppressed, and each of said side branches communicating with said main conduit through an opening the area of which is equal to approximately one-third of the cross-sectional area of the side branch.

5. An acoustic wave filter for suppressing a band of frequencies comprising a main conduit of rectangular cross-section, a pair of oppositely disposed side branches connected to said main conduit, and longitudinal partitions extending across said main conduit parallel to the width dimension, neither the width of said main conduit nor the spacing of said partitions exceeding the wave-length λ_0 corresponding to the highest frequency to be suppressed.

6. An acoustic wave filter in accordance with claim 5 in which said partitions extend into and divide said side branches.

7. An acoustic wave filter in accordance with claim 5 in which said main conduit has a curved section and guide partitions disposed parallel to the curved sides of said section are inserted therein, the spacing of said partitions not exceeding ½ λ_0.

8. An acoustic wave filter in accordance with claim 5 in which a portion of said main conduit is lined with a layer of sound absorbing material.

9. An acoustic wave filter in accordance with claim 5 in which each of said side branches communicates with said main conduit through an opening the area of which is equal to approximately one-third of the cross-sectional area of the side branch.

10. An acoustic wave filter in accordance with claim 5 which includes a second pair of oppositely disposed side branches connected to said main conduit, said two pairs of branches having frequencies of resonance which differ from each other but fall within the band of frequencies to be suppressed.

11. An acoustic wave filter for suppressing a band of frequencies comprising a main conduit of rectangular cross-section, a plurality of pairs of oppositely disposed side branches connected to said main conduit, longitudinal partitions extending across said main conduit and into said side branches, neither the width of said main conduit nor the spacing of said partitions exceeding the wave-length λ_0 corresponding to the highest frequency to be suppressed, said pairs of branches having frequencies of resonance which are all different but all of which fall within the band of frequencies to be suppressed, and a portion of said main conduit being lined with a layer of sound absorbing material.

12. An acoustic wave filter in accordance with claim 11 in which said main conduit has a curved section and guide partitions disposed parallel to the curved sides of said section are inserted therein, the spacing of said partitions not exceeding ½ λ_0.

13. An acoustic wave filter in accordance with claim 11 in which each of said side branches communicates with said main conduit through an opening the area of which is equal to approximately one-third of the cross-sectional area of the side branch.

14. An acoustic wave filter in accordance with claim 11 in which said main conduit at one end gradually flares to a larger cross-sectional area.

15. An acoustic filter for suppressing a band of frequencies comprising a main conduit of rectangular cross-section and a pair of oppositely disposed side branches connected to said main conduit, the width of said main conduit being approximately equal to the wave-length λ_0 corresponding to the highest frequency to be suppressed.

16. An acoustic wave filter in accordance with claim 15 in which the depth of said main conduit is greater than λ_0 and said main conduit is divided by longitudinal partitions parallel to the width dimension, the spacing of said partitions being approximately equal to λ_0.

17. An acoustic wave filter in accordance with claim 15 in which the depth of said main conduit is equal approximately to $h\lambda_0$ where h is any integer and said main conduit is divided by $(h-1)$ equally spaced longitudinal partitions disposed parallel to the width dimension.

18. An acoustic wave filter for suppressing a

band of frequencies comprising a main conduit of rectangular cross-section having a straight section and a curved section, a pair of oppositely disposed side branches connected to said main conduit and longitudinal partitions extending across said main conduit parallel to the width dimension, the width of said main conduit being approximately equal to the wave-length λ_0 corresponding to the highest frequency to be suppressed, the spacing of said partitions in said straight section being equal approximately to λ_0 and the spacing of said partitions in said curved section being equal approximately to $\frac{1}{2}\lambda_0$.

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