United States Patent [19]

Wirt et al.

[11] **3,819,007**

[45] **June 25, 1974**

[54] **CONTROLLABLE LAMINAR SOUND ABSORPTIVE STRUCTURE**

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[22] Filed: **Apr. 27, 1973**

[21] Appl. No.: **355,161**

[52] **U.S. Cl.** ..... **181/33 G**, 181/33 D, 181/50, 181/68, 161/68

[51] **Int. Cl.** **E04b 1/82**

[58] **Field of Search** ..... 181/33 G, 33 H, 33 HA, 181/33 HB, 48, 48.50; 161/68

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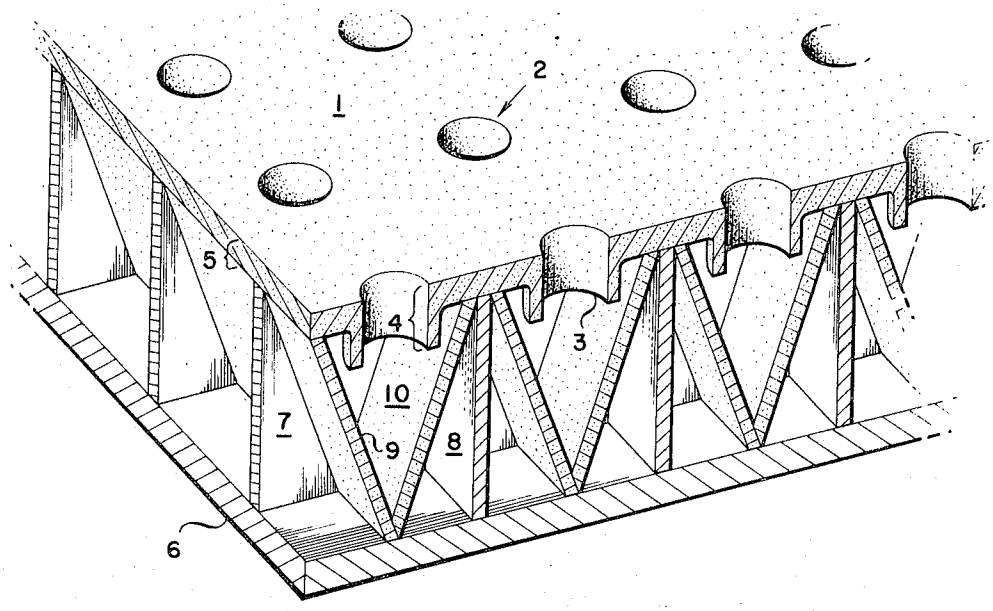
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Assistant Examiner—Vit W. Miska
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[57] **ABSTRACT**

An acoustical facing sheet comprising a permeable member having perforations therethrough and tubular elements extending therefrom on one side in register with said perforations. The structure provides a lumped acoustic impedance having an acoustic resistance proportional to frequency, and an acoustic inertance that is inversely proportional to frequency. It permits the design of highly efficient laminar-type sound attenuating panel structures having an unusually low first resonant frequency without impairing performance at the higher frequencies, and occupying smaller volume than prior devices.

12 Claims, 4 Drawing Figures



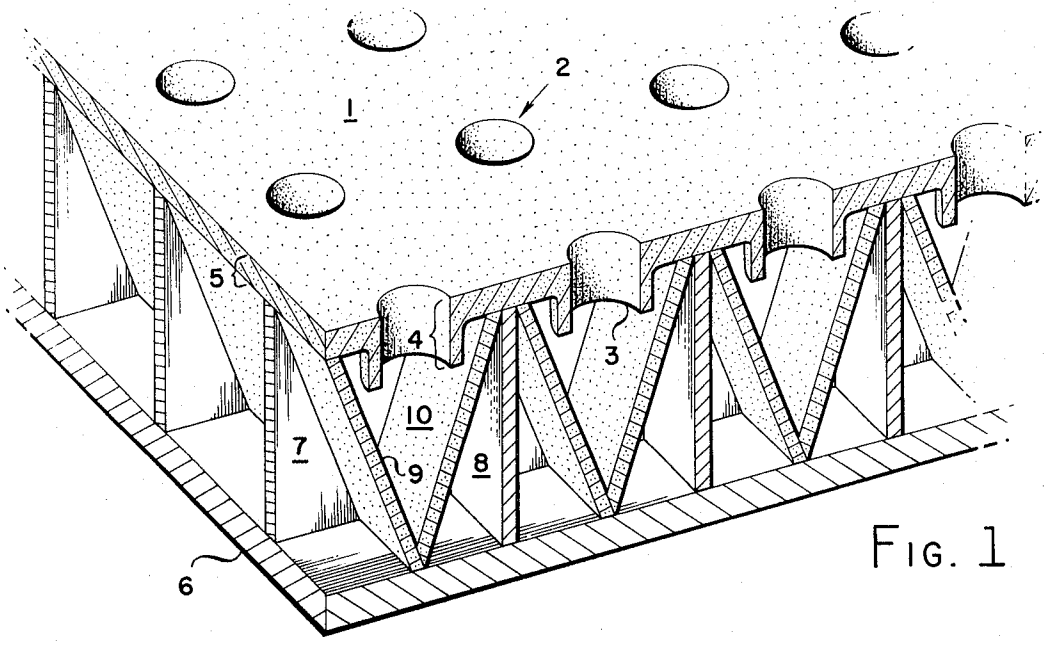


FIG. 1

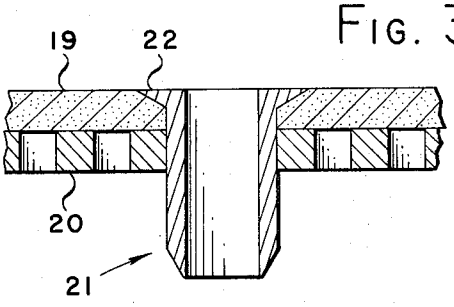


FIG. 3

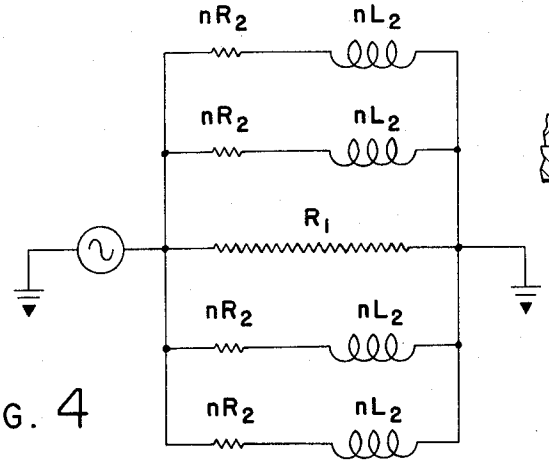


FIG. 4

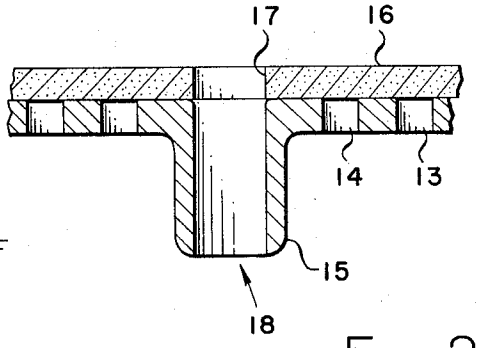


FIG. 2

CONTROLLABLE LAMINAR SOUND ABSORPTIVE STRUCTURE

BACKGROUND OF THE INVENTION

Permeable sheet materials are widely used in the construction of sound absorptive panels. When used as a facing over a compartmented airspace, such materials are known as "laminar absorbers." Such a structure has the property that the resistive component of its acoustic impedance is essentially constant and is not a function of frequency.

It has been discovered from an examination of the solutions to certain wave equations that attenuation in acoustically treated ducts could be singificantly improved if the acoustic resistance of the duct walls were a particular function of the frequency to be attenuated. The optimum value of the resistance starts at a predetermined value at low frequencies and increases uniformly with increasing frequency to within a predetermined value at the maximum frequency of interest. In the case of an aircraft turbine-engine inlet, to attenuate the highest frequency the resistance desired may be eight times the resistance desired to attenuate the lowest frequency. Materials of the prior art have not been able to provide these properties.

Typical laminar sound absorbers of the prior art are disclosed in U.S. Pat. Nos. 3,502,171 to Cowan and 3,507,355 to Lawson. A typical acoustic face sheet is also shown in U.S. Pat. No. 3,700,067 to Dobbs et al. These prior art devices do not yield the desired, previously-discussed, property whereby the resistance component of the acoustic impedance is a desired function of frequency.

SUMMARY OF THE PRESENT INVENTION

There is provided by the present invention an apertured facing sheet in which the resistance component of the acoustic impedance is completely controllable. Thus, it may be tailored to be optimum for any given application. The structure comprises a permeable facing sheet modified by the addition of an array of ducted ports of specified dimensions. This facing, used over any of several types of air-cavity structures, provides a lower tuning frequency without the usual high-frequency rolloff penalty. It closely follows an ideal facing sheet in that it is characterized by a resistance that increases with frequency and a large initial inertance (inductance) that decreases rapidly toward zero as frequency increases.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of a first embodiment showing the facing sheet constructed in accordance with the invention together with a back panel and a cavity-type structure interposed therebetween.

FIG. 2 is a side cross-sectional view of a single collared aperture, constructed in accordance with a second embodiment of the invention.

FIG. 3 is a side cross-sectional view of a third embodiment of the invention.

FIG. 4 is a schematic diagram of an equivalent electrical circuit network, useful in the exposition of the invention.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

Referring to the structure shown in FIG. 1, a typical embodiment comprises a sheet 1 of permeable material having a relatively large flow resistance. Typically the flow resistance is ten times the characteristic impedance of the fluid in which the device is to operate. The permeable sheet 1 may be fabricated from sintered or felted metal, paper, woven or felted fibers, or other similar porous materials. The sheet 1 is provided with regularly-spaced apertures or perforations therethrough, a typical one of which is indicated at 2. Although the exemplary embodiment of FIG. 1 shows a pattern of perforations arrayed in an orthogonal grid, it should be understood that other patterns or even random arrangements of the perforations may be employed. Also, the percentage of open area is a design parameter that may vary over a considerable range. The perforations, whether they be in a straight or staggered line may be of various shapes such as round, square, slotted, or of complex decorative shape. Each perforation (2) is provided with a tubular collar such as shown at 3 which extends from one side of the sheet and in registration with the corresponding perforation. Thus, each straight-through passage in the sheet 1 has an effective length 4 which is considerably greater than the thickness 5 of the sheet 1.

The facing sheet with its integral collared apertures comprises the essence of the invention; however, it should be understood that the invention is especially useful in conjunction with a laminar absorber, or other compartmented airspace type of sound absorber, such as shown in U.S. Pat. No. 3,734,234 entitled Sound Absorption Structure, of common assignee herewith.

FIG. 1 shows the present invention as used in conjunction with the aforesaid compartmented sound absorber. This assembly comprises impermeable backing sheet 6, impermeable wall members (typically such as those indicated at 7 and 8) which divide the device into a plurality of cellular compartments, and oblique permeable partitions 9 and 10 located within a compartment. The structure comprising elements 6–10 has the properties that the resistive component of its acoustic impedance is essentially constant and is not a function of frequency. This is in contradistinction to the property of the present invention wherein the acoustic resistance is proportional to frequency and the acoustic inertance is inversely proportional to frequency.

The acoustical behavior of the above-described assembly may be best understood in terms of its acoustical elements and their electrical analogs. Circuit elements and their acoustic analogs are listed below:

Electrical		Acoustical	Common Symbol
Resistance	~	Resistance	R
Inductance	~	Inertance	L
Capacitance	~	Capacitance	C

The facing sheet 1 may be regarded as a lumped impedance $R+j\omega L$ and the air space (the volume defined by 6–8) as a capacitance. The lumped impedance of the facing sheet and the impedance of the air space are in series and hence are additive. For all ordinary per-

meable facing sheets, R and L are approximate constants, independent of frequency.

There is shown in FIG. 2 a detailed portion of a second embodiment of the invention comprising a perforated structure having 50 percent open perforations in the planar, or sheet portion 12 of the structure. Typical perforations are indicated at 13 and 14. At spaced intervals, a depending hollow collar portion 15 extends downwardly from the bottom face of the sheet portion 12. A porous, or permeable, outer lamina overlies, or is bonded to, sheet portion 12. The outer lamina 16 is provided with apertures, such as the one indicated at 17, which are coaxially aligned with the passage 18 through collar portion 15. The described structural elements are repeated at fixed regular spacings in the manner shown in FIG. 1. The lamina 16 provides part of the desired flow resistance; the remaining part of the flow resistance is provided by sheet portion 12.

There is shown in FIG. 3 an alternative construction which is functionally the equivalent of the structure shown in FIG. 2. This embodiment comprises a two-part laminated sheet comprising flow resistive lamina 19 and 50 percent open perforate lamina 20. A rivet-like hollow tubular element 21 extends through the laminated sheet (19–20) and has its upper flange end 22 flush with the outer surface of lamina 19 and its lower end extending beyond the outer surface of lamina 20. The dependent end of the tubular element 21 may be chamfered as shown in FIG. 3 to permit the element to be driven through the laminated sheet (19–20) by a suitable tool (not shown) in order to install the element. Other suitable manufacturing techniques will be apparent to those versed in the art, it being only necessary that the effective length of the passage through the tubular element be considerably greater than the thickness of the laminated structure through which it extends.

The electrical network analog of an area of the sheet is shown in FIG. 4. A large resistance R_1 is connected in parallel with several other circuit branches. Each of the circuit branches consists of a small resistance, nR_2, in series with an inductance, nL_2, when n is the number of such side branches (per unit area).

The impedance of the nth resistance and inductance is the series combination of the two; therefore:

$$Z_n = nR_2 + j\omega nL_2$$

The inductive side branches are all in parallel so the total impedance of the side branches per unit area is:

$$Z_2 = R_2 + j\omega L_2$$

But, R_1 and Z_2 are also in parallel circuits and thus are combined by adding their admittances:

$$1/Z = 1/R_1 + 1/R_2 + j\omega L_2$$

$$Z = R_1(R_2 + j\omega L_2)/R_1 + (R_2 + j\omega L_2)$$

which, after rationalization, becomes:

$$Z = R + j\omega L = R_1^2 R_2 + R_2^2 R_1 + \omega^2 L_2^2 R_1/(R_1 + R_2)^2 + \omega^2 L_2^2$$

$$+ j\omega L_2 R_1^2/(R_1 + R_2)^2 + \omega^2 L_2^2$$

The trends of the circuit response may be visualized by noting the limiting cases:

$\omega \rightarrow \infty$ and $\omega \rightarrow 0$

Lim $R = R_1 R_2/R_1 + R_2$

$\omega \rightarrow 0$

and if $R_1 >> R_2$

Lim $R = R_2$

$\omega \rightarrow 0$

Lim $R = R_1$

$\omega \rightarrow \infty$

Thus, the resistance is about R_2 at low frequencies and about R_1 at high frequencies. The inductance is also a function of frequency and tends to vanish at high frequency:

Lim $L = L_2 R_1^2/(R_1 + R_2)^2$

$\omega \rightarrow 0$

and for $R_1 >> R_2$

Lim $L = L_2$

$\omega \rightarrow 0$

and for all values of R_1

Lim $L = 0$

$\omega \rightarrow \infty$

By direct analogy, the acoustic resistance of the permeable sheet 1 without the tubular collar 3 (as shown in FIG. 1) corresponds to R_1, the small acoustical resistance in each collared hole corresponds to nR_2 and the acoustic inertance of the mass of air in the tubular passages (3) corresponds to nL_2. Each acoustic resistance, nR_2, is is series with inertance, nL_2. The large acoustic resistance R_1 is in parallel with all the side branches exactly as in the electrical analogy.

Thus, it will be seen that a wide range of variations is possible. For example, in a practical construction permeable sheet materials may be fabricated which actually contain a small series inertance which has been neglected in the above-discussed analysis for the sake of simplicity.

The parallel branches need not be identical to each other. The essence of the invention is the paralleling of acoustic elements in the facing sheet such that the end effect is a resistance which increases with frequency. The decreasing value of net inertance is also a desirable characteristic since it means that, for example, a laminar absorber to be applied as a facing will have an unusually low first resonant frequency, but at higher frequencies the inertance will become small such that the high frequency performance is not impaired. By separately designing R_1, and nR_2, and nL_2, a wide range of characteristics may be obtained.

The value R_1 is controlled by the composition of the permeable sheet per se. The value nR_2 is controlled by the size of the perforations (2) through the sheet (1) and their depth. The value nL_2 is controlled by the size and length of the collared apertures (3). It is preferred that the perforations through the sheet (and their various coaxial passages) be quite closely spaced compared to a wavelength of the highest frequency of interest.

Table I below sets forth comparative test results which illustrate normal incidence sound absorption coefficients, as a function of frequency, obtained for various acoustical facings. The sound absorption coefficients were measured by means of a commercial Bruel and Kjaer Standing Wave Apparatus, using the standard test procedure set forth by ASTM C-384-58. The test specimens were assembled from the following components:

1. Permeable felted metal facing having a through-flow resistance of 100 cgs rayls;

2. A brass tubular collar having an inner diameter of 0.22 inch and a length 0.290 inch; and,

3. An absorptive main body of 1 inch thick fiberglass.

The specimens were assembled into a standard Bruel and Kjaer variable depth specimen holder with the 1 inch deep fiberglass main body absorber being spaced first at ¼ inch from the permeable facing sheet for the first series of tests, and then at 1 inch from the permeable facing sheet for the second series of tests. The 1 inch thick fiberglass material comprises the conventional main body absorber with which the novel facing sheet of the invention cooperates. This is the functional equivalent of the structure comprising elements 6–10.

The following three test configurations are representative of three separate structural designs each intended to provide good low frequency absorption in a limited space. The first design, identified as "Type A," comprises a resistive permeable facing sheet overlaying a main-body absorber, and is typical of acoustical panels such as shown in U.S. Pat. No. 3,712,846. The second design, identified as "Type B," comprises an impermeable facing sheet with spaced apertures therethrough overlying a main-body absorber, and is typical of devices such as shown in U.S. Pat. No. 3,174,580. The third design, identified as "Type C," is constructed in accordance with the present invention.

TABLE I

	2 INCH OVERALL DEPTH			1½ INCH OVERALL DEPTH		
Hz	Type A	B	C	Type A	B	C
100	0.16	0.17	0.11			
125	0.20	0.13	0.14			
160	0.20	0.15	0.10			
200	0.31	0.16	0.23	0.23	—	0.20
250	0.39	0.26	0.30	0.28	0.25	0.24
350	0.50	0.44	0.52	0.32	0.40	0.30
400	0.59	0.86	0.68	0.40	0.64	0.40
500	0.70	0.71	0.88	0.52	0.99	0.58
630	0.80	0.41	0.95	0.71	0.60	0.87
800	0.74	0.24	0.73	0.74	0.32	0.86
1000	0.70	0.20	0.80	0.70	0.24	0.78
1250	0.77	0.21	0.86	0.74	0.22	0.80
1600	0.76	0.14	0.84	0.70	0.19	0.74
2000	0.79	0.08	0.86	0.70	0.12	0.75
2500	0.84	0.10	0.85	0.75	0.13	0.80
3150	0.70	0.05	0.78	0.74	0.09	0.79
4000	0.70	0.13	0.71	0.74	0.13	0.76
5000	0.62	0.11	0.64	0.72	0.14	0.73
6300	0.53	0.09	0.57	0.62	0.11	0.62

PRIOR ART — TYPE A

A 100 rayl resistive facing was placed in front of a fiberglass main-body absorber, to serve as a protective facing and to increase the total acoustic resistance. It is well known, to those skilled in the art, that fiberglass alone will provide a first absorption coefficient maximum near 1,600 Hz where the overall depth of the facing and the main absorber is 2 inches, (or 2,500 Hz where the depth is 1.25 inches), but the lower frequency response can be improved by overdamping with the resistive facing at the expense of the high frequency absorption. In the case of the tests shown in Table I, the heavy damping resulted in absorption coefficients of about 0.75 starting at 500 Hz for the 2 inch depth and 630 Hz for the 1.25 inch depth.

PRIOR ART — TYPE B

An alternate, and well-known, approach to a low frequency problem is the Helmholtz resonator such as shown in U.S. Pat. No. 3,174,580 to Schultz. The resonator contains supplemental resistive material such as fiberglass in the cavity. An example of the large inertance (acoustical inertia) in the collared hole in series combination with the resonator airspace provides a low frequency absorption peak, but results in a nearly total loss of high frequency absorption. This is clearly illustrated in the data of Table I. The absorption spectra consists of single peaks $\alpha = 0.86$ at 400 Hz for the 2 inch depth and $\alpha = 0.99$ at 500 Hz for the 1.25 inch depth. Clearly such prior art design is most useful for the absorption of a single pure tone.

PRESENT INVENTION — TYPE C

The facing sheet structure of the present invention comprises a collared aperture and the resistive facing sheet in acoustically parallel combination. The resulting absorption coefficient spectra, as indicated in Table I, shows a substantial improvement in low-frequency response as compared to the Type-A configuration, and also an improved high-frequency response as compared to either the Type-B configuration or the Type-A configuration. These improvements are equally apparent in the case of either the 2 inch depth or the 1.25 inch depth.

The improved response of the present invention (Type-C) results directly from the fact that it provides both inertance and resistance that vary with frequency in a desirable and useful way. The inertance I of the Helmholtz resonator is constant. As a result, the positive reactance ωI ($\omega = 2\pi f$, f = frequency) increases in direct proportion to frequency. At some value of frequency this reactance cancels the negative reactance of the airspace and creates a resonant response. At all higher frequencies the constantly increasing reactance results in the rapid deterioration of the high-frequency absorption, because the large positive reactance reflects the sound and does not permit it to enter the cavity.

The resistive facing alone broadens the frequency response of the fiberglass by extending it to lower frequencies but can do so only at the expense of higher frequency absorption.

The present invention provides a large value of inertance to move the initial peak downward in frequency. As frequency increases, however, the inertance diminishes smoothly and rapidly such that the high-frequency response is not impaired. The resistance of the present invention asymptotically rises to that of the facing hseet alone as its inertance vanishes. Note in the date of Table I that the absorption coefficients of the Type-C and the Type-A converge at the highest frequency.

In summary, there is provided by the structures shown in FIGS. 1–3, apparatus having broadband absorption extending to moderately low frequencies and for which the allowable space is constrained.

It will be apparent to those versed in the art that various modifications may be made to the representative embodiments of the invention shown and described above.

What is claimed is:

1. An acoustical facing for a laminar sound absorber of the type comprising an array of open-ended resonant compartments, said facing comprising:

a sheet of permeable material through which have been formed a multiplicity of holes, said holes

being smaller than the open ends of said compartments and spaced apart for registration with said open ends; and,

a multiplicity of means for providing a passage which extends from each of said holes into a corresponding compartment of said array.

2. An acoustical facing as defined in claim **1** wherein the material comprising said permeable sheet is characterized by having a finite lumped acoustic impedance which is predominantly resistive.

3. An acoustical facing as defined in claim **1** wherein said passage providing means are characterized by having a lumped acoustic impedance which is partly resistive and partly positive reactive.

4. An acoustical facing as defined in claim **1** wherein the material comprising said permeable sheet is characterized by having a finite lumped acoustic impedance which is predominantly resistive, and wherein said passage providing means are characterized by having a lumped acoustic impedance which is partly resistive and partly positive reactive, and whereby the lumped acoustic impedances of said permeable sheet and said passage providing means are in parallel to the flow of acoustic energy.

5. An acoustical facing as defined in claim **1** wherein said sheet of permeable material comprises:

a first planar lamina of porous material; and

a second lamina, co-planar with said first lamina, having open perforations therethrough.

6. An acoustical facing as defined in claim **5** wherein each of said passage providing means comprises:

an outwardly extending hollow collar integral with said second lamina.

7. An acoustical facing as defined in claim **5** wherein each of said passage providing means comprises:

a hollow tubular element extending through said first and second laminae.

8. An acoustical facing as defined in claim **1** wherein the cross-sectional area of each of said passage providing means is substantially coextensive with the cross-sectional area of its corresponding hole.

9. An acoustical facing as defined in claim **1** wherein the axis of the passage through each of said passage providing means is normal to said sheet.

10. An acoustical facing as defined in claim **1** wherein said holes are of uniform size.

11. An acoustical facing as defined in claim **1** wherein said holes are circular and said passage providing means are cylindrical.

12. An acoustical facing as defined in claim **1** wherein the finite lumped acoustic impedance of said facing, defined as $R + j\omega L$, is a predetermined function of the angular frequency ω such that R increases monotonically with frequency and ωL first increases, and then decreases as frequency increases; where R is the resistive component of said impedance, j is $\sqrt{-1}$, ω is two π times the frequency of interest, and L is the acoustic inertance of said facing.

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