

DESCRIPTION

SOUND BARRIER USING SOUND ABSORBER

5 FIELD

[0001]

The present invention relates to a sound barrier using a sound absorber that can efficiently exert a sound absorbing effect when used indoors or outdoors.

10

BACKGROUND

[0002]

As an example of such a sound absorber, there has already been proposed a sound absorber composed of a sound absorbing material made of a fibrous substance, air permeable protective materials disposed respectively on both sides of the sound absorbing material in stacked relation, and a frame provided around a peripheral edge portion of the air permeable protective materials and the sound absorbing material that are in stacked relation to each other to integrate these three members (see, for example, Patent Literature 1).

20

CITATION LIST

Patent Literature

Patent Literature 1: JP 60-75509 U (see FIG. 1)

25 SUMMARY

Technical Problem

[0004]

According to the configuration of Patent Literature 1 mentioned above, the sound absorber is composed of a number of parts such as the sound absorbing material, the two air permeable protective materials, and the frame, which is disadvantageous in aspects of both assembly work and cost.

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[0005]

Further, the sound absorber is configured to absorb sound by decelerating air particles having a certain velocity energy when the air particles pass through the sound absorbing material and converting the velocity energy into thermal energy. In order to improve the sound absorbing effect of such a sound absorber to some extent, it is required to increase the thickness of the sound absorbing material. This causes an increase in size of the sound absorber as a whole, which is also disadvantageous.

[0006]

In view of the aforementioned circumstances, the present invention aims to solve the problems by providing a sound barrier using a sound absorber capable of reducing its size and the number of parts while having an enhanced sound absorbing effect.

15 Solution to Problem

[0007]

In order to solve the aforementioned problems, the sound barrier of the present invention is characterized by using a sound absorber including a plate member having a rigidity for causing a pressure gradient by generating a sound pressure difference between a front side and a back side around an end edge of the plate member; and a sound absorbing material arranged in the vicinity of the end edge of the plate member, the sound absorbing material being configured to consume a velocity energy of air particles accelerated by the pressure gradient, wherein the sound absorbing material is provided extending outwardly from the end edge of the plate member along a plane direction of the plate member, and at least one of the values of surface density and flow resistance of the sound absorbing material is set lower in an outer portion in a plane direction of the sound absorbing material than in an inner portion in the plane direction of the sound absorbing material.

30 [0008]

According to the configuration of the present invention, the plate

member having a rigidity generates a sound pressure difference between the front side and the back side around the end edge, and the sound pressure difference causes a pressure gradient between the front side and the back side around the end edge. This pressure gradient accelerates air particles. The
5 thus accelerated particles pass through the sound absorbing material. When the particles pass through the sound absorbing material, the velocity energy of the particles is consumed as thermal energy, so that sound is absorbed. In this way, acceleration of air particles causes an increase in thermal energy to be consumed by the sound absorbing material allowing the air particles to pass
10 therethrough. As a result, the sound absorbing effect is significantly enhanced. Moreover, the thinner the plate member, the more the pressure gradient increases. Thus, the sound absorbing effect can be improved dramatically. Furthermore, since sound is absorbed by the plate member and the sound absorbing material arranged in the vicinity of an end edge of the
15 plate member, a sound absorber capable of reducing its size with a reduced number of parts can be achieved. The plate member having a rigidity herein may be any material as long as being capable of generating a sound pressure difference between the front side and the back side around its end edge. Examples thereof include wood and composite paper formed by integrally
20 stacking a plurality of pieces of paper, in addition to various metals. Further, at least one of the values of surface density and flow resistance of the sound absorbing material is set lower in the outer portion in the plane direction of the sound absorbing material than in the inner portion in the plane direction of the sound absorbing material, and thereby the sound insulation effect (sound
25 absorbing effect) can be enhanced more, as compared to a uniform sound absorbing material having the same values of surface density and flow resistance throughout from the inner portion to the outer portion in the plane direction.

[0009]

30 In the sound barrier of the present invention, the sound absorbing material may have a thickness smaller than the thickness of the plate member.

[0010]

In the sound barrier of the present invention, the sound absorbing material may have a thickness decreasing upward.

[0011]

5 In the sound barrier of the present invention, the sound absorbing material may have the same thickness and may be formed into a multi-step shape having a plurality of steps in the up-down direction. In the sound barrier of the present invention, the sound absorbing material may have the same thickness in the up-down direction and may be configured so that, in the
10 up-down direction, the values of surface density and flow resistance are highest in a lower region, the values of surface density and flow resistance are lower in a middle region than in the lower region, and the values of surface density and flow resistance are lowest in an upper region.

15 Advantageous Effects of Invention

[0012]

As described above, according to the present invention, the sound absorber is composed of the plate member and the sound absorbing material arranged in the vicinity of the end edge of the plate member, which enables to
20 provide the sound barrier using the sound absorber capable of reducing its size and the number of parts while having an enhanced sound absorbing effect. Thus, advantages not only in aspects of both assembly work and cost but also in aspects of delivery and handling are achieved.

25 BRIEF DESCRIPTION OF DRAWINGS

[0013]

FIG. 1(a) is a front view of a sound absorber of the present invention, and FIG. 1(b) is a sectional view taken along the line A-A in FIG. 1(a).

FIG. 2 is a rear view of the sound absorber of the present invention.

30 FIGS. 3(a) to 3(g) are each a sectional view showing another sound absorber.

FIG. 4 is an explanatory view to be used for calculating a sound field around a plate member.

FIG. 5 is an explanatory view showing a state where a plane wave is perpendicularly incident on the plate member.

5 FIG. 6(a) is a perspective view showing a particle velocity amplitude in the shaded region of FIG. 5, and FIG. 6(b) is a plan view showing the particle velocity amplitude in the shaded region of FIG. 5 by contour lines.

FIG. 7 is a perspective view showing a sound pressure distribution around an end edge of the plate member.

10 FIG. 8(a) is a perspective view showing the distribution of the sound pressure amplitude around the end edge of the plate member, and FIG. 8 (b) is a plan view showing the same by contour lines.

FIG. 9 is an explanatory view showing an impedance of a cloth or a thin porous sound absorbing layer.

15 FIG. 10 is an explanatory view to be used for calculating a sound field around the cloth.

FIG. 11 is a front view of the sound absorber.

FIG. 12 is a graph showing sound absorption power with respect to frequency.

20 FIG. 13 is an explanatory view showing an example in which the sound barrier is provided between a road and a residential area.

FIG. 14 is an explanatory view used for calculating an attenuation of the sound barrier formed by using the sound absorber.

25 FIG. 15 is a graph showing a particle velocity distribution around the leading edge of the sound barrier.

FIG. 16 is a graph showing an insertion loss caused by the sound barrier.

FIG. 17 is a graph showing measured results and numerical solution of sound absorption power per sound absorber.

30 FIG. 18 is a graph showing the numerical solution and experimental results of insertion loss in the cases of the plate member provided with a cloth

and without the cloth.

FIG. 19 is a graph showing the numerical solution of insertion loss in the cases of the plate member provided with a uniform sound absorbing material and with a gradient sound absorbing material.

5 FIGS. 20(a) to 20(e) are each a sectional view of the upper part of the sound barrier showing various specific examples of the gradient sound absorbing material.

DESCRIPTION OF EMBODIMENTS

10 [0014]

FIGS. 1(a) and 1(b) and FIG. 2 show a sound absorber S. The sound absorber S includes a plate member 1 of square shape, and a sound absorbing material 2 of strip shape provided along each of four end edges of this plate member 1 and extending toward the respective sides away from the end faces.

5 This configuration is composed of four pieces of the sound absorbing material 2, which however may be composed of one piece, two pieces, or three pieces of the sound absorbing material. Further, the plate member 1 may be formed into a rectangular, circular, or elliptical shape, or further a triangular or polygonal shape, other than a square shape. The plate member 1 is configured to have a

10 thickness of 9 mm and dimensions of 0.6 m length $\times$ 0.6 m width. The sound absorbing material 2 in FIG. 1(a) is composed of a strip-shaped member having an upper side of 0.7 m, a lower side of 0.56 m, and a height (width) of 0.07 m, and has a portion overlapping the plate member 1 a length R of which is 0.01 m.

15 [0015]

The plate member 1 is composed of a material having a rigidity for causing a pressure gradient by generating a sound pressure difference between the front side and the back side around each end edge. As a material having a rigidity, wood is used herein. However, any materials can be used, such as

20 various metals and composite paper formed by integrally stacking a plurality of pieces of paper, as long as the material has a rigidity. Examples of such metals include iron, nickel, aluminum, copper, magnesium, and lead, and in addition, an alloy made of two or more of these metals. From the viewpoint of sound absorbing, a material having a surface density of 3 kg/m² or more is sufficient.

25 However, in order to promise advantageous effects to some extent when used as a sound barrier, a material having a surface density of 12 kg/m² or more is preferred.

[0016]

A wooden auxiliary projection 3 in the form of a plate having the same

30 thickness as the plate member 1 is arranged at each of four corners of the plate member 1, while extending toward the side away from the corner. In that

state, a coupling member 4 is arranged extending over the front surface of the plate member 1 and the front surface of each auxiliary projection 3, so that the plate member 1 and the auxiliary projection 3 are coupled and fixed to each other by fixtures 5 such as drawing pins and screws via the coupling member 4.

5 [0017]

The auxiliary projection 3 is provided with a triangular cutout 3A fitted into each corner of the plate member 1 at one end in the longitudinal direction (end on the plate member side) and a triangular projection 3B at the other end in the longitudinal direction (end on the side away from the plate member). A specific one of the auxiliary projections 3 is formed with a hole 3K that allows a string material (which may be a wire, a thread, or the like) 6 for hanging the sound absorber S to pass therethrough. It should be noted that the hole 3K may be formed not only in the one auxiliary projection 3, but also a plurality or all of the auxiliary projections 3. In FIGS. 1 and 2, the sound absorber S is hung in the form of a rhombus with one corner of the square plate member 1 facing upward by the string material 6 passing through the hole 3K that is formed in the one auxiliary projection 3. However, the sound absorber S, for example, may be hung at an angle of 45° from the posture of the sound absorber S of FIG. 1 into the form of a square by opening holes respectively in two auxiliary projections 3 and using two string materials respectively passing through the holes. The posture of the hung sound absorber S can be changed without limitation.

[0018]

Each piece of the sound absorbing material 2 is attached to two adjacent auxiliary projections 3 in the circumferential direction, among the auxiliary projections 3 provided on the plate member 1, while being tensioned therebetween. More specifically, each piece of the sound absorbing material 2, as viewed from the front, is in the form of a substantially inverted trapezoidal strip that is elongated in the left-right direction, and is arranged so as to have a part of its end on the plate member side in the short direction covering the end edge of the plate member 1, as well as having its both ends in the left-right

direction covering the respective parts of the two auxiliary projections 3. The sound absorbing material 2 arranged as above is fixed between the two auxiliary projections 3 by fixtures 7 such as drawing pins and screws. These fixtures 7 may be the same as or different from the fixtures 5.

5 [0019]

As the sound absorbing material 2, a woven fabric or knitted fabric with a surface density of 0.66 kg/m^2 and a flow resistance of 924 Ns/m^3 , for example, is used herein. However, a nonwoven fabric, a porous body made of inorganic fibers such as glass wool and rock wool, or a porous body made of various metal
10 fibers may be used as well.

[0020]

When the sound absorber S configured as above is arranged, for example, in a space where sound is occurring, the plate member 1 having a rigidity is capable of generating a sound pressure difference between the front
15 side and the back side around the end edge of the plate member 1. That is, supposed that a sound source side pressure is occurring on the front side of the plate member 1, the pressure amplitude on the back side, where no sound is occurring, opposite to the sound source side is smaller relative to the pressure amplitude on the front side. Therefore, a sound pressure difference is
20 generated between the front side and the back side around the end edge of the plate member 1, thereby causing a pressure gradient between the front side and the back side around the end edge. This pressure gradient accelerates air particles that transmit sound, around the end edge of the plate member 1. The thus accelerated particles pass through the sound absorbing material 2
25 provided along the end edge of the plate member 1 to be decelerated, thereby allowing velocity energy to be consumed and converted to thermal energy, so that sound is absorbed. In this way, acceleration of air particles causes an increase in thermal energy to be consumed by the sound absorbing material 2 allowing the air particles to pass therethrough. As a result, the sound
30 absorbing effect is significantly enhanced. This also eliminates the need to increase the thickness of the sound absorbing material 2. Moreover, the

thinner the plate member 1 is, the more the pressure gradient increases, so that the sound absorbing effect can be dramatically improved. Thus, the sound absorbing effect can be improved dramatically. Furthermore, sound absorption by the plate member 1 and the sound absorbing material 2 arranged in the vicinity of the end edge of the plate member 1 is enabled, and thus the sound absorber S capable of reducing its size with a small number of parts can be achieved.

[0021]

Next, a description will be made for each of the sound field surrounding the plate member 1 and the sound field surrounding the sound absorbing material 2. First, for the description of the sound field surrounding the plate member 1 that is a thin rigid plate, a method for calculating the sound field surrounding a plate member that is sufficiently thin relative to the wavelength as shown in FIG. 4 will be described. When Φ denotes the velocity potential, where Φ_1 denotes the value on the front side (the side on which the normal line extends) and Φ_2 denotes the value on the back side, among both sides of the plate member 1, since the air particle velocity on the front surface of the plate member 1 in the normal direction is 0, a unit normal vector in terms of $\vec{n}$ is represented by:

$$\frac{\partial \Phi_1}{\partial n} = \frac{\partial \Phi_2}{\partial n} = 0 \quad \text{Formula (1).}$$

In the case of a periodic stationary sound field, the velocity potential at a sound receiving point P is given, in consideration of Formula 1, from the integral formulas of Helmholtz and Kirchhoff by:

$$\Phi(P) = \Phi_D(P) + \frac{1}{4\pi} \iint_F \tilde{\Phi} \frac{\partial}{\partial n} \left(\frac{\exp(ikr)}{r} \right) dS \quad \text{Formula (2),}$$

where $\tilde{\Phi} = \Phi_1 - \Phi_2$ denotes a potential difference between both sides of the plate member 1, $\Phi_D(P)$ denotes direct sound at point P, $r = \overline{PQ}$, $k = \omega/c$ denotes wavenumber, ω denotes angular frequency, and c denotes sound velocity. It should be noted that the time-derivative term $\exp(-i\omega t)$ is omitted

herein.

[0022]

Meanwhile, a formula obtained by differentiating Formula (2) in the direction $\vec{n}_p$ at point P in a space is:

$$\frac{\partial \Phi(P)}{\partial n_p} = \frac{\partial \Phi_D(P)}{\partial n_p} + \frac{1}{4\pi} \iint_F \tilde{\Phi} \frac{\partial^2}{\partial n_p \partial n} \left(\frac{\exp(ikr)}{r} \right) dS \quad \text{Formula (3).}$$

It should be noted that, when ρ denotes air density, the sound pressure p and the particle velocity $\vec{v}$ respectively have the following relationships to the velocity potential Φ :

$$p = \rho \frac{\partial \Phi}{\partial t} = -i\omega \rho \Phi, \quad \vec{v} = -\text{grad} \Phi \quad \text{Formula (4),}$$

$$\text{and the particle velocity in the direction } \vec{n} \text{ is given by: } v_n = -\vec{n} \cdot \text{grad} \Phi = -\frac{\partial \Phi}{\partial n}.$$

In order to obtain the velocity potential $\Phi(P)$ at point P in a space or the

particle velocity component $-\frac{\partial \Phi(P)}{\partial n_p}$ in the direction $\vec{n}$ from Formulas (2) and

(3), the potential difference $\tilde{\Phi} = \Phi_1 - \Phi_2$ between both sides of the plate

member 1, which is an unknown function, is required to be known. For this,

point P is converged to the surface of the plate member 1 (to the limit as close as possible thereto) in Formula (3), and the following formula is obtained:

$$\frac{1}{2} \left\{ \frac{\partial \Phi_1}{\partial n_p} + \frac{\partial \Phi_2}{\partial n_p} \right\} = \frac{\partial \Phi_D(P)}{\partial n_p} + \frac{1}{4\pi} \iint_F \tilde{\Phi} \frac{\partial^2}{\partial n_p \partial n} \left(\frac{\exp(ikr)}{r} \right) dS \quad \text{Formula (5),}$$

where $\vec{n}_p$ denotes the normal line of the surface at point P. Since the plate

member 1 is a rigid plate, the left-hand side is 0, thereby giving the following

integral equation of the first kind (6) in which the velocity potential difference

$\tilde{\Phi}$ between both sides of the plate member 1 is an unknown function:

$$0 = \frac{\partial \Phi_D(P)}{\partial n_p} + \frac{1}{4\pi} \iint_F \tilde{\Phi} \frac{\partial^2}{\partial n_p \partial n} \left(\frac{\exp(ikr)}{r} \right) dS \quad \text{Formula (6).}$$

Integral equation (6) above has a kernel exhibiting very strong singularity

(strongly singular kernel) as follows:

$$\frac{\partial^2}{\partial n_p \partial n} \left(\frac{\exp(ikr)}{r} \right) = \frac{\exp(ikr)}{r^3} \{ [3(ikr - 1) - (ikr)^2] \cos(r, n_p) \cos(r, n) + (1 - ikr) \cos(n_p, n) \}$$

Formula (7).

By numerically solving Integral equation (6) using the Boundary Element Method (BEM) and substituting it into Formulas (2) and (3), the sound field surrounding the plate member 1 (sound pressure and particle velocity) can be obtained.

[0023]

FIGS. 6(a) and 6(b) show an example of the calculated distribution of the particle velocity amplitude $|v|$ within the shaded region in FIG. 5 where a plane wave with an amplitude of 1 at a velocity potential is perpendicularly incident on a rigid flat plate of 1 m $\times$ 1 m. It is understood from FIGS. 6(a) and 6(b) that there is a region in which the particle velocity amplitude is significantly increased in the very vicinity of the end edge of the rigid plate (the plate member 1). This phenomenon of occurrence of high particle velocity amplitude in the vicinity of the end edge is called an edge effect in this description. The reason why the particle velocity amplitude is significantly increased in the vicinity of the end edge (edge) is that the sound pressure gradient is significantly increased in the vicinity of the end edge, as shown in FIGS. 8(a) and 8(b) that illustrate the results of calculating the sound pressure distribution $|p|$ within the dotted portion shown in FIG. 7. High sound absorbing performance is considered to be obtained by placing a sound absorbing material such as a cloth and a thin porous material in the region where the particle velocity amplitude is very large (the region where air particles are very vigorously vibrating) to allow conversion of sound energy into thermal energy through friction of the air particles to the fibers of the cloth, the porous material, or the like. The particle velocity is proportional to the sound pressure gradient.

[0024]

Further, the same idea is possibly employed also to improve the sound insulation performance of sound barriers used in many cases for insulating

sound such as road noise and railroad noise. It is believed that a further sound reduction effect is exerted because of reduction in particle velocity, which is achieved by placing the sound absorbing material such as a cloth and a thin porous material in the vicinity of an end edge. In the case of a rigid

5 semi-infinite flat wall, it is possible to express the velocity potential in the diffraction region behind the sound barrier, as an integral value of the particle velocity distribution in the region above the end edge (edge).

[0025]

Subsequently, a consideration is given to the sound field surrounding

10 the sound absorbing material such as a cloth and a thin porous material. An air permeable cloth or a thin porous sound absorbing layer (hereinafter, the latter is also referred to as a cloth) as shown in FIG. 9 is assumed. When r_s denotes flow resistance, p_1 and p_2 respectively denote sound pressures on both sides of the cloth, and v_s denotes velocity of particles passing through the cloth,

15 the following relationship exists:

$$v_s = -\frac{p_1 - p_2}{r_s} \quad \text{Formula (8).}$$

Further, the cloth itself is also excited by the sound pressure difference $p_2 - p_1$ between both sides. When M_s denotes surface density of the cloth, v_m denotes vibration velocity of the cloth, and $\exp(-i\omega t)$ denotes the

20 time-derivative term, the following formula is obtained:

$$-(p_1 - p_2) = M_s \frac{dv_m}{dt} = -i\omega M_s v_m \quad \text{Formula (9).}$$

Accordingly, the air particle velocity v in the cloth expressed as the sum of the particle velocities of the two, v_s and v_m , is as follows:

$$v = v_s + v_m = -\left(\frac{1}{r_s} - \frac{1}{i\omega M_s}\right)(p_1 - p_2) \quad \text{Formula (10).}$$

25 When $-(p_1 - p_2)/v = Z_r$ is satisfied, the following relationship is obtained:

$$Z_r = -\frac{p_1 - p_2}{v} = \left(\frac{1}{r_s} - \frac{1}{i\omega M_s} \right)^{-1}$$

Formula (11), which leads to:

$$v = -\frac{p_1 - p_2}{Z_r} = \frac{i\omega\rho(\Phi_1 - \Phi_2)}{Z_r}$$

Formula (12).

[0026]

A consideration is given to the sound field as shown in FIG. 10 in the case where the cloth is present in a space. The sound field can be expressed by the direct sound and the velocity potential difference distributed on both sides of the cloth, using Formula (2) and Formula (3), in the same manner as in the plate member 1. However, in the case of the cloth, the relationship of:

$$v = -\frac{1}{2} \left\{ \frac{\partial\Phi_1(P)}{\partial n_p} + \frac{\partial\Phi_2(P)}{\partial n_p} \right\} = -\frac{i\omega\rho}{Z_r} \tilde{\Phi}(P) \quad (P \in F)$$

Formula (13)

is led from Formula (12). Therefore, the border integral equation is as follows:

$$-\frac{i\omega\rho}{Z_r} \tilde{\Phi}(P) = \frac{\partial\Phi_D(P)}{\partial n_p} + \frac{1}{4\pi} \iint_F \tilde{\Phi} \frac{\partial^2}{\partial n_p \partial n} \left(\frac{\exp(ikr)}{r} \right) dS \quad (P \in F)$$

Formula (14).

The sound pressure or particle velocity can be obtained by solving Formula (14) to determine $\tilde{\Phi}$ and substituting it into Formulas (2) and (3).

[0027]

The energy of the sound to be absorbed by the cloth (sound absorbing material) per unit area is calculated from the difference between the energy I_1 passing through the front surface of the cloth (sound absorbing material) and the energy I_2 passing through the back surface thereof. I_1 and I_2 are respectively obtained by the following formulas:

$$I_1 = \frac{1}{4} (p_1^* v + p_1 v^*)$$

Formula (15), and

$$I_2 = \frac{1}{4} (p_2^* v + p_2 v^*)$$

Formula (16).

p_1 and p_2 denote the respective sound pressures on the front surface and the back surface of the cloth (sound absorbing material), v denotes particle velocity, and $*$ denotes complex conjugation. On the entire surfaces of the

cloth (sound absorbing material), it can be determined by integrating them as follows:

$$\begin{aligned}
 & \iint_F |I_a| dS \\
 &= \frac{1}{4} \iint_F |p_1^* v + p_1 v^* - p_2^* v - p_2 v^*| dS \\
 &= \frac{\omega \rho}{4} \iint_F |\tilde{\Phi}^* v + \tilde{\Phi} v^*| dS
 \end{aligned}$$

Formula (17),

where $I_a = I_1 - I_2$, and $p_1 - p_2 = -i\omega\rho\tilde{\Phi}$.

[0028]

As the sound absorber S of the present invention has been described above, on the basis of the considerations on the sound field surrounding the plate member 1 and the sound field surrounding the sound absorbing material 2, particles vibrate extremely vigorously in the region in the vicinity of the end edge (edge) of the plate member 1 that is a thin rigid plate. A significant sound absorbing effect is expected by placing, in such a region, a sound absorbing material such as a cloth and thin porous sound absorbing material that does not much disturb the particle velocity distribution and thereby allowing conversion of sound energy into thermal energy through friction of air particles to the fibers of the sound absorbing material. It should be noted that the friction resistance is considered to be proportional to the particle velocity. FIG. 11 shows an example of the sound absorber S to which such a principle is applied.

[0029]

FIG. 12 shows the randomly incident sound absorption power of the sound absorber S shown in FIG. 11 when provided in a space, as a result of calculation in which Formula (6) and Formula (14) are simultaneously applied. It is seen that, in spite of absorbing only the sound around the end edge (edge), comparatively high sound absorption power is obtained therein. It should be noted that calculation was conducted for two types of the flow resistance rS , 415 Ns/m³ and 830 Ns/m³. The sound absorption coefficient multiplied by the

area may be referred to also as an equivalent sound absorbing area. As has been mentioned above, the sound absorber S is composed of the plate member 1 and the sound absorbing material 2 made of a cloth. The plate member 1 has a square shape with dimensions of 0.9 m $\times$ 0.9 m, and an annular cloth 2 having a width of 0.1 m is arranged along the outer peripheral edges of this plate member.

[0030]

The sound absorber S shown in FIGS. 1(a) and 1(b), and FIG. 2 may be configured as shown in FIGS. 3(a) to 3(g). That is, the sound absorbing material 2 of the sound absorber S shown in FIGS. 1(a) and 1(b), and FIG. 2 is configured to be thinner than the plate member 1, whereas FIG. 3(a) shows the case where the thickness of the sound absorbing material 2 is the same as the thickness of the plate member 1, and FIG. 3(b) shows the case where the thickness of the sound absorbing material 2 is larger than the thickness of the plate member 1 so that the sound absorbing material 2 exceeds the front and back of the plate member 1 to both sides in the thickness direction. Further, FIG. 3(c) shows the case where the thickness of the sound absorbing material 2 is smaller than the thickness of the plate member 1, and FIG. 3(d) depicts a shape provided with a tapered portion 1T in which the plate member 1 is tapered toward the end face side. Further, FIG. 3(e) shows the plate member 1 configured to have a curved surface that is moderately convex toward the left in the figure, and FIG. 3(f) shows the plate member 1 configured to have an end face 1A formed into a curved surface that is convex upward. In FIG. 3(g), the plate member 1 is provided with a narrow portion 1W having a thickness reduced toward the end face side.

[0031]

Meanwhile, FIG. 13 shows a sound barrier W of the present invention using the sound absorber S. The sound barrier W is capable of suppressing propagation of sound, such as driving noise and engine noise of a vehicle C, from the road to residential side, as much as possible, by absorbing sound from the road side. This sound barrier W includes a plate member 10 having a

rigidity for causing a gradient by generating a sound pressure difference around its end edge, so that the sound pressure difference is generated between the front side in an upper part of the roadside surface (referred to as a front surface) 10B of the plate member 10 and the back side opposite to the front side.

5 On the front surface in the lower part of the roadside surface 10B of the plate member 10, a sound absorbing treatment layer 10A is provided. The residential side surface (referred to as a back surface) of the sound barrier W may be a rigid surface, or may be subjected to sound absorbing treatment. A porous sound absorbing layer (which may be composed of a cloth, other than a
10 porous body made of inorganic fibers or a porous body made of various metal fibers) 11 that serves as an upwardly extending sound absorbing material is arranged on the upper end face of the plate member 10. The front side and the back side of the sound absorbing layer 11 are protected with a protective material 12 such as a wire mesh or a perforated metal. A rain cap 13
15 provided on the upper end of the protective material 12. Thus, the sound barrier W is formed.

[0032]

Accordingly, the sound barrier W configured as above is effective to reduce road traffic noise (which is applicable to railroad noise, etc). That is,
20 sound energy of the particles having an accelerated high velocity, which appears in the region in the vicinity of the end edge (edge), is converted into thermal energy by the sound absorbing layer 11, so that the particle velocity is reduced, thereby allowing a reduction in sound pressure within the region on the diffraction side. This can be understood from the example shown in FIG.
25 14 in which attempts are made to calculate the diffracted sound field by providing a cloth in the leading edge portion of the sound barrier (thin rigid semi-infinite flat plate). In the case of a semi-infinite sound barrier, the sound pressure within the region on the diffraction side can be calculated by integration of the particle velocity distribution on a plane extended to the upper
30 part of the sound barrier. Accordingly, a reduction in diffracted sound can be achieved by reducing the high particle velocity in such a region, particularly, in

the vicinity of the end edge (edge).

[0033]

FIG. 15 shows a particle velocity amplitude distribution obtained by calculation, when spherical waves are generated from a sound source position shown in FIG. 14, in an area above the sound barrier provided without a cloth. In the figure, the horizontal axis indicates the upward distance from the leading edge of the sound barrier. It can be seen that the particle velocity amplitude is significantly increased above the sound barrier, in the vicinity of the end edge (edge). The calculation was performed at a position 1 m away from the sound source with an intensity that caused an amplitude of the velocity potential of 1.

[0034]

FIG. 16 shows a result of calculating the attenuation (referred to also as insertion loss) of the level achieved by providing the sound barrier at a sound receiving position on the diffraction side shown in FIG. 14. In the graph, (a) indicates the result in the case of being provided only with the sound barrier, (b) indicates the result in the case of being provided with a cloth having a width of 50 cm along the upper part of the leading edge, (c) indicates the result in the case where the cloth is not provided and the height of the sound barrier is extended to the upper end of the cloth. It should be noted that these calculation results were obtained at 125 Hz, and the cloth had a flow resistance of 830 Ns/m³. These results demonstrate that the effect of the cloth provided therein is more than expected.

[0035]

FIG. 17 is a graph showing the measured results and numerical solution of sound absorption power per sound absorber. The measured results are measured with the sound absorber S shown in FIGS. 1(a) and 1(b), and FIG. 2 being hung in an indoor space. The numerical solution and the measured results almost match each other. Further, as the frequency increases, the sound absorption power also increases, which is particularly effective for sound of high frequency.

[0036]

In recent years, various sound barriers having an improved edge are proposed, most of which however seem to be ineffective for their high cost. There also cannot be found a sound barrier that utilizes an edge effect as described herein. Though being very simple and compact, the present invention is believed to be widely applicable because of good performance, low production cost, ease of installation, etc. Further, the more the area of the plate member 1 that forms the sound absorber S is increased, the sound absorber S can absorb lower frequency sound. Therefore, the area (size) of the plate member 1 can be varied corresponding to the frequency of the sound intended to be absorbed.

[0037]

FIG. 18 is a graph showing numerical solution and experimental results of sound insulation (sound absorption) by the sound barrier. Specifically, a small model of the sound barrier shown in FIG. 14 was produced, and the experimental results and numerical solution (values calculated using Formula (14) above) of insertion loss at a point a specific distance away from the sound barrier are obtained using this model and shown in a graph of FIG. 18. Two walls, that is, a wall composed of a wooden plate member with a thickness of 9 mm and dimensions of 90 cm length $\times$ 180 cm width and a sound barrier provided with a cloth (with dimensions of 5 cm length $\times$ 180 cm width) as a sound absorbing material along the upper end of the plate member, were prepared as the model. The graph of FIG. 18 depicts a polygonal line K1 obtained by plotting the measured results of insertion loss obtained using the aforementioned sound barrier and connecting the plotted points by straight lines, a polygonal line K2 obtained by plotting the numerical solution of insertion loss calculated from Formula (14) on the supposition that the plate member of the sound barrier is a semi-infinite barrier and connecting the plotted points by straight lines, a straight line K10 obtained by plotting the numerical solution of insertion loss calculated from Formula (14) on the supposition that the wall configured to have a height increased such that the

upper end of the wall has the same height as the upper end of the cloth provided on the plate member of the sound barrier is a semi-infinite barrier and connecting the plotted points by straight lines, a polygonal line K11 obtained by plotting the numerical solution of insertion loss calculated from Formula (14) on the supposition that the plate member of the wall is a semi-infinite barrier and connecting the plotted points by straight lines, and a polygonal line K12 obtained by plotting the measured results of insertion loss obtained using the wall and connecting the plotted points by straight lines. The cloth has a surface density of 0.6 kg/m^2 and a flow resistance of 789 Ns/m^3 . The frequency of the measured results plotted herein is the one-tenth value of the frequency employed for measurement of the model.

[0038]

The graph of FIG. 18 shows that the values of the polygonal line K2 are higher than the values of the straight line K10. It can be seen from this that the insertion loss (sound insulation effect) calculated from Formula (14) on the supposition that the plate member of the sound barrier is a semi-infinite barrier is higher than the insertion loss (sound insulation effect) caused by the wall configured to have the same height as the upper end of the cloth of the sound barrier. In contrast, the values of the polygonal line K11 are lower than the values of the straight line K10. It can be seen from this that the insertion loss (sound insulation effect) calculated from Formula (14) on the supposition that the wall is a semi-infinite barrier is lower by the reduced height of the wall than the insertion loss (sound insulation effect) caused by the wall configured to have the same height as the upper end of the cloth of the sound barrier.

Further, the values of the polygonal line K1 and the values of the polygonal line K2 are very close to each other. It is obvious from this that the numerical solution (values of the polygonal line K2) of the insertion loss calculated from Formula (14) on the supposition that the plate member of the sound barrier is a semi-infinite barrier is highly reliable. Further, the values of the polygonal line K11 and the values of the polygonal line K12 are very close to each other. It is obvious from this that the numerical solution (values of the polygonal line

K11) calculated from Formula (14) on the supposition that the wall provided without the cloth is a semi-infinite barrier is highly reliable. The sound insulation effect includes a sound absorbing effect as a part.

[0039]

5 In short, it is obvious from the graph of FIG. 18 that the insertion loss (sound insulation effect) is increased by providing a sound absorbing material (the cloth in FIG. 18) along the upper end of the plate member in the sound barrier. Moreover, the numerical solution of insertion loss determined by calculation is almost equal to the measured results, and is thus highly reliable.

10 [0040]

FIG. 18 shows the case where a higher sound insulation effect is obtained when a cloth having a surface density of 0.6 kg/m^2 and a flow resistance of 789 Ns/m^3 is provided along the upper end of the plate member that forms the sound barrier than when the wall is provided without the cloth.

15 On the other hand, FIG. 19 is a graph showing the result that a sound barrier using a sound absorbing material configured to have a surface density and a flow resistance both of which decrease upward to the upper portion of the sound absorbing material (referred to as a gradient sound absorbing material so as to be distinguished from the uniform sound absorbing material mentioned below) exerts a sound insulation effect that is still higher than a sound barrier using a uniform sound absorbing material having a surface density and a flow resistance which are constant from the lower portion to the upper portion. The graph of FIG. 19 depicts the insertion loss concerning the noise level in motor vehicles (A-weighted sound pressure level), and is plotted according to

20 the numerical solution of insertion loss that is highly reliable, as mentioned above. It should be noted that the uniform sound absorbing material means a sound absorbing material configured to have a surface density and a flow resistance the values of which remain the same throughout from the bottom to the top.

25 [0041]

30 The graph of FIG. 19 depicts a polygonal line H obtained by plotting the

numerical solution of insertion loss calculated on the supposition that the plate member having the same height as the sound barrier provided with the cloth along the upper end of the plate member is a semi-infinite barrier and connecting the plotted points by straight lines, five polygonal lines U1 to U5
5 obtained by plotting the numerical solution of insertion loss calculated on the supposition that the plate member of the sound barrier provided with the uniform sound absorbing material along the upper end of the plate member is a semi-infinite barrier and connecting the plotted points by straight lines, and five polygonal lines G1 to G5 obtained by plotting the numerical solution of
10 insertion loss calculated on the supposition that the plate member of the sound barrier provided with the gradient sound absorbing material along the upper end of the plate member is a semi-infinite barrier and connecting the plotted points by straight lines. Table 1 below shows the numerical solution (dB) of insertion loss corresponding to the distance (m) from the wall. The numerical
15 solution was obtained from Formula (14) described above.

[0042]

Table 1

Sound absorbing material	Distance (m)									
	5	10	15	20	25	30	35	40	45	50
H: Rigid barrier (extended by 0.5 m)	23.6	22.3	21.9	21.7	21.5	21.5	21.4	21.3	21.3	21.3
G3: Surface density 12 kg/m ² , Flow resistance 400 Ns/m ³	27.1	25.8	25.2	24.9	24.8	24.6	24.5	24.5	24.3	24.2
G5: Surface density 24 kg/m ² , Flow resistance 800 Ns/m ³	30.2	28.7	27.9	27.6	27.4	27.2	27.1	27.1	26.9	26.8
G4: Surface density 48 kg/m ² , Flow resistance 1600 Ns/m ³	34.0	32.1	31.0	30.6	30.3	30.0	29.9	29.7	29.5	29.4
G2: Surface density 96 kg/m ² , Flow resistance 3200 Ns/m ³	36.4	33.5	32.2	31.6	31.2	30.9	30.7	30.4	30.3	30.3
G1: Surface density 192 kg/m ² , Flow resistance 6400 Ns/m ³	34.3	31.5	30.4	29.8	29.4	29.2	29.0	28.7	28.7	28.7
U3: Surface density 12 kg/m ² , Flow resistance 400 Ns/m ³	27.1	26.0	25.5	25.3	25.1	25.0	24.9	24.9	24.8	24.7
U5: Surface density 24 kg/m ² , Flow resistance 800 Ns/m ³	29.3	28.0	27.5	27.3	27.0	26.9	26.8	26.7	26.7	26.6
U4: Surface density 48 kg/m ² , Flow resistance 1600 Ns/m ³	29.5	27.9	27.4	27.1	26.9	26.8	26.6	26.5	26.5	26.5
U2: Surface density 96 kg/m ² , Flow resistance 3200 Ns/m ³	27.5	26.0	25.5	25.3	25.0	24.9	24.8	24.7	24.7	24.7
U1: Surface density 192 kg/m ² , Flow resistance 6400 Ns/m ³	25.8	24.4	23.9	23.7	23.5	23.4	23.3	23.2	23.2	23.2

[0043]

The uniform sound absorbing material of the polygonal line U1 has a
5 surface density of 192 kg/m^2 and a flow resistance of 6400 Ns/m^3 . The uniform
sound absorbing material of the polygonal line U2 has a surface density of 96 kg/m^2
and a flow resistance of 3200 Ns/m^3 . The uniform sound absorbing
material of the polygonal line U3 has a surface density of 12 kg/m^2 and a flow
resistance of 400 Ns/m^3 . The uniform sound absorbing material of the
10 polygonal line U4 has a surface density of 48 kg/m^2 and a flow resistance of
 1600 Ns/m^3 . The uniform sound absorbing material of the polygonal line U5
has a surface density of 24 kg/m^2 and a flow resistance of 800 Ns/m^3 .

[0044]

The gradient sound absorbing material of the polygonal line G1 has a
15 surface density of 192 kg/m^2 and a flow resistance of 6400 Ns/m^3 in the lower
end portion of the sound absorbing material, which values are configured to
decrease upward to the upper end so as to be zero or an approximate value of
zero at the upper end. The gradient sound absorbing material of the polygonal
line G2 has a surface density of 96 kg/m^2 and a flow resistance of 3200 Ns/m^3 in
20 the lower end portion of the sound absorbing material, which values are
configured to decrease upward to the upper end so as to be zero or an
approximate value of zero at the upper end. The gradient sound absorbing
material of the polygonal line G3 has a surface density of 12 kg/m^2 and a flow
resistance of 400 Ns/m^3 in the lower end portion of the sound absorbing
25 material, which values are configured to decrease upward to the upper end so
as to be zero or an approximate value of zero at the upper end. The gradient
sound absorbing material of the polygonal line G4 has a surface density of 48 kg/m^2
and a flow resistance of 1600 Ns/m^3 in the lower end portion of the sound
absorbing material, which values are configured to decrease upward to the
30 upper end so as to be zero or an approximate value of zero at the upper end.
The gradient sound absorbing material of the polygonal line G5 has a surface

density of 24 kg/m^2 and a flow resistance of 800 Ns/m^3 in the lower end portion of the sound absorbing material, which values are configured to decrease upward so as to be zero or an approximate value of zero at the upper end.
[0045]

5 The graph of FIG. 19 shows that the values of the polygonal lines U1 to U5 and the values of the polygonal lines G1 to G5 are both higher than the values of the polygonal line H. It can be understood from this that the sound barrier provided with the cloth as a sound absorbing material along the upper end of its plate member exerts more excellent sound insulation effect than the
10 wall provided without such a sound absorbing material. In the graph, the polygonal line G2 shows the highest insertion loss (sound insulation effect). Further, the polygonal lines G1, G2, G4, and G5 except for the polygonal line G3 each show higher values of insertion loss (sound insulation effect) than the polygonal line U5 which has the highest insertion loss (sound insulation effect)
15 among the polygonal lines U1 to U5. Still, the polygonal line G3 shows higher insertion loss (sound insulation effect) than the polygonal line U1, which has the lowest insertion loss (sound absorbing effect) in the graph.
[0046]

 In short, it is obvious from the graph of FIG. 19 that the insertion loss
20 (sound insulation effect) is increased by providing a uniform sound absorbing material along the upper end of the plate member in the sound barrier. Further, it is obvious from the graph of FIG. 19 that the insertion loss (sound insulation effect) is more increased by providing a gradient sound absorbing material, than providing a uniform sound absorbing material, along the upper
25 end of the plate member therein. FIG. 19 shows the cases of five types of gradient sound absorbing materials. However, it can be inferred that the insertion loss (sound insulation effect) is increased by producing a gradient sound absorbing material that has an arbitrary surface density within the range of 12 kg/m^2 to 192 kg/m^2 and an arbitrary flow resistance within the
30 range of 400 Ns/m^3 to 6400 Ns/m^3 in combination.
[0047]

Various specific examples of the sound barrier are described with reference to FIGS. 20(a) to 20(e). The sound barrier W includes the plate member 10 having a rigidity for causing a pressure gradient by generating a sound pressure difference around its end edge, and a gradient sound absorbing material 14, provided along the upper end of the plate member 10, for consuming the velocity energy of air particles accelerated by the pressure gradient. In FIG. 20(a), the gradient sound absorbing material 14 is composed of three types of sound absorbing materials 14A, 14B, and 14C, the thickness of which increases downward. That is, the three sound absorbing materials 14A, 14B, and 14C each having a different thickness are arranged in the up-down direction so that the gradient sound absorbing material 14 has a reduced thickness in its upper part, and thus the gradient sound absorbing material 14 is formed into a multi-step shape having a plurality of steps in the up-down direction. The values of surface density and flow resistance of the sound absorbing material 14A on the lower side are higher than the values of surface density and flow resistance of the sound absorbing material 14B in the middle, that is, one step up from the lower side. The values of surface density and flow resistance of the sound absorbing material 14C on the top are lower than the values of surface density and flow resistance of the sound absorbing material 14B one step down from the top. In FIG. 20(b), the gradient sound absorbing material 14 is formed into a substantially triangular shape having a linearly (or curved) gradient surface so as to have a thickness decreasing upward. The values of surface density and flow resistance of this gradient sound absorbing material 14 gradually decrease upward, so as to be zero or an approximate value of zero at the upper end. With such a configuration, the values of surface density and flow resistance of the gradient sound absorbing material 14 fluctuate linearly (continuously) along the up-down direction, which can eliminate a reduction in sound insulation effect in non-linear portions in the case of non-linear (discontinuous) fluctuation. Thus, effective sound insulation can be achieved. In FIG. 20(c), the gradient sound absorbing material 14 is composed of six sound absorbing materials 14A not only having

the same thickness and the same size but also having the same values of surface density and flow resistance. That is, three of the sound absorbing materials 14A are arranged in layers in the thickness direction on the upper end of the plate member 10, two of the sound absorbing materials 14A are
5 arranged in layers on the upper ends of those three sound absorbing materials 14A, and one of the sound absorbing materials 14A is arranged on the upper ends of those two sound absorbing materials 14A. Also in this case, the gradient sound absorbing material 14 is formed into a multi-step shape having a plurality of steps in the up-down direction. Such an arrangement of the
10 sound absorbing materials allows the values of surface density and flow resistance of the three sound absorbing materials 14A on the lowest step to be highest, and the values of surface density and flow resistance of the one sound absorbing material 14A on the top step to be lowest. In FIG. 20(d), the gradient sound absorbing material 14 is composed of five sound absorbing
15 materials 14A, 14B, and 14C each having the same thickness but a different height (dimension in the up-down direction). That is, the second sound absorbing material 14B that is lower in height than the first sound absorbing material 14C that is highest is arranged on each of both sides in the thickness direction of the first sound absorbing material 14C, and the third sound
20 absorbing material 14A that is lower in height than these second sound absorbing materials 14B is arranged on each of the outer surfaces of the second sound absorbing materials 14B. Also in this case, the gradient sound absorbing material 14 is formed into a multi-step shape having a plurality of steps in the up-down direction. Such an arrangement of the sound absorbing
25 materials allows the thickness of the gradient sound absorbing material 14 to decrease upward, in the order of: the lower side that has the total thickness of five pieces of sound absorbing materials, including two pieces of the third sound absorbing materials 14A, two pieces of the second sound absorbing materials 14B, and one piece of the first sound absorbing material 14C > the middle side
30 that has the total thickness of three pieces, including two pieces of the second sound absorbing materials 14B and one piece of the first sound absorbing

material 14C > the top side that has the thickness of one piece, including one piece of the first sound absorbing material 14C. Accordingly, the values of surface density and flow resistance of the gradient sound absorbing material 14 decrease upward sequentially from the lower side. In FIG. 20(e), the gradient sound absorbing material 14 is configured so that, in the up-down direction, the values of surface density and flow resistance are highest in a lower region 14a, the values of surface density and flow resistance are lower in a middle region 14b than in the lower region 14a, and the values of surface density and flow resistance are lowest in an upper region 14c, though having the same thickness in the up-down direction. The gradient sound absorbing material 14 of FIG. 20(e) is composed, for example, of a sponge or a foamed product, in which the shape or size of pores is determined so that pores formed in the lower region 14a are most closely formed and the flow resistance of the pores in the lower region 14a is highest. In contrast, the shape or size of pores is determined so that pores formed in the upper region 14c are most sparsely formed and the flow resistance of the pores in the upper region 14c is lowest.

[0048]

Although the gradient sound absorbing material 14 is composed of the three sound absorbing materials 14A, 14B, and 14C in FIG. 20(a), the gradient sound absorbing material 14 may be composed of one sound absorbing material. Further, FIGS. 20(a), 20(c), 20(d), and 20(e) show the cases where the values of surface density and flow resistance of the sound absorbing material vary in three steps in the up-down direction. However, the values of surface density and flow resistance may be configured to vary in four or more steps so as to vary almost linearly in the up-down direction. Further, the values of surface density and flow resistance of the gradient sound absorbing material may be configured to vary in two steps in the up-down direction, that is, the values of surface density and flow resistance of the gradient sound absorbing material may be set lower in the upper portion than in the lower portion of the gradient sound absorbing material. When the values of surface density and flow resistance of the gradient sound absorbing material are both set lower in the

upper portion than in the lower portion of the gradient sound absorbing material, the sound insulation effect is further enhanced. However, only either one of the value of surface density or the value of flow resistance may be set lower in the upper portion than in the lower portion of the gradient sound absorbing material.

[0049]

It should be noted that the present invention is not limited to the aforementioned embodiments, and various modifications can be made without departing from the spirit of the present invention.

[0050]

In the aforementioned embodiments, the sound absorbing material 2 is provided almost throughout the entire end edge of the plate member 1.

However, the sound absorbing material 2 may be provided on only a part thereof. Further, the sound absorbing material 2 is arranged so as to cover a part of the end edge of the plate member 1. However, the sound absorbing material 2 may be arranged without covering the end edge of the plate member 1 at all.

[0051]

In the aforementioned embodiments, the sound absorber S may be fixed to the floor, etc., so as to be used as a partition (partition member), in addition to being hung in use.

[0052]

Further, although the sound absorbing material is arranged along the upper end of the plate member in the aforementioned embodiments, the sound absorbing material may be arranged along a lateral end of the plate member. In short, as long as the sound absorbing material is provided extending outwardly from an end edge of the plate member along the plane direction of the plate member, the position to which the sound absorbing material is attached is not particularly limited.

REFERENCE SIGNS LIST

[0053]

1: Plate member

1A: End face

1W: Narrow portion

5 2: Sound absorbing material

3: Auxiliary projection

3A: Cutout

3B: Projection

3K: Hole

10 4: Coupling member

5: Screw

6: String material

7: Screw

10: Plate member

15 10A: Sound absorbing treatment layer

11: Sound absorbing layer

12: Protective material

13: Cap

14: Gradient sound absorbing material

20 S: Sound absorber

W: Sound barrier

CLAIMS

1. A sound barrier using a sound absorber, the sound absorber comprising:
a plate member having a rigidity for causing a pressure gradient by generating a sound pressure difference between a front side and a back side around an end edge of the plate member; and
a sound absorbing material arranged in the vicinity of the end edge of the plate member, the sound absorbing material being configured to consume velocity energy of air particles accelerated by the pressure gradient, wherein
the sound absorbing material is provided extending outwardly from the end edge of the plate member along a plane direction of the plate member; and
at least one of values of surface density and flow resistance of the sound absorbing material is set lower in an outer portion in a plane direction of the sound absorbing material than in an inner portion in the plane direction of the sound absorbing material.
2. The sound barrier according to claim 1, wherein
the sound absorbing material has a thickness smaller than the thickness of the plate member.
3. The sound barrier according to claim 1 or 2, wherein
the sound absorbing material has a thickness decreasing upward.
4. The sound barrier according to claim 1 or 2, wherein
the sound absorbing material has the same thickness and is formed into a multi-step shape having a plurality of steps in the up-down direction.
5. The sound barrier according to claim 1 or 2, wherein
the sound absorbing material has the same thickness in the up-down direction and is configured so that, in the up-down direction, the values of surface density and flow resistance are highest in a lower region, the values of surface density and flow resistance are lower in a middle region than in the lower region, and the values of surface density and flow resistance are lowest in an upper region.