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Savkar et al.

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[45] **July 22, 1975**

[54] **ACOUSTIC ATTENUATOR PROVIDING RELATIVELY HIGH INSERTION LOSS AT LOW FREQUENCIES**

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[21] Appl. No.: **447,953**

Related U.S. Application Data

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[52] **U.S. Cl.** ..... **181/56;** 181/33 HB; 181/63

[51] **Int. Cl.²** **F01N 1/08**

[58] **Field of Search** ..... 181/33 HA, 33 HB, 33 HC, 181/33 HD, 42, 46, 50, 56, 63, 70, 49

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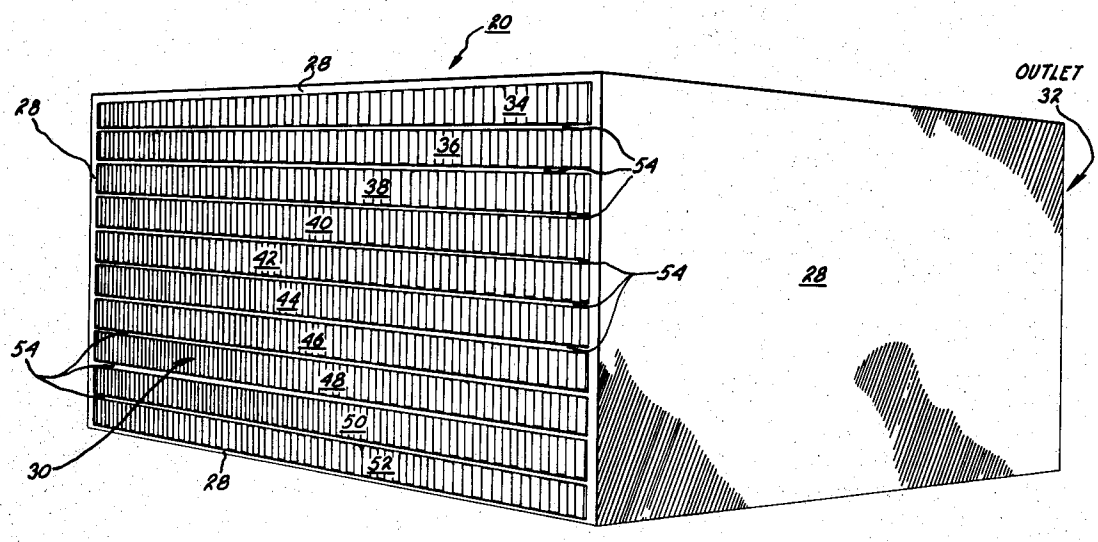
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[57] **ABSTRACT**

A flowing fluid (e.g., air, gas, and water) through which acoustic pressure waves are propagating is passed through an attenuator comprising, in accordance with one embodiment of the invention, multiple parallel longitudinal fluid flow paths wherein the fluid flowing in each longitudinal path successively encounters a number of short, thin, flat plates which are arranged in series and longitudinally spaced along said path. The longitudinal spacing between each plate in series in each path is of sufficient length, as is the length of each plate, to ensure the formation of separate and distinct boundary layer flow regions on each of the plates. Low frequency acoustic pressure waves excite the boundary layer flow regions on the surfaces of each plate in the series so that the boundary layers become oscillatory and are shed from the trailing edges of each plate in the form of oscillatory wakes. The fluid flow character in the oscillatory boundary layers and in the oscillatory wakes is rotational and does not effectively propagate low frequency acoustic pressure waves into the far field. Accordingly, a fraction of the low frequency acoustic energy is repetitively attenuated at each plate in the series by the conversion into a non-acoustic form of energy. Intermediate and high frequency acoustic energies are also attenuated because of such effects as: scattering by the plates; viscous dissipation of the acoustic energies at the surfaces of the plates; and, axial acoustic impedance mismatching enhanced by the formation of separation bubbles at the leading edges of each of the plates.

25 Claims, 17 Drawing Figures



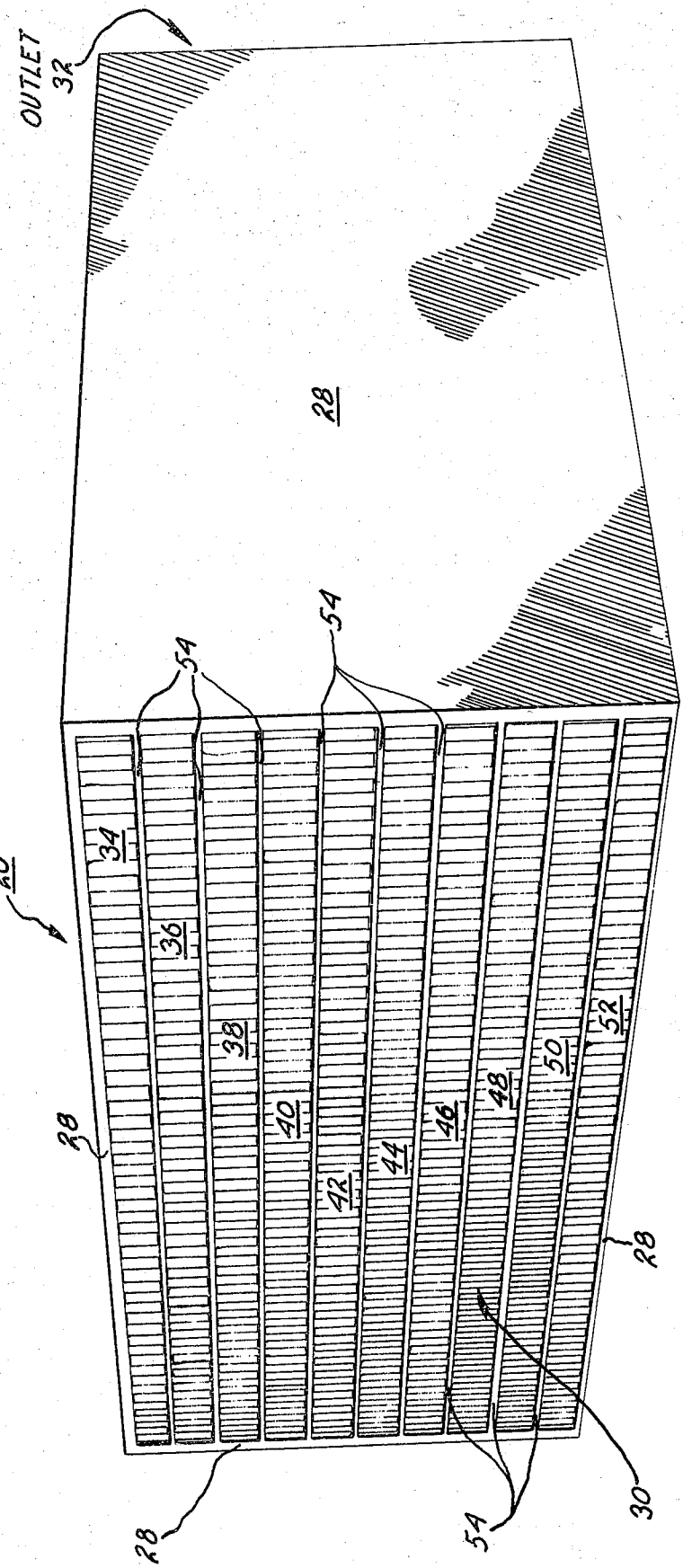


Fig.1

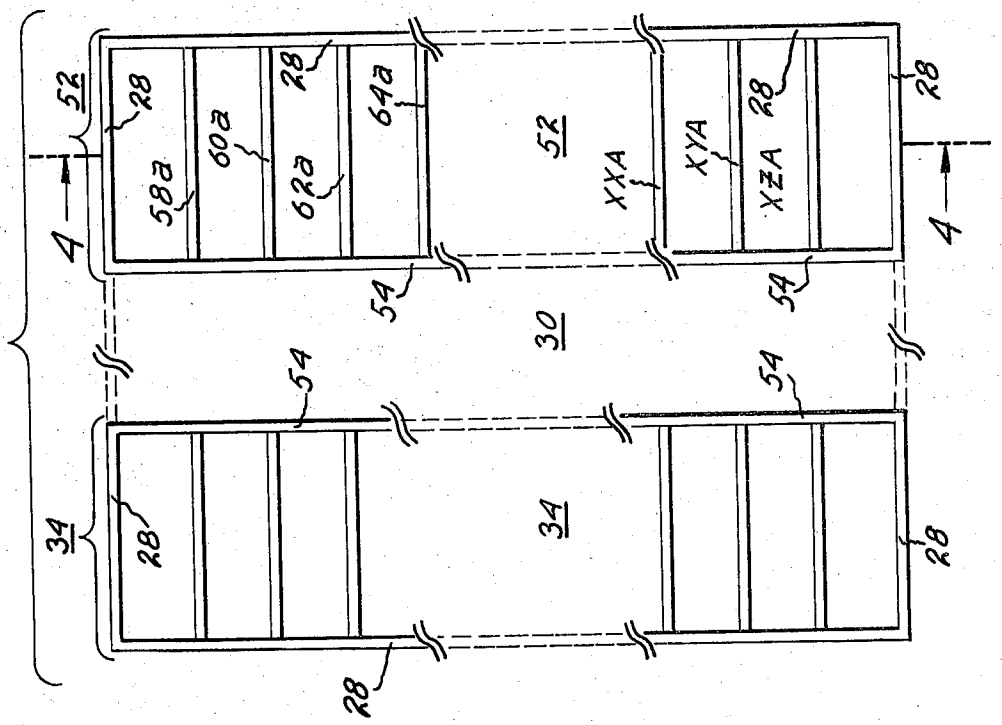

52
28
58a
60a
28
62a
64a
52
XXA
XYA
28
XZA
28
4
4
54
54
30
54
54
34
28
34
28
28

Fig.3

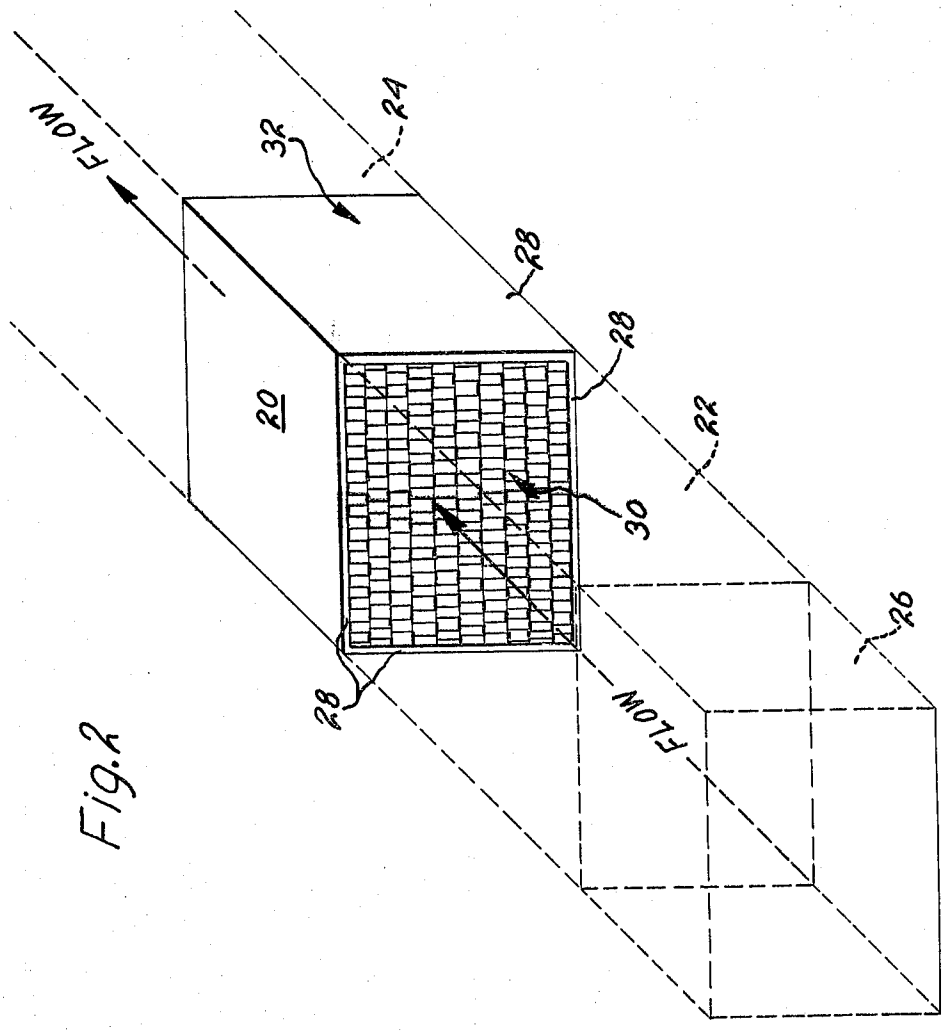

FLOW
32
24
28
28
20
22
30
26
28
FLOW

Fig.2

Fig.5

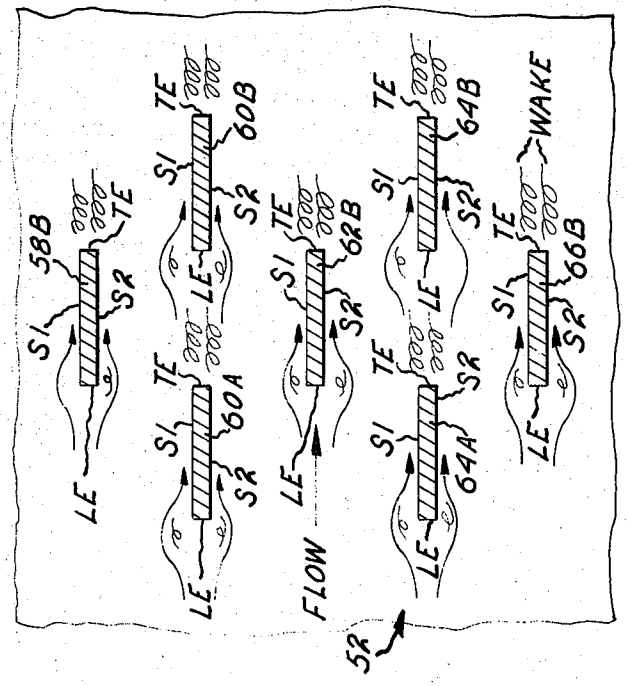

S1
S2
LE
TE
58B
60B
60A
62B
64B
64A
66B
WAKE
FLOW
52

Fig.4

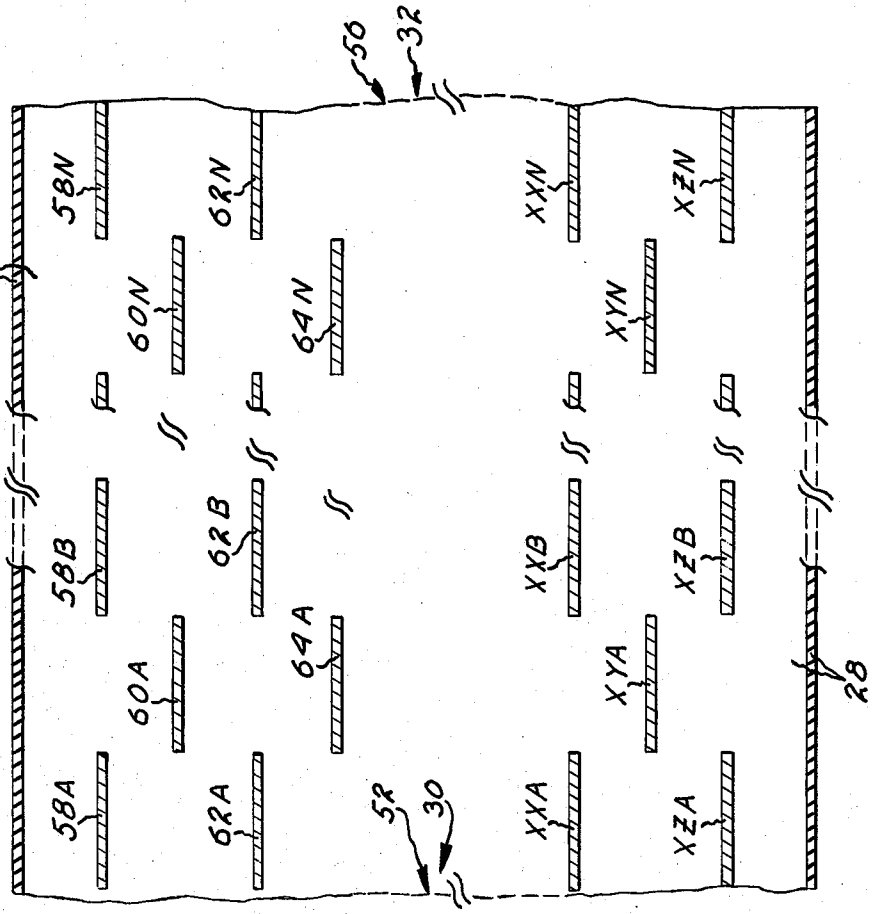

28
58N
60N
62N
64N
XXN
XYN
XZN
58B
62B
64A
XXB
XYA
XZB
60A
62A
58A
XXA
XZA
52
30
50
32

Fig.5a

Fig.7

Fig.6

Fig. 9

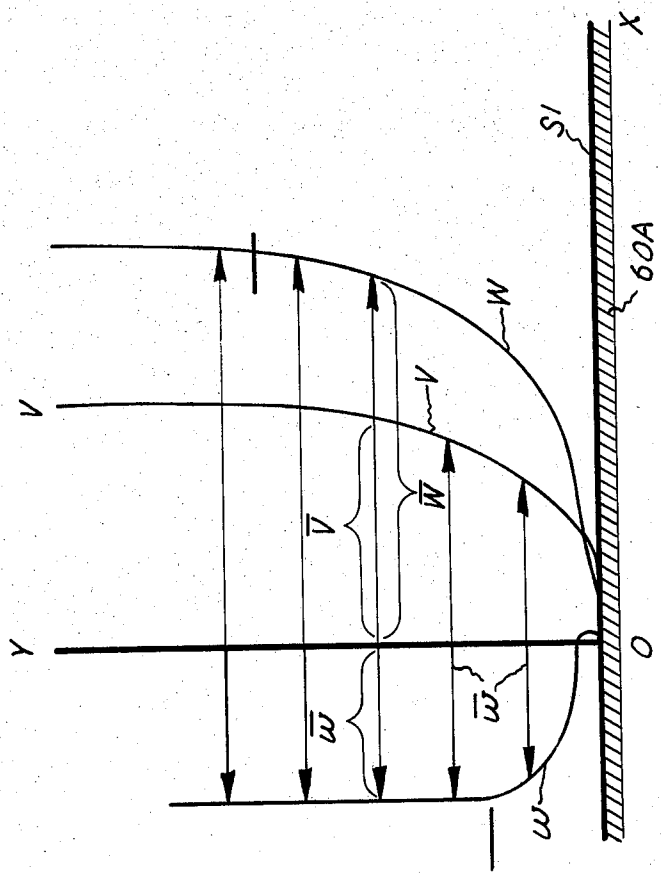
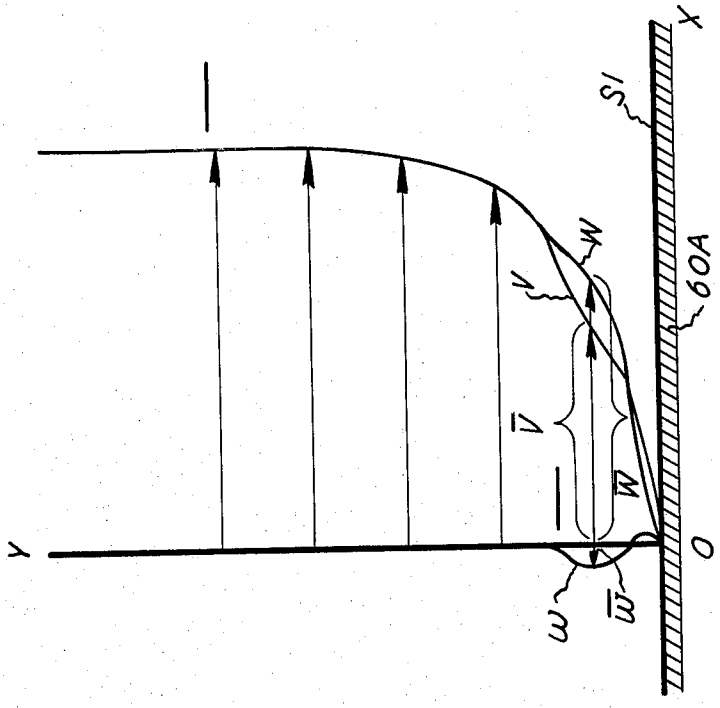
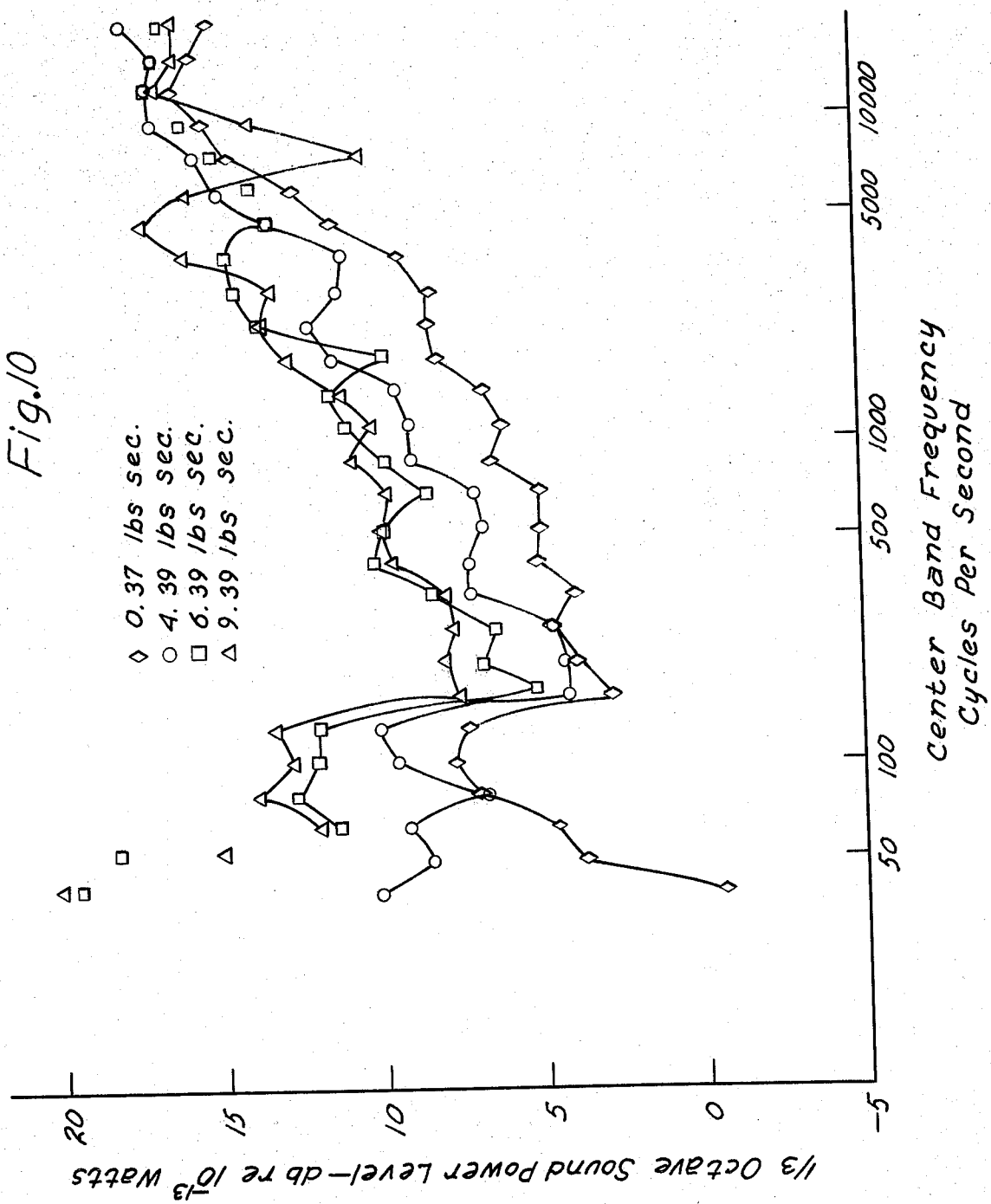

X
S1
60A
W
V
$\overline{V}$
$\overline{W}$
Y
O
$\overline{w}$
$\overline{\omega}$
w

Fig. 8


X
S1
60A
W
V
$\overline{V}$
$\overline{W}$
Y
O
w
$\overline{w}$


Fig.10
◇ 0.37 lbs sec.
○ 4.39 lbs sec.
□ 6.39 lbs sec.
△ 9.39 lbs sec.
1/3 Octave Sound Power Level—db re 10^{-13} Watts
20
15
10
5
0
-5
50
100
500
1000
5000
10000
Center Band Frequency
Cycles Per Second

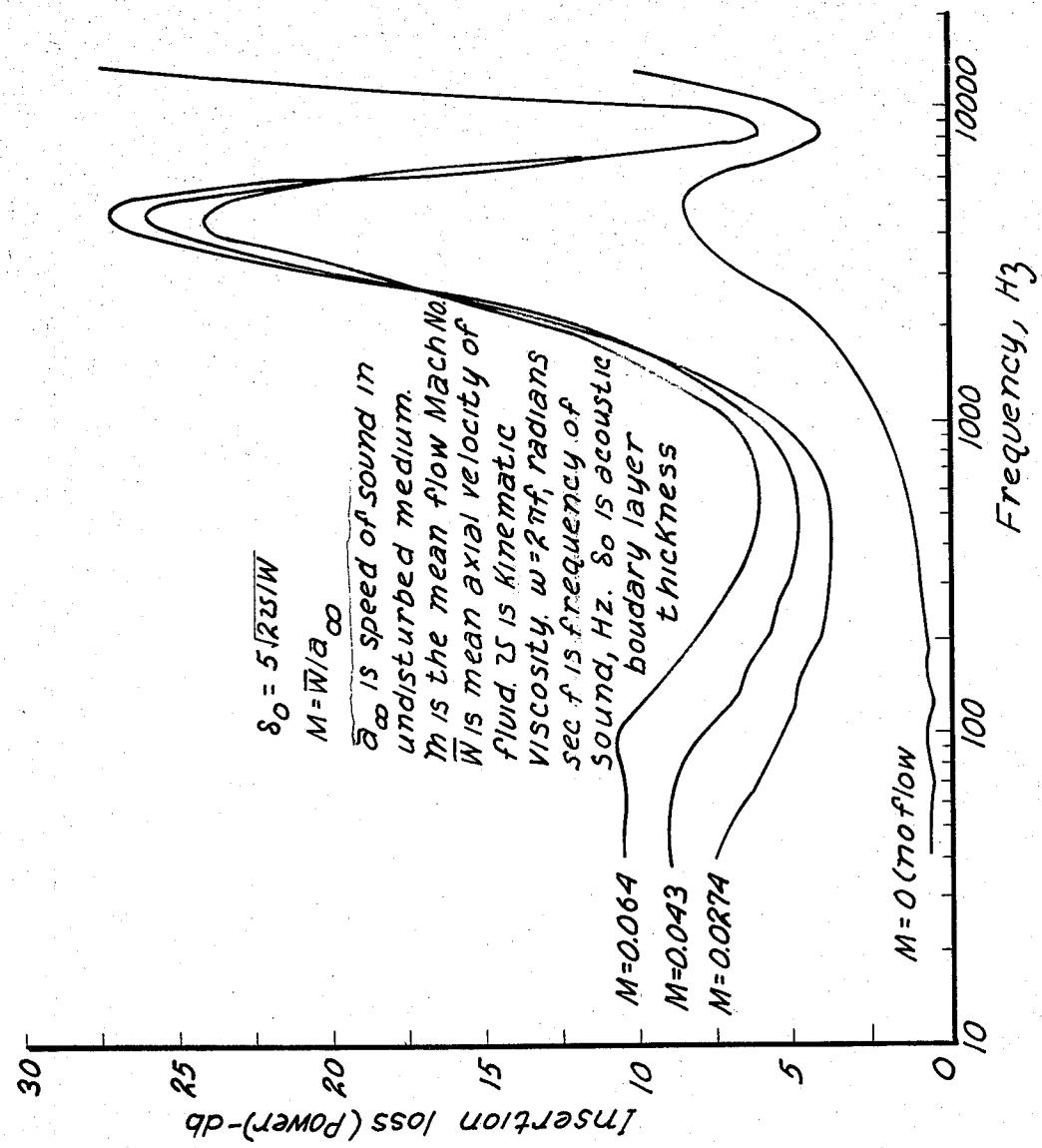

Insertion loss (Power)-db
30
25
20
15
10
5
0
10
100
1000
10000
Frequency, Hz
M=0.064
M=0.043
M=0.0274
M=0 (no flow
$\delta_0 = 5\sqrt{R2S/W}$
$M = \bar{W}/a_\infty$
a_∞ is speed of sound in undisturbed medium.
M is the mean flow Mach No.
$\bar{W}$ is mean axial velocity of fluid. S is kinematic viscosity. $w = 2\pi f$, radians sec. f is frequency of sound, Hz. δ_0 is acoustic boudary layer thickness

Fig. 11

Fig. 12

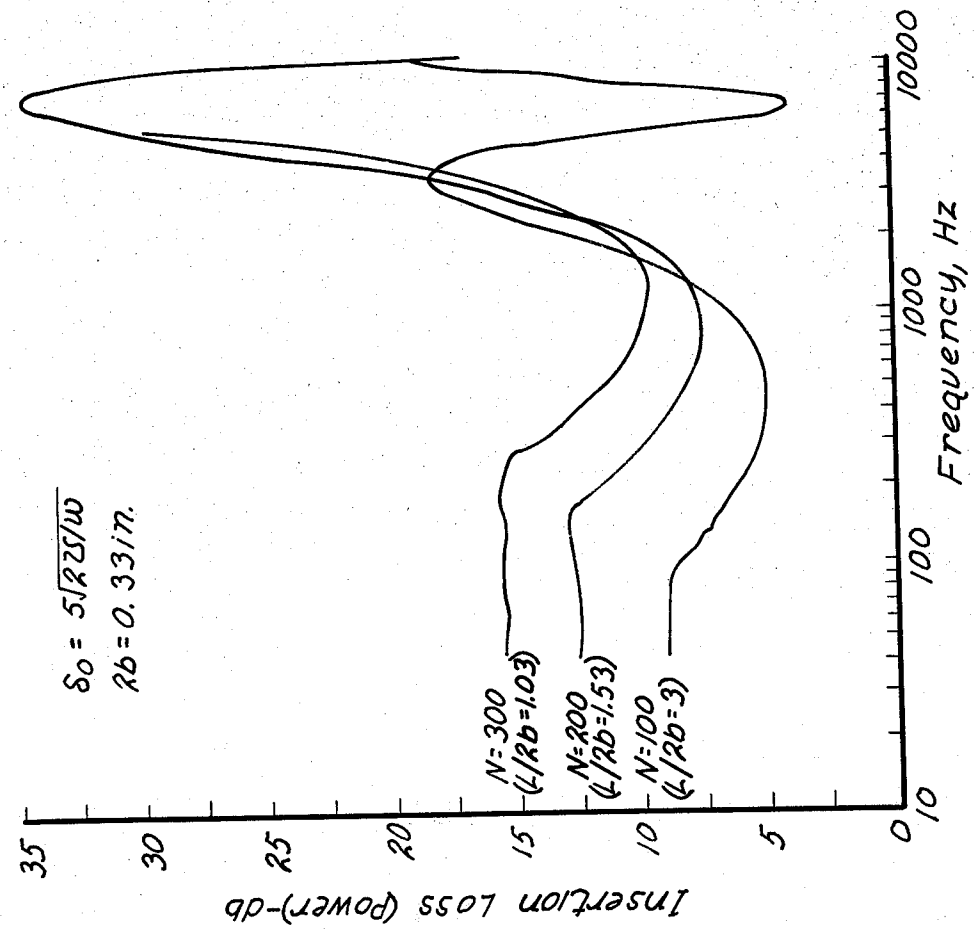

Insertion Loss (Power)-db
35
30
25
20
15
10
5
0
10
100
1000
10000
Frequency, Hz
N=300 (L/2b=1.03)
N=200 (L/2b=1.53)
N=100 (L/2b=3)
δo = 5√2S/ω
2b = 0.33 in.

Fig.13

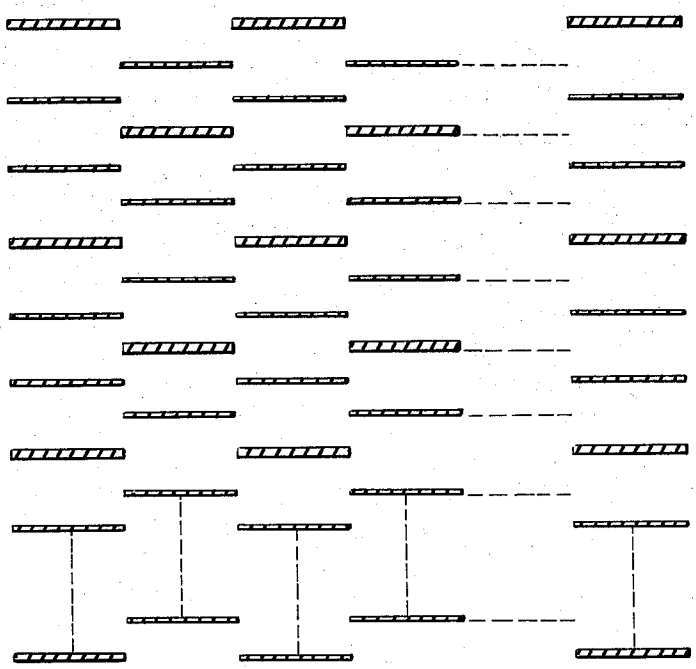


Fig.14

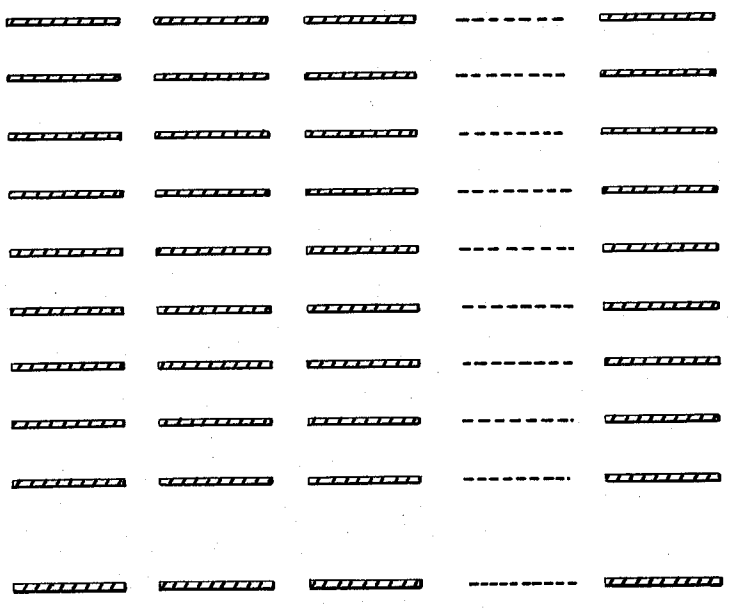


Fig.15

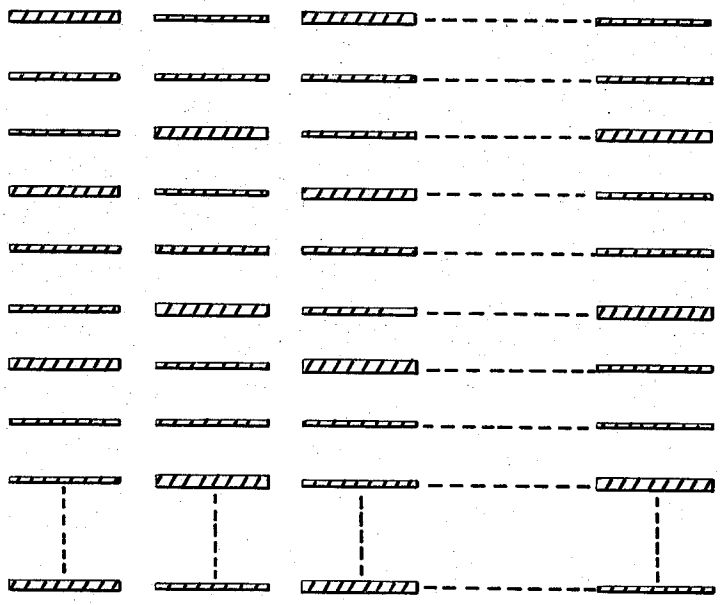
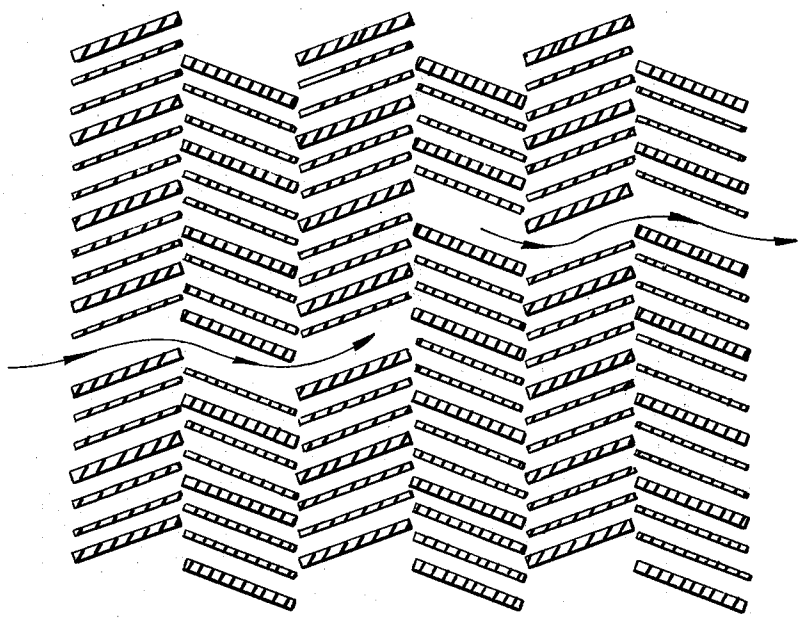


Fig.16



ACOUSTIC ATTENUATOR PROVIDING RELATIVELY HIGH INSERTION LOSS AT LOW FREQUENCIES

The invention hereinafter described was made under contract with the U.S. Government under contract 0-35510 with the U.S. Maritime Administration of the Department of Commerce. The U.S. government is licensed in accordance with the terms of the aforesaid contract and has reserved the rights set forth in sections 1(*f*) and 1(*g*) of the Oct. 10, 1963 Presidential Statement of Government Patent Policy.

This is a continuation, of application Ser. No. 308,323, filed Nov. 21, 1972.

The subject invention pertains, in general, to attenuating the acoustic energy content of low, intermediate and high frequency acoustic pressure waves; and, more particularly, to a broadband acoustic attenuator which is especially effective in attenuating the acoustic energy content of low frequency acoustic pressure waves which are being propagated in a moving fluid such as, for example, in an air-stream or in a flowing stream of gaseous or liquid matter.

BACKGROUND OF THE INVENTION

Noise generated by gas turbines, aircraft engines, etc. and propagated as acoustic pressure waves in the fluids flowing through such machines is both a nusiance and a hazard. For a variety of reasons suppression of such noise at the source (i.e., in and at the machine) is not always possible or practical. Hence, much effort has been directed toward suppressing such noise after it has been generated at locations relatively remote from the machine where the noise is being generated. Thus, a variety of silencers for suppressing noise in fluid streams have been proposed. In an effort to keep fluid flow energy losses at minimum levels many of the proposed silencers have employed Helmholtz resonators or acoustic filters of the muffler type. However, for a number of reasons such silencers have not proven satisfactory, especially at low frequencies. For example, in order to provide adequate suppression or filtering of low frequency noise such silencers require chambers having intolerable large dimensions. Moreover, in order to increase the attenuation quantities of so-called sound absorbent materials are used in prior art silencers. For example, mufflers are packed with fibrous materials which absorb some of the acoustic energy. However, such absorbent materials loose their attenuation properties with age; e.g., such materials are contaminated with water and debris as time passes.

SUMMARY OF THE INVENTION

One object of the invention is to provide a broadband acoustic attenuator.

Another object of the invention is to provide a broadband acoustic attenuator which, in addition to providing significant attenuation of the acoustic energy content of intermediate and high frequency acoustic pressure waves, is particularly effective in attenuating the acoustic energy content of low frequency acoustic pressure waves.

Another object of the invention is to provide a broadband acoustic attenuator for attenuating the acoustic energy content of low, intermediate and high frequency acoustic pressure waves which are being propagated in a moving fluid such as, for example, an airstream, gaseous stream, etc.

Another object of the invention is to provide an acoustic attenuator which does not employ acoustic energy absorbing material, such as the fibrous absorbent material commonly used in many prior art silencing devices.

Another object of the invention is to provide an acoustic attenuator which is relatively compact, easily constructed and rugged.

The subject acoustic attenuator is intended for insertion in the flow path of a noise-propagating moving fluid and in accordance with one illustrative embodiment of the invention there is provided an acoustic attenuator, for attenuating the acoustic energy content of acoustic pressure waves, embracing a broad band of acoustic frequencies, propagating through a flowing fluid, comprising a longitudinal conduit having inlet and outlet openings which are spaced apart from each other along a longitudinal central axis of the conduit. The inlet and outlet openings define an entrance and exit, respectively, for the flowing fluid aforesaid which the aforesaaid acoustic pressure waves are propagating. Situated within the conduit is a multiplicity of short axially-extending serially-arranged thin, flat plates; each plate being stationary and having a pair of parallel flat surfaces disposed in back-to-back relationship as well as a leading edge and a trailing edge. Each series of plates extends longitudinally from the inlet opening to the outlet opening of the conduit and the plates in each series are longitudinally separated from each other so that spaces exist between adjacently situated plates; i.e., a space between the trailing edge of one plate and the leading edge of the next plate. The fluid, through which the acoustic pressure waves are propagating, enters the inlet opening and flows in a longitudinal or axial direction over the back-to-back parallel flat surfaces of each plate in each series of plates and finally exits at the outlet opening of the attenuator. It has been discovered, and verified by testing, that there occurs a relatively high attenuation of the acoustic energy content of low frequency acoustic pressure waves being propagated through the flowing fluid as it passes through such an attenuator. It has also been discovered, and verified by testing, that the acoustic energy content of intermediate and high frequency acoustic pressure waves propagating through the fluid passing through such an attenuator is significantly attenuated.

Hereinafter set forth in connection with the detailed description of various embodiments of the subject attenuator are theoretical explanations for the aforesaid attenuations; e.g., a theoretical explanation of the attenuation occurring at low frequencies is extensively set forth hereinafter. However, it is to be understood that such explanations are provided principally for the purpose of contributing to an understanding of the attenuation processes involved and that the explanations are theoretical.

Other objects, as well as the various features and advantages of the invention, appear hereinafter wherein the invention is disclosed by means of illustrative embodiments.

DRAWINGS

FIG. 1 is a perspective view of a first embodiment of an acoustic attenuator according to the invention.

FIG. 2 is another perspective illustration showing the acoustic attenuator of FIG. 1 located in a fluid flow path between intake and exhaust ducts through which noise-propagating fluid is flowing; the noise, or acoustic energy disturbances, being generated, initially, by a source such as, for example, a gas turbine.

FIG. 3 is an interrupted end view of the acoustic attenuator of FIG. 1 showing an entrance for flowing fluid; said flowing fluid having acoustic pressure waves of low, intermediate and high frequencies propagating therethrough.

FIG. 4 is an interrupted longitudinal cross section, taken along the section line 4—4 in FIG. 3, showing the interior of the acoustic attenuator of FIG. 1.

FIG. 5 is an enlarged fragmentary view, similar to that shown in FIG. 4, showing, inter alia, some fluid flow patterns at the plates of the acoustic attenuator of FIG. 1.

FIG. 5*a* is an enlarged longitudinal section view of one of the plates of the attenuator of FIG. 1.

FIGS. 6, 7, 8 and 9 are diagrams for four successive instants of time showing: a velocity profile of the fluid flow in the boundary layer region adjacent the surface of one plate of the attenuator of FIG. 1; a separate velocity profile of fluid particle movement in the same boundary layer flow region caused by low frequency acoustic pressure waves; and, a composite, or resultant, fluid velocity profile obtained by the superposition of both of the aforesaid velocity profiles.

FIG. 10 is a graph showing the insertion loss, or acoustic attenuation, obtained for various mass flows of air passing through the acoustic attenuator of FIG. 1 and propagating acoustic pressure waves of a broad range of frequencies.

FIG. 11 is a graph showing the calculated insertion loss, or acoustic attenuation, provided by an acoustic attenuator like that shown in FIG. 1, for different flow parameters as a function of acoustic pressure wave frequency.

FIG. 12 is another graph showing the insertion loss, or acoustic attenuation, provided by an acoustic attenuator, like that shown in FIG. 1, having rows of attenuator plates with different numbers of serially arranged plates as a function of acoustic pressure wave frequency.

FIG. 13 is a diagram of a second embodiment of the acoustic attenuator of the invention showing a staggered configuration of attenuator plates, similar to that shown at FIG. 4, but including some plates having thicker cross sections which are included in the subject attenuator for improving the insertion loss, or attenuation, of intermediate and high frequency acoustic energies.

FIG. 14 is a diagram of a third embodiment of the acoustic attenuator of the invention showing a regular row and column array of attenuator plates, all plates having the same thickness dimension.

FIG. 15 is a diagram of a fourth embodiment of an acoustic attenuator in accordance with the invention showing a row and column array of attenuator plates, like that shown in FIG. 14, but including some plates having thicker cross sections, said thicker plates being included for improving the insertion loss, or acoustic attenuation, of intermediate and high frequency acoustic energies.

FIG. 16 is a diagram of a fifth embodiment of an acoustic attenuator in accordance with the invention showing angularly arranged, or canted, attenuator plates, some of which have thicker cross sections than others; the angular disposition of the plates and the inclusion of plates having thicker cross sections being purposeful for improving the insertion loss, or acoustic attenuation, of intermediate and high frequency acoustic energies.

DETAILED DESCRIPTION

An acoustic attenuator **20** in accordance with a first embodiment of the invention is illustrated in perspective views at FIGS. **1** and **2**. As shown at FIG. **2** the attenuator **20** is located in a fluid flow path in series between an intake duct **22** and an exhaust duct **24**. The intake duct **22** is coupled to a source **26** from which a fluid (e.g., air, gas or water) is discharged into the intake duct **22**. The source **26** also generates noise; i.e., acoustic pressure waves of low, intermediate and high frequency. The acoustic pressure waves are propagating through the flowing fluid, i.e., leaving the source **26** and entering the intake duct **22**. Source **26** may, for example, be a jet engine, gas turbine, etc. The source **26** may, at any given instant of time or during a given time period, be generating a particular acoustic frequency or band of acoustic frequencies. As shown in FIG. **2** the fluid flow directions are indicated by the labeled arrows. In the descriptions and discussions which appear hereinafter, it is to be assumed, unless otherwise stated, that the acoustic pressure waves generated by source **26** are propagating through the flowing fluid in the same general direction as the fluid flow direction; i.e., in the direction indicated by the labeled arrows showing fluid flow direction in FIG. **2**.

In FIGS. **1, 2, 3** and **4** structural details of the acoustic attenuator **20** are illustrated. As shown, the attenuator **20** is comprised of four wall members **28 . . . 28** defining a conduit having inlet and outlet openings **30** and **32**, respectively spaced from each other at opposite ends of a longitudinal central axis through the center of the conduit. The longitudinal central axis extends in the general direction of the fluid flow direction. Inlet opening **30** is, as shown in FIG. **1**, divided into a number of inlet sections **34, 36, 38, 40, 42, 44, 46, 48, 50** and **52**. These inlet sections **34 . . . 52** are separated from each other by wall members **54 . . . 54**. The wall members **54 . . . 54** extend in parallel, longitudinally from inlet opening **30** to the outlet opening **32**. Thus, each of the wall members **54 . . . 54** is also disposed in parallel relationship with two of the wall members **28** as indicated at FIG. **1**. For each of the inlet sections **34 . . . 52** there is a corresponding outlet section at the outlet opening **32** of the conduit forming the attenuator **20**. Some of the aforesaid outlet sections are identified hereinafter in connection with FIGS. **3** and **4**.

FIG. **3** is an end view of the acoustic attenuator **20** showing portions of the first and last inlet sections **34** and **52** of inlet opening **30**.

FIG. **4** is a longitudinal cross section, taken along section line **4—4** of FIG. **3**, of a portion of the acoustic attenuator **20**. As shown in FIG. **4**, an outlet section **56** of the outlet opening **32** is situated longitudinally opposite a corresponding inlet section **52** of inlet opening **30**. For convenience of illustration, consistent with clarity, the views shown in FIGS. **3** and **4** are illustrated with a number of breaks in the height, width and length dimensions of the attenuator **20**. Looking into the inlet section **52** (FIG. **3**) one can observe the leading edges

of a number of thin flat plates. The other inlet sections **34 . . . 50** comprising the inlet opening **30** also present the leading edges of a like number of thin flat plates. For example, the inlet section **52** includes a first row of plates **58A, 62A . . . XXA, XZA.** As indicated at FIGS. **3** and **4,** beyond inlet opening **52** and the first row of plates, hereinbefore identified, is a second row of plates **60A, 64A . . . XYA.** As shown in FIG. **4** the plates **60A . . . XYA.** of the second row of plates are staggered, or offset, relative to the plates **58A . . . XZA** of the first row of plates, the plates of the second row dividing the spaces between, the plates of the first row substantially in half. Similarly, as indicated at FIG. **4** there is a third row of plates **58B, 62B . . . XXB** and **XZB.** Each of the plates in the third row is in line with a corresponding plate **58A . . . XZA** in the first row of plates. Thus, in the first, third . . . Nth rows (odd numbered rows) the respective plates **58A, 58B . . . 58N** form a series of spaced-apart, thin, flat plates which extend longitudinally, in an axial direction, substantially parallel to the flow of fluid (i.e., within a few degrees), from the inlet section **52** of inlet opening **30** to the outlet section **56** of the outlet opening **32** of attenuator **20.** Similarly, in the second, fourth . . . Nth rows the respective plates **60A . . . 60N** form another series of spaced apart plates which extend longitudinally, in an axial direction, substantially parallel to the flow of fluid (i.e., within a few degrees) from inlet section **52** to outlet section **56** and the plates in these even numbered rows are staggered, or offset, relative to the plates in the odd numbered rows. All of the aforesaid plates **58A . . . XZN** may be suitably secured at one end thereof to the wall member **28** and to the other end thereof to the wall member **54.** In the alternative, bent ribbons of metal resembling corrugated strips may be employed (as suggested in FIG. **1**) with the vertical sections of such metal ribbons serving as the individual plates. Thus, the plates **58A . . . XZN** are rigid and stationary relative to each other as well as relative to wall members **28** and **54.**

FIG. **5** is a fragmentary view of part of FIG. **4** showing enlarged illustrations of some of the thin flat plates **58B, 60A, 60B, 62B, 64A, 64B** and **66B.** The aforesaid plates are disposed in the flow path between inlet section **52** and outlet section **56** of the attenuator **20.** As indicated each plate includes a pair of smooth, flat surfaces **S1** and **S2** arranged back-to-back. The cross section dimension of each plate is relatively thin as compared with its length. Each plate includes a leading edge LE as well as a trailing edge TE; the former being subjected to oncoming fluid flow before the latter. For example, in the enlarged view, FIG. *5a*, the plate **60A** includes: the pair of flat, smooth, back-to-back surfaces **S1** and **S2**; the leading edge LE: and, the trailing edge TE. As shown in FIGS. **5** and *5a*, fluid flowing in the direction indicated by the FLOW arrow initially contacts the leading edges LE of the various plates. Separation bubbles, as indicated, are formed at each of the leading edges LE. After forming the separation bubbles, the flowing fluid separates at the leading edges LE of the plates and flows over the back-to-back flat surfaces **S1** and **S2** of the plates toward the trailing edges TE thereof. For example, at plate **60A** in FIG. *5a*, the flowing fluid forms separation bubbles at the leading edge LE and separates into two streams which pass over the surfaces **S1** and **S2** in a direction toward the trailing edge TE. On each of the surfaces **S1** and **S2** of plate **60A** boundary layer flow regions are formed immediately adjacent the surfaces **S1** and **S2.** These boundary layer flow regions begin at a point just after the regions where the separation bubbles are formed. In FIG. *5a*, the dotted lines **BL1** and **BL2** designate the envelopes of the boundary layer flow regions. The boundary layer flow regions are formed in the spaces immediately adjacent the surfaces **S1** and **S2**; i.e., a first boundary layer flow region is formed in the space between the plate surface **S1** and the line **BL1,** a second boundary layer flow region is formed in the space between the plate surface **S2** and the line **BL2.** In FIG. *5a* the thicknesses of the boundary layer flow regions have been exaggerated; i.e., the thickness of the first boundary layer flow region is the distance between the surface **S1** and the dotted line **BL1**; the thickness of the second boundary layer region is the distance between the surface **S2** and the line **BL2.** The varying thicknesses of the two boundary layers next to plate **60A** in FIG. *5a* are, in fact, much smaller than illustrated; the boundary layer thicknesses being exaggerated as to their thickness dimension for purposes of more clearly illustrating, inter alia, the attenuation processes hereinafter discussed in detail. A comprehensive treatment of boundary layer flow is contained in the textbook, BOUNDARY-LAYER THEORY by H. Schlicting, translated by J. Kestin, 6th Edition, published by McGraw-Hill Book Company.

In the boundary layer flow regions, hereinbefore identified, the fluid flow is rotational in the character. However, the fluid flow is irrotational in character beyond the boundary layer flow region; i.e., above and below the dotted lines **BL1** and **BL2** in FIG. *5a*. As indicated in FIGS. **5** and *5a*, the fluid flow leaving the trailing edges TE of each of the plates forms oscillatory wakes. These oscillatory wakes include a number of vortices. Because of the presence of low frequency acoustic pressure waves, the boundary layer flow regions adjacent the back-to-back surfaces **S1** and **S2** of each plate include acoustic boundary layers, or layers of oscillating vorticity, wherein vortex flow patterns occur. Thus, because of the presence of the low frequency acoustic pressure waves, the boundary layer flow regions are said to be oscillatory. This is discussed in greater detail hereinafter with reference to FIGS. **6, 7, 8** and **9.**

FIGS. **6, 7, 8** and **9** are graphical representations showing fluid flow velocity profiles adjacent a plate surface **S1** at four successive instants of time. These figures also include separate velocity profiles of fluid particle movement caused by the low frequency acoustic pressure waves. For example, in FIG. **6** the surface **S1** of the plate **60A** is illustrated as extending longitudinally along an X axis, or abscissa, from a point **0** on the surface **S1.** The upwardly extending Y axis, or ordinate, represents the distance from point **0** on the abscissa from the surface **S1** extending into the boundary layer flow region above the surface **S1.**

In FIG. **6,** the curved line W is the envelope of the mean fluid flow velocities within and beyond the boundary layer flow region above the surface **S1** of the plate **60A.** The mean fluid flow velocities are represented by the vectors $\overline{W}$. Thus, the curved line W is the locus or envelope of the terminations of the individual velocity vectors $\overline{W}$. Beginning at the surface **S1** the fluid flow velocity vector $\overline{W}$ is zero and increases with increasing distance in a direction parallel to the Y axis from the surface **S1.** Also illustrated in FIG. **6** is an-

other curved line w which is the locus or envelope of axially-directed acoustic particle velocities $\overline{w}$. The curved line $\overline{w}$ represents the envelope of locus of the terminations of the individual acoustic particle velocities $\overline{w}$ at a given instant of time. Hence, individual fluid particles, being influenced by a fluid flow pressure and an acoustic pressure, have a total velocity $\overline{V} = (\overline{W} + \overline{w})$. In FIG. **6** the curved line V represents the envelope or locus of the summation of the two velocities $\overline{W}$ and $\overline{w}$. In FIGS. **7, 8** and **9** envelopes *w*, W and V are shown together with representative velocity vectors $\overline{w}$, $\overline{W}$ and $\overline{V}$ at other successive instants of time. A comparison of FIGS. **6, 7, 8** and **9** indicates that the total velocity $\overline{V}$ varies from instant to instant and, as a result, the boundary layer regions become oscillatory. The fluid flow patterns in the boundary layer regions cause an oscillating layer of vorticity to be set up in the boundary layer regions. The layer of oscillatory vorticity thus set up is shed in the form of an oscillatory wake from the trailing edges TE of each of the plates in each series of the attenuator **20.** For example, the oscillatory wakes are shed from the trailing edges TE of each of the plates **58A, 58B, . . . 58N.** For two successive plates in series, FIG. **5** provides a graphical illustration of wake shedding. In converting the acoustic fluid motion in the boundary layer regions to a markedly rotational flow wherein layers of vorticity and oscillatory wakes are created, a fraction of the acoustic energy is converted into a form which is no longer sound. Thus, at each of the plates in the series attenuation of the low frequency content of the acoustic pressure waves is repeated. As indicated in FIG. **5** the oscillatory wakes being shed from the trailing edges TE of each of the plates eventually decay through viscous dissipation.

FIG. **10** is a graphical representation indicating the insertion loss provided by the attenuator **20** in the acoustic propagating flow path shown in FIG. **2.** As indicated at FIG. **10,** the ordinate represents ⅓ octave sound power levels in db re 10^{-13} watts (i.e., the decibel sound power level is related to 10^{-13} watts) and the abscissa is representative of centerband frequencies measured in cycles per second. The power levels in db re 10^{-13} watts are measured in Hertz or cycles per second. The power levels in db re 10^{-13} watts were measured at the different centerband frequencies for four different mass flows of air; e.g., 0.37 lb/sec. mass flow of air, 4.3 lb/sec. mass flow of air, 6.39 lb/sec. mass flow of air, and 9.39 lb/sec. mass flow of air. Explanations of, as well as significant features pertaining to, ⅓ octave sound levels and centerband frequencies are discussed in the text HANDBOOK OF NOISE MEASUREMENT (6th Edition), authored by Arnold P. G. Peterson and Ervin E. Gross, Jr., published by General Radio Company. Thus, FIG. **10** represents in graphical form actual tests of attenuated sound power level for four different mass flows through which acoustic frequencies as indicated are propagating. The result of incorporating the attenuator **20** (FIG. **20**) is clearly evident in that the power levels are significantly diminished and the lower centerband frequencies indicating that significant attenuation occurs, especially at the lower frequencies. Indeed, attenuation can be observed to occur across a broad band of frequencies.

FIG. **11** is a graphical representation showing calculated insertion loss versus frequency at 4 flow conditions: e.g., where M (the mean flow Mach number) is 0, 0.0274, 0.043, and 0.064. The calculations are carried out for an attenuator like the attenuator **20** wherein 135 plates are located in each series and wherein the overall length between the leading edge and trailing edge of each plate is L = 0.75 inch; $2b$ = 0.33 inch, where b = the half width of the channel formed between two plates.

As can be seen from FIG. **11,** the insertion loss, especially at the lower frequencies, increases markedly as flow increases from a mean flow Mach number of 0 through 0.064. It is also apparent from FIG. **11** that at the higher frequencies (e.g., circa 10,000 hz), an appreciable attenuation also occurs.

FIG. **12** is a set of curves based on a calculation showing the insertion loss as function of frequency for different numbers N of plates arranged in series in an attenuator, like the attenuator **20.** As indicated, the number N of serially arranged plates increased from 100 through 200 to 300 the insertion loss increases at the lower frequencies. It will be noted that in order to provide the various numbers N of plates in series, for a fixed overall length between inlet **30** and outlet **32** of the said device **20,** the ratio $L/2b$ is also changed to accommodate the required number N of plates in each series.

FIG. **13** is a view similar to that shown in FIG. **4** of the arrangement of plates in a second embodiment of the invention. As indicated in FIG. **13** some of the plates have a thicker cross-section dimension than others. This is done to enhance intermediate and higher frequencies attenuation.

FIG. **14** is another view similar to that shown in FIG. **4** showing a third embodiment of the invention wherein each of the plates is arranged in a row-and-column array without staggering the various plates, as is the case in FIG. **4.** In FIG. **4,** an advantage is gained in reducing the overall size of the attenuator **20** by staggering intermediate rows-and-columns of plates.

FIG. **15** is a view similar to that shown in FIG. **14** and FIG. **4** and FIG. **15** is a fourth embodiment of the invention which is in effect a variation of the embodiment shown in FIG. **14.** In FIG. **15,** some of the plates have a thicker cross-section dimension than others in order to improve intermediate and high frequency attenuation characteristics of the attenuator.

FIG. **16** is a fifth embodiment of the invention wherein, as shown, the plates in successive columns are canted or aligned at an angle so that the incoming fluid flow meets each plate at other than 0 angle of incidence which improves the intermediate and high frequency attenuation. Moreover, some of the plates have a thicker cross-section dimension than others in order to further improve intermediate and high frequency attenuation characteristics.

While specific embodiments of the invention have been illustrated and described in some detail for the purpose of illustrating the invention, it is to be understood that the invention may be otherwise embodied without departing from the spirit and scope of the invention which is hereinafter defined in the appended claims.

What is claimed is:

1. Apparatus for attenuating the acoustic energy content of acoustic pressure waves propagating through a flowing fluid comprising: a conduit having inlet and outlet openings adapted for the entrance and exit, respectively, of the flowing fluid; and, at least one series of substantially rigid, acoustically nonabsorptive plates

mounted within said conduit and extending from said inlet opening toward said outlet opening, each plate in said series having a leading edge which is initially contactable by the flowing fluid and a trailing edge from which the flowing fluid can leave the plate, each plate in said series having at least one relatively flat surface extending from the leading edge to the trailing edge of the plate in a direction substantially parallel to the flow of said fluid, said plates in said series being spaced apart so that a space exists between the trailing edge of one plate and the leading edge of the next succeeding plate in the series.

2. The apparatus according to claim 1 wherein some of said plates have thicker cross sections than others.

3. Apparatus for attenuating the acoustic energy content of low frequency acoustic pressure waves propagating through a flowing fluid comprising: a conduit having inlet and outlet openings for the entrance and exit, respectively, of the flowing fluid, and, at least one series of substantially rigid, acoustically nonabsorptive plates mounted within said conduit and extending from said inlet opening toward said outlet opening, each plate in the series having a leading edge which is initially contacted by the flowing fluid and a trailing edge from which the flowing fluid leaves the plate, each plate in said series having at least one surface extending from the leading edge to the trailing edge of the plate in a direction substantially parallel to the flow of said fluid, said plates in said series being spaced apart so that a space exists between the trailing edge of one plate and the leading edge of the next succeeding plate in the series so that the flowing fluid forms a boundary layer flow region on the surface of the first plate encountered in the series and re-forms new boundary layer flow regions on the surfaces of each of the successive plates encountered in the series, the low frequency acoustic pressure waves causing said boundary layer flow regions to become oscillatory whereby each oscillatory boundary layer flow region in succession substantially impedes propagation of low frequency acoustic pressure waves.

4. Apparatus for attenuating the acoustic energy content of acoustic pressure waves, includng at least those of low frequency, propagating through a flowing fluid comprising: an elongated conduit having inlet and outlet openings spaced apart from each other and located at opposite ends of a longitudinally extending central axis of said conduit, said openings being in planes which are parallel with each other, said central axis being orthogonally disposed with respect to said planes, said inlet and outlet openings providing an entrance and exit, respectively, for the flowing fluid and the low frequency acoustic pressure waves propagating through the fluid; and, one row-and-column array of relatively thin acoustically nonabsorptive plates mounted within said conduit, each thin plate in said array having a leading edge which is initially contacted by the flowing fluid and a trailing edge from which the flowing fluid subsequently leaves the plate, each thin plate having a pair of relatively flat, parallel surfaces which extend longitudinally from its leading edge to its trailing edge, said pair of parallel surfaces being disposed in back-to-back relationship, each column of plates in said array extending along a line parallel with said central axis, the plates in each said column being arranged in a series along said line and extending from said inlet opening toward said outlet opening of said conduit with the back-to-back parallel surfaces of each plate in the series along said line being in parallel with said longitudinal central axis, the trailing and leading edges of successive serially-arranged plates in each column being separated by longitudinally extending spaces, each row of plates in said array having included therein one plate of each column in said array and extending along a line crosswise of said central axis, the flowing fluid, including the acoustic pressure waves propagating therethrough, passing through said conduit in a direction generally parallel with said central axis from said inlet opening toward said outlet opening, the flowing fluid forming, during its passage through said conduit, separate back-to-back boundary layer flow regions on the back-to-back surfaces, respectively, of each of the serially-arranged plates in each column of said array, said low frequency acoustic pressure waves exciting the boundary layer flow regions and causing said boundary layer flow regions to become oscillatory thereby forming in each oscillatory boundary layer flow region a layer of oscillating vorticity wherein flow vortices form, each said layer of vorticity being shed from the trailing edge of each plate in the form of an oscillatory wake into the longitudinally extending space between the trailing edge of one plate and the leading edge of the next succeeding plate in the column whereby propagation of the low frequency acoustic pressure waves through said oscillatory boundary layer flow regions, said layers of vorticity and said oscillatory wakes is substantially impeded so that the acoustic energy content of said low frequency acoustic pressure waves is attenuated.

5. The apparatus according to claim 4 wherein some of said plates have relatively thicker cross sections than others.

6. The apparatus according to claim 5 wherein the plates having the thicker cross sections are included in each row and column of said array and are arranged in symmetrical relationship with respect to said central axis.

7. The apparatus according to claim 4 further comprisng a second row-and-column array of like plates, the rows and columns of said second array of plates being staggered with respect to the rows and columns of said one array.

8. Apparatus for attenuating the acoustic energy content of acoustic pressure waves, including at least low frequency waves, propagating through a flowing fluid comprising: a conduit having inlet and outlet openings for the admission and discharge of the flowing fluid; and, a plurality of plates mounted within said conduit, each plate having a leading edge and a trailing edge and a pair of parallel, relatively flat, acoustically nonabsorptive back-to-back surfaces essentially parallel to the fluid flow extending from the leading edge to the trailing edge, said plates of said plurality being spaced apart from one and other so that the flowing fluid can establish individual pairs of boundary layer flow regions on said back-to-back surfaces of each plate successively encountered as the fluid flows from said inlet opening toward said outlet opening, the low frequency acoustic pressure waves causing each boundary layer flow region to become an oscillatory boundary layer flow region wherein fluid flow vorticities are formed and shed from the trailing edges of each plate.

9. The apparatus according to claim 8 wherein some plates in said plurality have thicker cross section di-

mension between the parallel surfaces thereof than other plates in said plurality.

10. Apparatus for attenuating the acoustic energy content of acoustic pressure wave propagating through a flowing fluid comprising: one series of stationary plates mounted in a flow path adapted to be traversed by the flowing fluid and by the acoustic pressure waves propagating through the flowing fluid, said series of plates extending longitudinally in the general direction of the flow of the fluid, each plate in said series having a leading edge and a trailing edge longitudinally spaced therefrom, each plate having a pair of relatively flat, acoustically nonabsorptive parallel surfaces disposed in back-to-back relationship and extending longitudinally from said leading edge thereof to said trailing edge thereof, in a direction substantially parallel to the flow of said fluid, the distance between said pair of surfaces being relatively smaller than the distance from said leading edge to said trailing edge, the plates in said series being longitudinally separated so that a longitudinally extending space exists between the trailing and leading edges of successive plates in said series.

11. Apparatus according to claim **10** wherein the acoustic pressure waves include at least low frequency acoustic pressure waves and wherein said distance from the leading edge to the trailing edge of each plate as well as said longitudinally extending space between the leading and trailing edges of successive plates are of sufficient length to insure the formation of new pairs of boundary layer flow regions on the surfaces of each plate successively encountered by the flowing fluid.

12. Apparatus according to claim **10** wherein the distance between the pair of surfaces is greater for some plates in the series than for others.

13. Apparatus according to claim **10** further comprising additional series of like plates said additional series together with said one series forming one row-and-column array of plates.

14. Apparatus according to claim **13** wherein some plates in said one and additional series have greater distance between the pairs of surfaces thereof than other plates in said one and additional series.

15. Apparatus according to claim **13** wherein said plates having the greater distance between the pairs of surfaces thereof are symmetrically spaced throughout the row-and-column array.

16. Apparatus according to claim **13** further comprising a second row-and-column array of like plates arranged in staggered relationship relative to said one row-and-column array.

17. Apparatus according to claim **16** wherein in each array said longitudinally extending space between the trailing and leading edges of successive plates in the same column is substantially equal to the distance L between the leading and trailing edges of each plate and wherein in each array the distance $2b$ between the surfaces of successive plates in the same row is substantially twice the distance b between the trailing edge of a plate in one row of one array to the leading edge of a corresponding plate in a corresponding row of the second array whereby the plates in the columns of said second array divide the fluid flowing between adjacent columns in the one array.

18. Apparatus according to claim **17** wherein in each column of both arrays there are N plates in series.

19. Apparatus according to claim **18** wherein N ranges from 100 to 300 inclusive and the ratio $L/2b$ ranges from 3 to 1.03, inclusive.

20. Apparatus according to claim **19** wherein some plates in both arrays have more thickness than the remaining plates.

21. Apparatus according to claim **20** wherein said plates are formed from metal corrugations.

22. Apparatus according to claim **21** wherein said plates are formed from strips of corrugated metal adjacently arranged.

23. Apparatus for attenuating the acoustic energy contact of acoustic pressure waves propagating through a flowing fluid comprising: a series of longitudinally spaced acoustically nonabsorptive surfaces mounted in a flow path substantially parallel thereto adapted to be traversed by the flowing fluid, said surfaces in said series having sufficient length and sufficient spacing between successive surfaces to enable the flowing fluid to establish a new boundary layer flow region on each surface successively encountered.

24. The apparatus accoading to claim **23** wherein said surfaces include a leading edge first contacted by the flowing fluid and forming separation bubbles thereat.

25. The apparatus according to claim **23** wherein said acoustic pressure waves are of low frequency and cause said boundary layer flow regions to become oscillatory.

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