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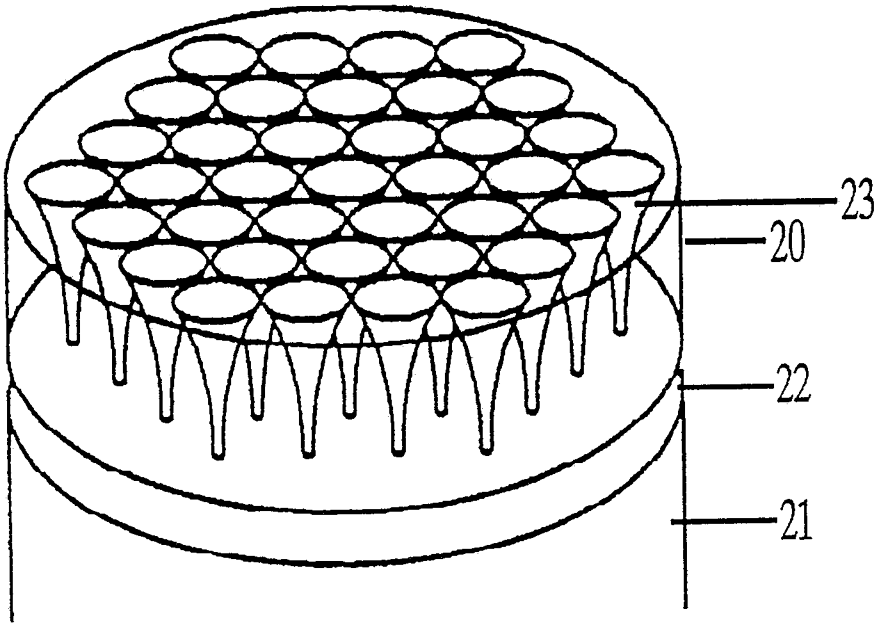

(57) Abstract

A device for matching acoustic impedance between an ultrasonic transducer (21) and a medium is disclosed. The device includes a body (20) comprising a material having a high acoustic impedance on an ultrasonic signal. The body contains a plurality of acoustic impedance matching horns (23) extending between two surfaces of the body wherein the mouths of the horns are disposed in one surface and the throats of the horns are disposed in another surface, the magnitudes of the lengths and flares of the horns are such that the horns are capable of transmitting the ultrasonic signal; and the magnitude of the flare of each horn is such so as to provide a substantially smooth transition in acoustic impedance to the ultrasonic signal between the mouth and throat of the horn.

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A COUPLING DEVICE

TECHNICAL FIELD

This invention relates to a device for matching acoustic impedance between an ultrasonic transducer and a medium, in combination a device for matching acoustic impedance between an ultrasonic transducer and a medium, and a transducer, a process of constructing a device for matching acoustic impedance between an ultrasonic transducer and a medium, a system and method for transmitting ultrasonic signals between an ultrasonic transducer and a medium, a system and method for detecting ultrasonic signals between an ultrasonic transducer and a medium, and systems and methods for transmitting and detecting ultrasonic signals between an ultrasonic transducer and a medium.

BACKGROUND ART

A difficulty in acoustics is that devices which will produce sound by virtue of their vibration, are nearly always of a different acoustic impedance to the medium in which it is desired to have the sound propagate. The amount of acoustic energy transferred from one medium to another is determined by the impedance match. The worse the match, the more energy is reflected from the interface rather than transmitted through the medium.

A common problem in the use of ultrasonic transducers in air and other gases is the very large impedance mismatch between the transducer and the medium. The wave impedance of a piezoelectric material such as barium titanate exceeds that of air by a factor close to 10^5 and, even when the transducer is operated in a resonant mode, the effective acoustic mismatch is still of order 10^3. The intrinsic mismatch for a nonresonant stretched-foil transducer is rather less, but, without the assistance of resonance matching, the acoustic mismatch is still very large.

While better matching would improve power output when the transducer is used in the transmitting mode, the improvement in performance that could be achieved by better matching becomes particularly important in the receiving mode, particularly when signal levels are low. It is often not desirable to use a resonant transducer with very high Q, because of the associated degradation in time resolution.

These problems are, of course, not unique to air as a medium, nor to the ultrasonic frequency range, but the most common solution to this problem in the field of ultrasonic signal impedance matching is to join the two media with one or more thin layers of solid, liquid or other material of selected acoustic impedance sandwiched between them. The number, acoustic impedance and thickness of these layers determine the overall impedance match and thus the efficiency of energy flow. The materials may be metals, alloys, liquids, ceramics, glasses or one of a huge array of composite materials mixed to have desired acoustic impedances.

The more layers of intermediate impedance which can be sandwiched between the two media to be matched, the more energy is transmitted. However, each layer ought to have an acoustic impedance which is the geometric mean of the acoustic impedances to each side of it and the layers need to be sufficiently thick or the signals sufficiently short that reflections within the layers do not have cancelling effects.

For continuous wave operation or for long signals, resonant phenomena can, in theory, be used to give perfect energy transfer. In this method the layers operate by the combination of physical characteristics so that the impedance is tailored to be the geometric mean of the acoustic impedances to be matched and the thickness is such as to make the matching layer operate at 1/4 wave resonance.

This can be seen in the following equation which gives the transmissivity of a single matching layer of impedance z_2 between two media of different and arbitrary impedances, z_1 and z_3.

$$T = \frac{4}{2 + \left[\frac{z_3}{z_1} + \frac{z_1}{z_3}\right]\cos^2 k_2 l + \left[\frac{z_2^2}{z_1 z_3} + \frac{z_1 z_3}{z_2^2}\right]\sin k_2 l}$$

The thickness of the matching layer is l and k_2 is the wave number in the matching layer, $k_2 = 2\Pi / \lambda$. In this equation, if the thickness, l, is $\lambda/4$ and the matching layer impedance, z_2 is $\sqrt{(z_1 z_3)}$ then the transmissivity is $T = 1$. These values assume steady continuous wave operation, not pulsed. A 1/4 wave layer in resonance has a high impedance at one end and a low impedance at the other end. Thus, sandwiched between two media, it will look like a high impedance to one medium and a low impedance to the other. The matching materials are glued directly or closely fixed in some other way to the media to be matched.

The disadvantages of the known impedance matching techniques for ultrasonic signals include:

(a) It is often difficult to find materials with the right acoustic impedance.

(b) The most useful materials, the composites, often have very high attenuation of the ultrasonic signals by virtue of their inhomogeneity,

(c) The glue required to stick the layers together also constitutes a matching problem,

(d) The wavelengths are often very small but getting the thickness right is critical as they must be 1/4 wave resonant,

(e) In the case 1/4 wave resonant matching, a number of cycles of the sound are required to build up the resonance before the layer becomes effective. This means that for pulsed operation the acoustic attenuation of the material needs to be very small since pulses commonly used are only two or three cycles. Even with a very high Q two or three cycles does not represent much of an energy build up,

(f) The bandwidth is very narrow because the layers operate at resonance and are generally selected for a reasonably high Q (for the reasons given in e),

(g) Liquid matching substances present a problem in containment, and

(h) Selection of materials for acoustic impedance and attenuation properties generally means that other important properties such as thermal conductivity, corrosion resistance, boiling point, strength, hardness and the like cannot be tailored to requirements. Many of the modern uses of acoustic transducers involve very hostile environments for example in furnace, corrosive liquid and radioactive environments.

OBJECTS OF INVENTION

It is an object of this invention to provide a device for matching acoustic impedance between an ultrasonic transducer and a medium.

Another object is to provide in combination a device for matching acoustic impedance between an ultrasonic transducer and a medium, and a transducer.

Further objects are to provide a process of constructing a device for matching acoustic impedance between an ultrasonic transducer and a medium, a system and method for transmitting ultrasonic signals between an ultrasonic transducer and a medium, a system and method for detecting ultrasonic signals between an ultrasonic transducer and a medium, and systems and methods for transmitting and detecting ultrasonic signals between an ultrasonic transducer and a medium.

DISCLOSURE OF INVENTION

According to a first embodiment of this invention there is provided a device for matching acoustic impedance between an ultrasonic transducer and a medium, the device comprising:

a body comprising a material having a high acoustic impedance to an ultrasonic signal, the body containing a plurality of acoustic impedance matching horns extending between two surfaces of the body wherein:

(a) the mouths of the horns are disposed in one surface and the throats of the horns are disposed in another surface;

(b) the magnitudes of the lengths and flares of the horns are such that the horns are capable of transmitting the ultrasonic signal; and

(c) the magnitude of the flare of each horn being such so as to provide a substantially smooth transition in acoustic impedance to the ultrasonic signal between the mouth and throat of the horn.

According to a second embodiment of this invention there is provided in combination:

(i) a device for matching acoustic impedance between an ultrasonic transducer and a medium, the device comprising:

a body comprising a material having a high acoustic impedance to an ultrasonic signal, the body containing a plurality of acoustic impedance matching horns extending between two surfaces of the body wherein:

(a) the mouths of the horns are disposed in one surface and the throats of the horns are disposed in another surface;

(b) the magnitudes of the lengths and flares of the horns are such that the horns are capable of transmitting the ultrasonic signal; and

(c) the magnitude of the flare of each horn being such so as to provide a substantially smooth transition in acoustic impedance to the ultrasonic signal between the mouth and throat of the horn; and

(ii) an ultrasonic transducer having a transmission/receiving surface capable of transmitting/receiving the ultrasonic signal;

wherein the transmission/receiving surface is disposed in relation to the surface in which the mouths are disposed whereby acoustic coupling between the ultrasonic signal from/to the transmission/receiving surface and the mouths is not substantially shunted by the acoustic impedance of the medium between the transmission/receiving surface and the mouths.

According to a third embodiment of this invention there is provided in combination:

(i) a device for matching acoustic impedance between an ultrasonic transducer and a medium, the device comprising:

a body comprising a material having a high acoustic impedance to an ultrasonic signal, the body containing a plurality of acoustic impedance matching horns extending between two surfaces of the body wherein:

(a) the mouths of the horns are disposed in one surface and the throats of the horns are disposed in another surface;

(b) the magnitudes of the lengths and flares of the horns are such that the horns are capable of transmitting the ultrasonic signal; and

(c) the magnitude of the flare of each horn being such so as to provide a substantially smooth transition in acoustic impedance between the mouth and throat of the horn; and

(ii) an ultrasonic transducer having a transmission/receiving surface capable of transmitting/receiving the ultrasonic signal;

wherein the transmission/receiving surface is disposed in relation to the surface in which the throats are disposed whereby acoustic coupling between the ultrasonic signal from/to the transmission/receiving surface and the throats is not substantially shunted by the acoustic impedance of the medium between the transmission/receiving surface and the throats.

According to a fourth embodiment of this invention there is provided a process of constructing a device for matching acoustic impedance between an ultrasonic transducer and a medium, the process comprising:

forming a plurality of acoustic impedance matching horns in a body formed of a material having a high acoustic impedance to an ultrasonic signal, whereby the acoustic impedance matching horns extend between two surfaces of the body and wherein:

(a) the mouths of the horns are disposed in one surface and the throats of the horns are disposed in another surface;

(b) the magnitudes of the lengths and flares of the horns are such that the horns are capable of transmitting the ultrasonic signal; and

(c) the magnitude of the flare of each horn being such so as to provide a substantially smooth transition in acoustic impedance between the mouth and throat of the horn.

According to a fifth embodiment of this invention there is provided a system for transmitting ultrasonic signals between an ultrasonic transducer and a medium, the system comprising: the combination of the second or third embodiments; and means to drive the transducer at a frequency corresponding to the acoustic frequency, operatively associated with the transducer.

According to a sixth embodiment of this invention there is provided a system for detecting ultrasonic signals between an ultrasonic transducer and a medium, the system comprising: the combination of the second or third embodiments; and means to detect a signal from the transducer at a frequency corresponding to the acoustic frequency, operatively associated with the transducer.

According to a seventh embodiment of this invention there is provided a system for transmitting and detecting ultrasonic signals between an ultrasonic transducer and a medium, the system comprising: the combination of the second or third embodiments; means to drive the transducer at a frequency corresponding to the acoustic frequency, operatively associated with the transducer; and means to detect a signal from the transducer at a frequency corresponding to the acoustic frequency, operatively associated with the transducer.

According to a eighth embodiment of this invention there is provided a system for transmitting and detecting ultrasonic signals between an ultrasonic transducer and a medium, the system comprising: (a) a first combination comprising the combination of the second or third embodiments; means to drive the transducer of the first combination at a frequency corresponding to the acoustic frequency, operatively associated with the transducer of the first combination; and means to detect a signal from the transducer of the first combination at a frequency corresponding to the acoustic frequency, operatively associated with the transducer of the first combination; and (b) a second combination comprising the combination of the second or third embodiments; means to drive the transducer of the second combination at a frequency corresponding to the acoustic frequency, operatively associated with the transducer of the second combination; and means to detect a signal from the transducer of the second combination at a frequency corresponding to the acoustic frequency, operatively associated with the transducer of the second combination.

According to an ninth embodiment of this invention there is provided a method for transmitting ultrasonic signals between an ultrasonic transducer and a medium, the method comprising: driving the transducer of the system of the fifth embodiment whereby it transmits ultrasonic signals of frequency above the lower cutoff frequency of the horns.

According to a tenth embodiment of this invention there is provided a method for detecting ultrasonic signals between an ultrasonic transducer and a medium, the method comprising: detecting ultrasonic signals of frequency above the lower cutoff frequency of the horns with the system of the sixth embodiment.

According to a eleventh embodiment of this invention there is provided a method for transmitting and detecting ultrasonic signals between an ultrasonic transducer and a medium, the method comprising:

driving the transducer of the system of the seventh embodiment whereby it transmits ultrasonic signals of frequency above the lower cutoff frequency of the horns; and

detecting ultrasonic signals of frequency above the lower cutoff frequency of the horns with the system of the seventh embodiment.

According to an twelfth embodiment of this invention there is provided a method for transmitting and detecting ultrasonic signals between an ultrasonic transducer and a medium, the method comprising:

driving the transducer of the first or second combinations of the eighth embodiment whereby it transmits ultrasonic signals of frequency above the lower cutoff frequency of the horns; and

detecting the ultrasonic signals generated by the transducer of the first or second combinations of the eighth embodiment with the transducer of the second or first combinations of the eighth embodiment.

Generally, the body is a plate, the mouths of the horns are disposed on one side of the plate and the throats of the horns are disposed on the other side of the plate. Alternatively, the body may comprise a curved or spherical surface in which the mouths of the horns are disposed and/or may comprise a curved or spherical surface in which the throats of the horns are disposed. Generally the surface of the body having the throats is adjacent the transmission/receiving surface of the ultrasonic transducer and this surface of the body may have a shape to match the shape of the transmission/receiving surface of the ultrasonic transducer. The body may comprise a curved or spherical surface in which the mouths of the horns are disposed and the axes of the horns pass through a common point proximate the throats of the horns so as to form a multi cellular arrangement of the horns.

Typically, the transmission/receiving surface of the ultrasonic transducer is substantially planar.

The preferred horn shape is catenoidal but other shapes including exponential, parabolic and conical shapes are also suitable. The mouths of the horns are to be taken throughout the specification and claims to be of having an equal to or greater diameters than the diameters of the throats of the horns. The mouths of the horns are generally closely packed. Preferably the packing is such that it is radially symmetrical so that the area of the mouths of the horns is maximised and energy losses caused by facots such as cancellations (destructive interferences) of ultrasonic waves entering or leaving the horns is minimised. Generally the mouths of the horns are arranged in an hexagonal close packed array. When arranged in an hexagonal close packed array adjacent centres of the mouths are optimally spaced by less than $\lambda/2$ where λ is the wavelength of the ultrasonic signal to be coupled to the surrounding bulk medium. When the body is a plate the lengths and flares of the horns are determined in accordance with the plate thickness such that the selected operational frequency range is above the lower "cut-off" frequency of the horns in the plate as will be described in further detail below. In practice, the plate thickness is about $\lambda/2$ where λ is the wavelength of the ultrasonic signal to be coupled to the surrounding bulk medium. It is preferred that the plate thickness is less than λ because this results in any resonance effects being kept very small. The plate is placed in front of the radiating surface of an ultrasonic transducer at a distance which varies according to the application. This requires the distance to be such that the impedance of the medium in the gap between the plate and transducer does not significantly shunt the throat impedance of the holes.

The ultrasonic impedance matching device of this invention relies on a fundamentally different principle to the 1/4 wave plates described in relation to the background art. An acoustic horn is a length of material, which may be air contained in a pipe or it may be a solid horn of, for example, ceramic material usually but not necessarily of monotonically varying cross section.

The ultrasonic impedance matching horn parameters which affect its usefulness are its input impedance, its output impedance, its flare, its shape, its gain and its length. The input impedance generally closely matches the source impedance for maximum energy transfer. The output impedance should closely match the load impedance for maximum energy transfer.

The flare of a ultrasonic impedance matching horn must not change too quickly with the result that the cross sectional area of the conduit does not change too quickly. This criterion is usually expressed in terms of a flare parameter which determines the maximum rate of flare for any given horn geometry and frequency in terms of wavelength. Thus, for a given flare and horn length there is a minimum frequency, f_c, below which waves do not propagate in the horn. This is the lower "cut-off" of the horn.

The ultrasonic pressure gain of a horn is the ratio of the output radius to the input radius, r_o/r_i. The intensity gain is the corresponding ratio of the areas, S_o/S_i. The form of the horn gain versus frequency for a given horn is different for different geometries when the frequency is near lower cut off but at frequencies more than twice lower cut off all gains tend to the same value. Common horn shape choices are conical, parabolic, exponential and catenoidal. These ones happen to be readily calculable. However, for this invention, the optimum horn shape is immaterial if the horn is operated well above cut-off. A conical horn approaches the optimum gain slowly with length whilst exponential and catenoidal horns operate with full gain when frequency is not too far above lower cut-off. The catenoidal horn has a more extreme curve to its shape than the exponential, giving it a slightly higher lower cut-off frequency for the same length, but making the exponential easier to fabricate. The exponential horn gain drops quickly to zero as the frequency goes down to the cut-off. The catenoidal horn gain goes rapidly to infinity as the frequency decreases to cut-off. These horn shapes and transmissivities are illustrated in Figure 6. Clearly the most desirable operating condition is a catenoidal horn just above cut-off. In practice gains much larger than r_o/r_i are possible if the catenoidal horn is operated just above cut-off. The length of a horn for a given flare and frequency will simply give higher gains for longer horns since the ratio r_o/r_i increases. For a given gain, increasing the horn length lowers the cut off frequency since it reduces the flare rate. In either case the horn will exhibit length resonances like any other pipe and these maxima and minima superimpose on the gain curve for an "infinite" horn. If the mouth of the horn is sufficiently large that $kr_o > 3$ no resonances will occur and the sound will beam out the end.

Generally, in the second and third embodiments the combination is capable of transmitting and/or receiving ultrasonic vibrations having a vibrational peak in the frequency range 20kHz - 200kHz.

Typically the range is 22kHz-160kHz, 80kHz-120kHz, 95kHz-105kHz, 15kHz-60kHz, or 15kHz-30kHz or 30kHz-110kHz.

The device is generally formed of very rigid material to minimise energy absorption loss by the device. Examples of horn materials include epoxy resin(s), metals including steel covered with a damping material, lead and aluminium, metal alloys, teflon, particle boards, carbon fibre and wood,

Examples of transducer materials include lead zirconate-titanate, quartz, barium titanate, fluorspar, sodium potassium tartrate tetrahydrate, tourmaline and lithium niobate.

Another example of a transducer material is a piezoelectric foil which typically comprises a polyvinylidene fluoride ("PVDF") foil or a foil comprising a copolymer of PVDF. A piezoelectric transducer of the type described in New Zealand Patent Application No. 237971, the contents of which are incorporated herein by cross reference, is also suitable,

The transducer material or foil has at least two electrodes located thereon, typically one electrode on each side of the foil. The electrodes may be the same or different material, typically the same material. Examples of electrode materials are metals such as Au, Pd, Pt, Ti, Zn, Al, Ag, Cu, Sn, Ga, In, Ni, conducting polymers which require doping with doping agents such as iodine, fluorine, alkali metals and their salts, metal carbonates and arsenic halides, include polyacetylene, polyacetylene copolymers, polypyrroles, polyacrylonitriles, polyaromatics, polyanilines, polythiophenes, polycarbazoles, polybetadiketone and polydipropargylamine, polyacenaphthene/N-vinyl heterocyclics with Lewis acids, poly(heteroaromatic vinylenes), polyphthalocyanines, polymer reacted with 1,9-disubstituted phenalene, polycarotenoids, heterocyclic ladder polymers, alternating aromatic and quinonoid sequences, polyisothianaphthene and poly(para-phenylene) sulphide and polymers which do not require doping such as poly(diether-linked bis-o-nitrile), polyacetylene and polydiacetylene with spacer units, poly(peri-naphthalene), poly(carbon diselenide), transition metal poly(benzodothiolene), poly(thiophene sulfonates) and acetylene-terminated Schiff base.

Generally, the medium is a fluid such as a gas, including air or other gases including gas for domestic, commercial or industrial use or fluids including water and sea water.

When the medium to be coupled to is air or gas for domestic, commercial or industrial use, for example, the device of the invention is typically arranged in relation the transducer so that the throats of the horns are adjacent and opposite the transmission/receiving surface of the ultrasonic transducer so as to present a high impedance to the transducer and the mouths of the horns present a low impedance to the surrounding air thereby substantially providing in use an impedance match between ultrasonic signals emerging from the mouths of the horns. The conduits which form the horns and interconnect the mouths and the throats of the horns provide a smooth uniform impedance change from the high impedance at the throats to the low impedance at the mouths.

BRIEF DESCRIPTION OF DRAWINGS

Figure 1 is a perspective view of an impedance matching device according to this invention fitted to a transducer;

Figure 2 is a plan view of an ultrasonic impedance matching device according to this invention;

Figure 3 is an enlarged elevation of part of the device shown in Figure 2; and

Figure 4 is a schematic sectional elevation of an impedance matching device according to this invention fitted to a transducer;

Figure 5 is a schematic sectional side elevation of system for transmitting or receiving an ultrasonic signal according to this invention;

Figure 6 illustrates three horn shapes and the respective transmissivities as functions of frequency;

Figure 7 is a graph of measured sound gain as a function of frequency for horn mouth radius 1.0 mm, horn throat radius 0.28 mm and cut-off frequency 22kHz;

Figure 8 is a graph of measured sound gain as a function of frequency for horn mouth radius 1.2 mm, horn throat radius 0.30 mm and cut-off frequency 22kHz;

Figure 9 is a graph of measured sound pressure gain as a function of gap spacing for the design shown in Table II but the horn throat radii of (a) 0.18 mm and

(b) 0.30 mm.

BEST MODE AND OTHER MODES FOR CARRYING OUT INVENTION

Referring to Fig. 5 there is depicted system 500 for transmitting and detecting ultrasonic signals between ultrasonic transducer 501 and a gaseous medium 502. System 500 includes device 503 for matching acoustic impedance between ultrasonic transducer 501 and medium 502. Device 503 has body 504 comprising a material having a high acoustic impedance to the ultrasonic signal transmitted and/or received by transducer 501. Body 504 contains a plurality of acoustic impedance matching horns 505 extending between two surfaces 506 and 507 of body 504. Mouths 508 of horns 505 are disposed in surface 506 and throats 509 of horns 505 are disposed in surface 507. The magnitudes of the lengths and flares of horns 505 are such that horns 505 are capable of transmitting the ultrasonic signal. Further, the magnitude of the flare of each horn 505 is such so as to provide a substantially smooth transition in acoustic impedance to the ultrasonic signal between the mouth 508 and throat 509 of the horn 505.

Ultrasonic transducer 501 has a transmission/receiving surface 510 capable of transmitting/receiving the ultrasonic signal. Transmission/receiving surface 510 is separated from surface 507 in which throats 509 are disposed, by gap 511 by utilising spacers 512 and 513. Transducer 501 and device 503 are supported by supports 514 and 515 as are spacers 512 and 513. Supports 514 and 515 generally form a gas tight seal between device 503 and transducer 501. The size of gap 511 is selected so that ultrasonic coupling between the ultrasonic signal from/to the transmission/receiving surface and throats 509 is not substantially shunted by the acoustic impedance of the medium in gap 511. Surfaces 510 and 516 of transducer 501 have electrically conductive films thereon. Surfaces 510 and 516 are electrically coupled to switch 519 by lines 517 and 518 respectively. Switch 519 is in turn electrically coupled to switch 520 via lines 521 and 522 and amplifier 523 via lines 524 and 525. Amplifier 523 is electrically coupled to oscilloscope 526 via filter 527 via lines 528, 529, 530 and 531. Switch 520 enables switching between pulse generator 532 via lines 533 and 534 and square/sine wave generator 535 via lines 536 and 537. Switch 519 enables switching between switch 520 and amplifier 523.

In use, system 500 is located in gaseous medium 502 in which ultrasonic signals are required to be transmitted/detected. Transducer 501 is driven by ultrasonic electrical signals from pulse generator 532 or square/sine wave generator 535 via switches 519 and 520. Ultrasonic signals are transmitted from surface 510 and pass through horns 505 to medium 502 though which they pass to reflecting surface 538.

Ultrasonic vibrations reflected from reflecting surface 538 pass through horns 505 via gaseous medium 502 and cause transducer 501 to vibrate ultrasonically and are converted to ultrasonic electrical signals by transducer 501. The electrical signals from transducer 501 pass to amplifier 523 via switch 519 where they are amplified and then filtered by filter 527 and displayed subsequently on cathode ray oscilloscope 526.

EXAMPLE 1

In this example referring to Fig. 1 impedance matching device, horn plate 20, matches the output from a ceramic, PZT disc transducer 21 of diameter d=24mm operating at 100 kHz to the air. The impedance of transducer 21 is 3 x 10^7 mks Rayls and the impedance of air is 400 mks Rayls.

In the specific case of ultrasonic transduction into air, a horn 23 works by presenting the transducer face with a larger impedance, the throat impedance of the horn, than it would see operating straight into air. The horn transforms the throat impedance to the mouth impedance at horn mouths 40 (Fig.3) which more closely matches the air impedance.

However, transducer 21 sees the impedances of the horn throats 41 (Fig.3) shunted by the impedance of the air cavity in spacing gap 22 between transducer 21 and the throats 41 of horns 23 in horn plate 20. The impedance of an air cavity is a compliance or "capacitance" whose value, C, is proportional to the volume:

$C = V/\rho c^2$ and $Zc = 1/j\omega C$. (ρ is air density, c is speed of sound in air).

At high frequencies this volume must be very small or its resulting low impedance will shunt out the radiation impedance as seen transformed by the horns. At ultrasonic frequencies, greater than 40 kHz and typical transducer sizes, of radii up to 1.0 cm and more, it is extremely difficult to make this volume small enough.

One preferred way according to this invention of overcoming the problem is by providing perforated a hexagonally close packed array 31 of small horns as shown in Fig. 2. The individual horns in the horn plate 20 are air filled. The output diameter is $\lambda_{min}/2$ and so their centres are $\lambda/2$ i.e. 1.6 mm apart. Thus each horn 23 is driven by an area of the PZT equivalent to a piston of radius $\equiv \lambda_{min}/4$. This means that the volume of the cavity in front of each little horn 23 is only of radius $\lambda_{min}/4$ and height equal to spacing gap 22 separating horn plate 20 and transducer 21.

It is still necessary to keep gap 22 as small as possible. If the throat radius is r_i = 0.14 mm, calculation of the throat impedance shows that the gap between plate 20 and transducer 21 must be < 0.05 mm and really needs to be smaller than this to get the full gain of the horn. Nevertheless gap 22 must not be so small that boundary layer effects stop the ultrasonic signal from the whole of the transducer 21 from coupling to a horn throat 41. This provides a natural limit on the allowed throat diameters and thus on the horn gain.

The pressure gain of a horn 23 without resonances or effects from being close to cut off, or significant shunting by the volume in front of the PZT, is $r_o/r_i = 6$ or 15 dB.

The flare parameter, β, at 100 kHz is $\lambda/2\pi = 0.53$ mm. With $r_i = 0.14$ mm and $r_o = 0.8$ mm the minimum horn length can be calculated once the horn shape is decided. The minimum exponential horn length is $\beta \ln(r_o/r_i) = 0.53 \ln(6) \cong 1$ mm. In this example the horn will operate well above cut off and is conservatively selected to be $l = 2.4$ mm. These parameters of the impedance matching plate are:

flare parameter	$\beta = 0.53$ mm
output radius	$r_o = 0.8$ mm
throat radius	$r_i = 0.14$ mm
horn length (plate thickness)	$l = 2.4$mm
	$d = 12$ mm

Number of horns = 75

Any material can be used to form the plate 20 so long as it is reasonably rigid and has a high ultrasonic impedance. To form such small holes moulding is an ideal technique and in this example an epoxy resin was used. A series of pins is turned out of brass, each $\cong$ 15 mm long with the end turned to the desired horn shape. These pins are bundled tightly together so that they occupy the least space. In this way they naturally adopt hexagonal close packing. The epoxy is poured into a brass ring 33 of depth $\cong$ 0.3mm i.e. slightly greater than the final horn plate thickness 42 {Fig.3} (i.e. horn length). The bundle of pins is lowered tapered ends first into the epoxy and the epoxy is allowed to set. Once set the pins may be pulled out one by one after being slightly warmed. The resultant disc is brass ring 33 with epoxy plate 32 in the middle, perforated by close packed array of horn shaped holes 31. Referring to Figure 3 horn plate 20 is finished on both sides using fine wet and dry paper on an optical flat. During this process the throat radii, r_i, can be adjusted.

Figure 4 shows the impedance matching horn plate 20 fitted to transducer 21. Generally, gap 22 between plate 20 and transducer 21, which is $\cong$ 0.05 mm, is formed by placing conducting spacer ring 50, e.g. cut from metal foil, between transducer 21 and plate 20. Transducer 21, plate 20 and spacer ring 50 are supported by supports 51 and 52. The electrical contact to the front of the piezoelectric transducer (PZT) is made via supports 51 and 52 which are insulated from back contact 53 of transducer 21 by insulator layers 54 and 55, the brass edge of plate 20 and foil spacer ring 50. At 100 kHz the signal output from the PZT showed an increase by a factor of 3, with horn plate 20 fitted. At 100 kHz the full gain of horn plate 20, 6 times, was not realised due to shunting effects of gap 22 between transducer 21 and horn plate 20.

EXAMPLE 2

The lower cutoff frequency of a horn is determined by the flare rate of the horn profile, and details of the cut off behaviour by details of the profile. Its upper cutoff frequency is determined by the total curvature of the wavefront at the horn mouth, and thus by the mouth diameter and the semiangle of the cone tangent to the horn surface. Between these two cutoff frequencies, and assuming the throat to be terminated by a relatively high impedance, the pressure gain above the free-field value for a source on the axis is between 1 and 2 times the ratio of the mouth diameter to the throat diameter. The floating factor is 1 if the diameter of the horn mouth is small compared with the wavelength, and 2 if it is large or if the mouth is surrounded by a baffle. Below the lower cutoff frequency the pressure gain tends to unity, while above the upper cutoff frequency the gain is small and strongly frequency dependent.

The bandwidth of a horn increases, for given throat and mouth diameters, as its length increases, but this clearly leads to dimensional difficulties if the device is to be used in a confined space. Suppose we assume a transducer diameter of, say, 10 mm and seek a pressure gain of about 10 dB, then this requires a mouth diameter of about 30 mm (The floating factor is 2 for a horn of this size, but there is a balancing factor 2 because the diameter of the transducer itself is large compared with the wavelength.). If the operating frequency is to be 100 kHz, then the length of the horn must exceed about 100 mm in order to operate below the upper cutoff frequency. At 200 kHz the allowable wavefront curvature at the mouth is halved, so that the required horn length is doubled. (In neither case is the lower cutoff frequency the problem.)

The present invention overcomes this difficulty by replacing this single horn by an array of much smaller horns, distributed over a horn plate which covers the surface of a transducer (see Fig. 5, for example). The transducer surface itself is separated by a very small distance from the side of the plate through which the throats of the small horns open. Each horn can be designed to operate efficiently at the desired high ultrasonic frequency, say 100 kHz, and effectively serves only the small area of transducer surface located close to its open throat. It has been found that an arrangement of this sort operating at 100 kHz requires a plate no more than 2 mm in thickness covering the transducer surface, and can readily give a pressure gain, and thus an increase in transducer output, of 10 dB.

It is useful to sketch the design parameters of this device in qualitative terms. The acoustic impedance of the transducer is usually so great that it is a reasonable approximation to consider both it and the solid material of the matching horn plate as being completely rigid. This then simplifies the problem to a consideration of the pressure generated across the transducer surface by an axially incident sound wave. This must be compared with the value in the absence of the matching plate, which will be just twice the free-field pressure, since the transducer diameter is large compared with the wavelength. We can thus forget the floating factor 2 referred to above.

It is possible in accordance with this invention to design a horn to achieve a large gain at a fixed frequency if all its dimensions are available for adjustment. However the individual horn mouths can be widened only until they form a close-packed array on the plate surface, and the distance between horn axes will then be equal to the mouth diameters. Symmetry dictates that there is no acoustic flow across the polygonal boundaries defining the 2-dimensional cell associated with each horn throat, and therefore each horn can be viewed independently. It is clearly necessary for efficiency that there be only a small phase shift due to wave propagation in the space between the plate and the transducer surface in each cell. This sets the upper limit to the diameter of each cell at about a half wavelength, and so sets the same limit on the horn-mouth diameter. For operation at a frequency of say 100 kHz, the wavelength is about 3 mm.

The diameter of the horn throat is set by a compromise between the desirability of a small diameter to give a large pressure gain in the horn, and the desirability of a larger diameter to allow optimum matching to the space between the plate and the transducer surface. The nominal pressure gain of the horn, discussed above, refers to a situation in which the horn throat is rigidly blocked, and of course this is not so in the present invention. We must therefore turn attention to the loading effect of the gap between the back face of the horn-plate and the front face of the transducer. The incident pressure excites standing waves in this space, and they are damped both by motion of the transducer and, more importantly, by viscous and thermal losses at the two bounding surfaces. For optimum matching efficiency it is desirable to make the gap as thin as possible, conditional upon its width being much greater than the boundary-layer thickness. The boundary-layer thickness at the ultrasonic frequencies with which we are dealing is less than about 5 microns, so that the gap can be a few tens of microns, which is reasonable to achieve in practice. For matching of the cell to the horn, the area of the annular entry to the cell is generally small compared with the area of the horn throat, which dictates a throat diameter that is preferably an order of magnitude greater than the gap height. For a frequency near 100 kHz, this implies a throat diameter of a few tenths of a millimetre. These dimensions lead to an overall pressure gain of about 10 dB.

For horns as small as this, the dimensional limits are set by the lower rather than the upper cutoff frequency, and, for the diameter ratio suggested above, the horn needs to be rather more than half a wavelength long. This gives a matching-plate thickness of a few millimeters, which is mechanically convenient.

From above it follows that for a device and combination of the invention the available parameters can be optimised to produce useful gain without occupying appreciable space in the vicinity of the transducer.

An obvious advantage of the multi-horn plate is that it lends itself to fast and cheap manufacture. Since the constituent material is only required to be acoustically inert compared to air, great flexibility is allowed in its choice and the optimum dimensions lend themselves to fabrication by injection moulding. However, in the laboratory, we need to make individual plates with different characteristics without recourse to elaborate production methods.

The experimental plates were cast using a casting araldite To make the molds, the individual horn shapes were turned from narrow diameter brass rod using a numerically controlled jeweller's lathe. These horn pins had the horn shape at one end and a residual cylindrical section about 10 mm long. According to the desired diameter of the completed plate, bundles of the pins were held tightly in a teflon ring machined to a hexagonal shape, with the horn shaped points all protruding from one side. With this encouragement the pins readily organised themselves into a close packed order.

The casting resin was mixed and warmed to remove air bubbles and then poured into a brass holding ring set on a flat base. The pin bundle, coated with teflon mold release, was lowered, horn end first, into the resin. The individual pins were lightly tapped to make sure that their tips were all lined up on the base. After 24 hours the resin had solidified and the teflon ring was removed. The pins slid out readily one by one if they were individually warmed with the tip of a soldering iron. The plate was then allowed to harden for a further 24 hours until it was ready for finishing. Achieving an effective finish on the plates involved several steps, starting with initial rough flattening of both sides on a lathe. On the horn mouth side this was followed by careful lapping with sand paper down to 320 grade. The horn throat side was treated similarly, but on some plates this was followed by lapping on sandpaper of successively finer grades down to 2400, whilst others were finished using an optical finish grinder and final polishing was done using a 5 micron powder. Although this gave a surface roughness as small as 2 - 3 micron, the flatness was no better than 10 micron. Theoretical studies by the inventors suggested that typical spacings between transducer face and horn plate will be in the range 10 - 50 micron so that this flatness is inadequate. The surfaces finished with the optical grinder were flat to 2 - 3 micron but subsequent polishing sacrificed flatness in return for polish. Most of the plates were therefore not polished, but the importance of the finish was investigated and is discussed below.

A number of sets of pins was made. The throat and mouth radii, lengths, cut-off frequencies and shapes are summarised in Table I. Included is the major diameter of each type of finished plate excluding the holding ring.

TABLE I - DETAILS OF EXPERIMENTAL HORNS

Type#	Throat rad (mm)	Mouth rad (mm)	Length (mm)	Cut-off (kHz)	Plate dia (mm)	Shape
1	0.14	0.8	2.4	40	20	exponential
2	0.20	1.2	2.4	39	22	exponential
3	0.20	1.2	4.5	22	20	exponential
4	0.17	1.0	3.6	27	22	exponential
5	0.17	1.0	4.5	22	22	exponential
6	0.28	1.7	4.5	22	17	exponential
7	0.28	1.7	4.5	30	17	catenoidal

Evidently the maximum gain of a plate at a chosen frequency is tuneable via the horn parameters listed in Table I and the selection of the optimum spacing gap. To this end plate types 3 and 5 were selected for particular attention, since they have the same cut off frequency, and sets of 6 of each were made. A set of two of type 4 was made and one only of the other types listed in Table I was needed.

During the initial rough finishing of the sets of plates types 3 and 5, an increasing amount was turned off the horn throat side for each plate in the set. This,successively, reduced the horn length and thus increased the throat diameter without affecting the cut-off frequency. Horn throat diameters between 0.35 and 0.75 mm resulted. These were measured using a profile projector. The variation in throat diameters over a single plate was typically less than 5% although the smallest throat sizes were proportionally less smooth around the throat opening.

The plates were used with a PZT-4 transducer 12 mm thick and 30 mm across. It had five useful resonances up to 200 kHz, of which the lowest was a radial mode at 60 kHz. The transducer was mounted in a case, making electrical contact to the back, and a fine wire contact was attached to the rim of the front using epoxy, so that it did not get in the way of the plates. The transducer was driven from the output of a HP-4194 gain-phase analyser, and the acoustic signal was detected with a 1/8th inch condenser microphone, B&K 4180, positioned about 12 cm in front of the plate. The microphone was equipped with a conical screen to eliminate unwanted reflections.

For most of the experiments the transducer and plate were used as the transmitter but, when used as a receiver, a second transducer of the same type acted as the sound source. All the readings were normalised using the output of the transducer with a hexagonally shaped mask the same area as the active area of the horn plate placed in front of it, to give a true reading of the gain. Such a procedure was essential since the high Q of the transducer rendered its acoustic output highly variable with respect to frequency. The results are all given as the ratio of the detected sound pressure with the horn plate to that of the same quantity with the mask, p/p_0.

In order to be able to vary the spacing gap, d, the transducer was mounted on a table having a microscope traversing mechanism and the multi-horn plate was mounted separately. In this way the transducer-plate spacing could be continuously varied with a resolution of 2 - 3 microns.

The frequency response of the transducer plus matching plate was measured between 2 kHz and 200 kHz using the swept frequency of the gain-phase analyser. The spacing gap was adjusted to give maximum response at 60 kHz in each case, as will be described below. Typical results are shown plotted as points in Figs. 7 and 8.

Measurements to determine the optimum spacing gap were all performed at 60 kHz largely for reasons of convenience, since the transducer output at this frequency was high, the radial mode driving the transducer in the thickness direction by virtue of Poisson coupling. Measurements of the output were made at 5 micron intervals, with a 2 - 3 micron resolution, starting with the plate resting against the transducer face.

Fig. 9 shows the measured results for the horn plate of Table II, modified by surface grinding to give two different values of the horn throat radius.

TABLE II - TYPICAL DESIGN PARAMETERS

Horn mouth diameter	2 mm
Horn throat diameter	0.36 mm and 0.60 mm

Horncut-off frequency	30 kHz
Horn length	2.5 mm
Spacing gap width	varied (see Fig. 9)

The curves show a broad maximum for a spacing of about 30 microns, and the peak gain is a little more than 10 dB.

A notable feature of the experimental measurements is the relative insensitivity of the gain to the radius of the horn throats, caused by approximate balance between the loss in horn gain and the improvement of coupling to the gap as the throat radius is increased. The same applies to the gap spacing, which could be set anywhere in the range 20 - 40 microns with little effect on the gain. The lack of sensitivity in these two fine dimensions is clearly a great advantage when manufacture is considered.

In summary, the matching plates developed in this example are able to provide gain of about 10 dB over a frequency range from about 30 to 90 kHz. It is straightforward to scale the design to produce plates of higher or lower operating frequency. This example and the previous example also show that it is possible to fabricate adequately precise multi-horn plates by hand in the laboratory, and gives confidence that these devices could be produced simply, cheaply and to adequate tolerance in a manufacturing operation. The two fine dimensions, the separation gap between the multi-horn plate and the transducer surface, and the radius of the horn throat, are fortunately not critical in magnitude, so that simple assembly and testing techniques should be adequate.

The ultrasonic impedance matching device of this invention has the following advantages:

1. The plate may be formed from any material whose ultrasonic impedance is high so that other engineering imperatives can be catered for e.g. corrosion, price, ease of fabrication, material properties.

2. There is considerable flexibility of design. The horn parameters can be varied continuously without restrictions imposed by material considerations.

3. No gluing or other problems with attachment arise.

4. The horns are non resonant in that they do not rely on a resonant principle to operate so that the plate operates identically for both continuous waves and pulses. By the same token the horn length resonance possibilities can be utilised to further enhance continuous wave output.

5. The dimensions of the horn are not as critical for good operations as 1/4 wave matching layers. The frequency range of operation for any particular design is

relatively wide. Thus it has a wider bandwidth and is easier to make.

6. As the frequency is reduced the shunting is reduced (shunt impedance α $1/\omega$). In addition, the output radius, $r_i = \lambda/4$, increases ($\cong 1/\omega$) while the input radius may be kept at 0.1 mm so that the gain, equal to r_0/r_i, increases as $1/\omega$. Thus, the horn matching plate works best at the lower ultrasonic frequencies, 40 - 100 kHz, which is the frequency range not presently covered by solid matching layer technology.

INDUSTRIAL APPLICABILITY

A combination of the invention is especially useful in systems for detecting and/or transmitting ultrasonic vibrations in air or other gases including gas for domestic, commercial or industrial use or fluids including water and sea water.

CLAIMS

1. A device for matching acoustic impedance between an ultrasonic transducer and a medium, the device comprising:

a body comprising a material having a high acoustic impedance to an ultrasonic signal, the body containing a plurality of acoustic impedance matching horns extending between two surfaces of the body wherein:

(a) the mouths of the horns are disposed in one surface and the throats of the horns are disposed in another surface;

(b) the magnitudes of the lengths and flares of the horns are such that the horns are capable of transmitting the ultrasonic signal; and

(c) the magnitude of the flare of each horn being such so as to provide a substantially smooth transition in acoustic impedance to the ultrasonic signal between the mouth and throat of the horn.

2. The device of claim 1 wherein the body is a plate, the mouths of the horns are disposed on one side of the plate and the throats of the horns are disposed on the other side of the plate.

3. The device of claim 1 or 2 wherein the mouths of the horns are closely packed.

4. The device of claim 1 wherein the mouths of the horns are in an hexagonal close packed array.

5. The device of claim 2 wherein the mouths of the horns are in an hexagonal close packed array.

6. The device of claim 4 or 5 wherein the adjacent centres of the mouths are spaced by less than $\lambda/2$ where λ is the wavelength of the ultrasonic signal.

7. The device of claim 2 or 5 wherein the plate thickness is equal to or less than about λ and greater or equal to about $\lambda/4$ where λ is the wavelength of the ultrasonic signal.

8. The device of claim 2 or 5 wherein the plate thickness is about $\lambda/2$ where λ is the wavelength of the ultrasonic signal.

9. The device of claim 1 or 2 for matching acoustic impedance for an ultrasonic signal having a vibrational peak in the frequency range 20kHz - 200kHz.

10. The device of claim 1 or 2 for matching acoustic impedance for an ultrasonic signal having a vibrational peak in the frequency range 40kHz - 100kHz.

11. The device of claim 1 or 2 for matching acoustic impedance for an ultrasonic signal having a vibrational peak in the frequency range 20kHz - 200kHz from a piezoelectric transducer to a gas selected from the group consisting of air, gas for domestic use, gas for commercial use and gas for industrial use .

12. The device of claim 1 or 2 wherein the shape of the horns is selected from the group consisting of catenoidal, exponential, parabolic and conical.

13. In combination:

(i) a device for matching acoustic impedance between an ultrasonic transducer and a medium, the device comprising:

a body comprising a material having a high acoustic impedance to an ultrasonic signal, the body containing a plurality of acoustic impedance matching horns extending between two surfaces of the body wherein:

(a) the mouths of the horns are disposed in one surface and the throats of the horns are disposed in another surface;

(b) the magnitudes of the lengths and flares of the horns are such that the horns are capable of transmitting the ultrasonic signal; and

(c) the magnitude of the flare of each horn being such so as to provide a substantially smooth transition in acoustic impedance to the ultrasonic signal between the mouth and throat of the horn; and

(ii) an ultrasonic transducer having a transmission/receiving surface capable of transmitting/receiving the ultrasonic signal;

wherein the transmission/receiving surface is disposed in relation to the surface in which the throats are disposed whereby acoustic coupling between the ultrasonic signal from/to the transmission/receiving surface and the throats is not substantially shunted by the acoustic impedance of the medium between the transmission/receiving surface and the throats.

14. The device of claim 13 wherein the body is a plate, the mouths of the horns are disposed on one side of the plate and the throats of the horns are disposed on the other side of the plate.

15. The combination of claim 13 or 14 wherein the mouths of the horns are closely packed.

16. The combination of claim 13 wherein the mouths of the horns are in an hexagonal close packed array.

17. The combination of claim 14 wherein the mouths of the horns are in an hexagonal close packed array.

18. The combination of claim 16 or 17 wherein the adjacent centres of the mouths are spaced by less than $\lambda/2$ where λ is the wavelength of the ultrasonic signal.

19. The combination of claim 14 or 17 wherein the plate thickness is equal to or less than about λ and greater or equal to about $\lambda/4$ where λ is the wavelength of the ultrasonic signal.

20. The combination of claim 14 or 17 wherein the plate thickness is about $\lambda/2$ where λ is the wavelength of the ultrasonic signal.

21. The combination of claim 13 or 14 for matching acoustic impedance for an ultrasonic signal having a vibrational peak in the frequency range 20kHz - 200kHz wherein the transducer is capable of transmitting/receiving an ultrasonic signal having a vibrational peak in the frequency range 20kHz - 200kHz.

22. The combination of claim 13 or 14 for matching acoustic impedance for an ultrasonic signal having a vibrational peak in the frequency range 40kHz - 100kHz ultrasonic signal having a vibrational peak in the frequency range 40kHz - 100kHz.

23. The combination of claim 13 or 14 for matching acoustic impedance for an ultrasonic signal having a vibrational peak in the frequency range 20kHz - 200kHz from a piezoelectric transducer capable of transmitting/receiving an ultrasonic signal having a vibrational peak in the frequency range 20kHz - 200kHz to a gas selected from the group consisting of air, gas for domestic use, gas for commercial use and gas for industrial use .

24. The combination of claim 13 or 14 wherein the shape of the horns is selected from the group consisting of catenoidal, exponential, parabolic and conical.

25. In combination:

(i) a device for matching acoustic impedance between an ultrasonic transducer and a medium, the device comprising:

a body comprising a material having a high acoustic impedance to an ultrasonic signal, the body containing a plurality of acoustic impedance matching horns extending between two surfaces of the body wherein:

(a) the mouths of the horns are disposed in one surface and the throats of the horns are disposed in another surface;

(b) the magnitudes of the lengths and flares of the horns are such that the horns are capable of transmitting the ultrasonic signal; and

(c) the magnitude of the flare of each horn being such so as to provide a substantially smooth transition in acoustic impedance to the ultrasonic signal between the mouth and throat of the horn; and

(ii) an ultrasonic transducer having a transmission/receiving surface capable of transmitting/receiving the ultrasonic signal;

wherein the transmission/receiving surface is disposed in relation to the surface in which the mouths are disposed whereby acoustic coupling between the ultrasonic signal from/to the transmission/receiving surface and the mouths is not substantially shunted by the acoustic impedance of the medium between the transmission/receiving surface and the mouths.

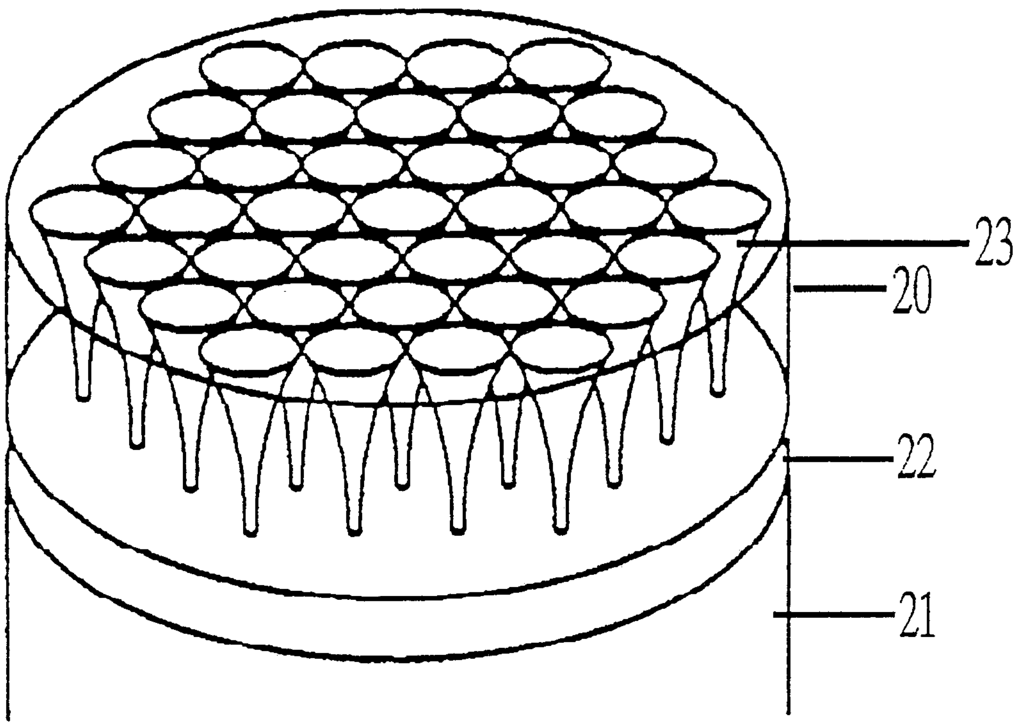


Figure 1

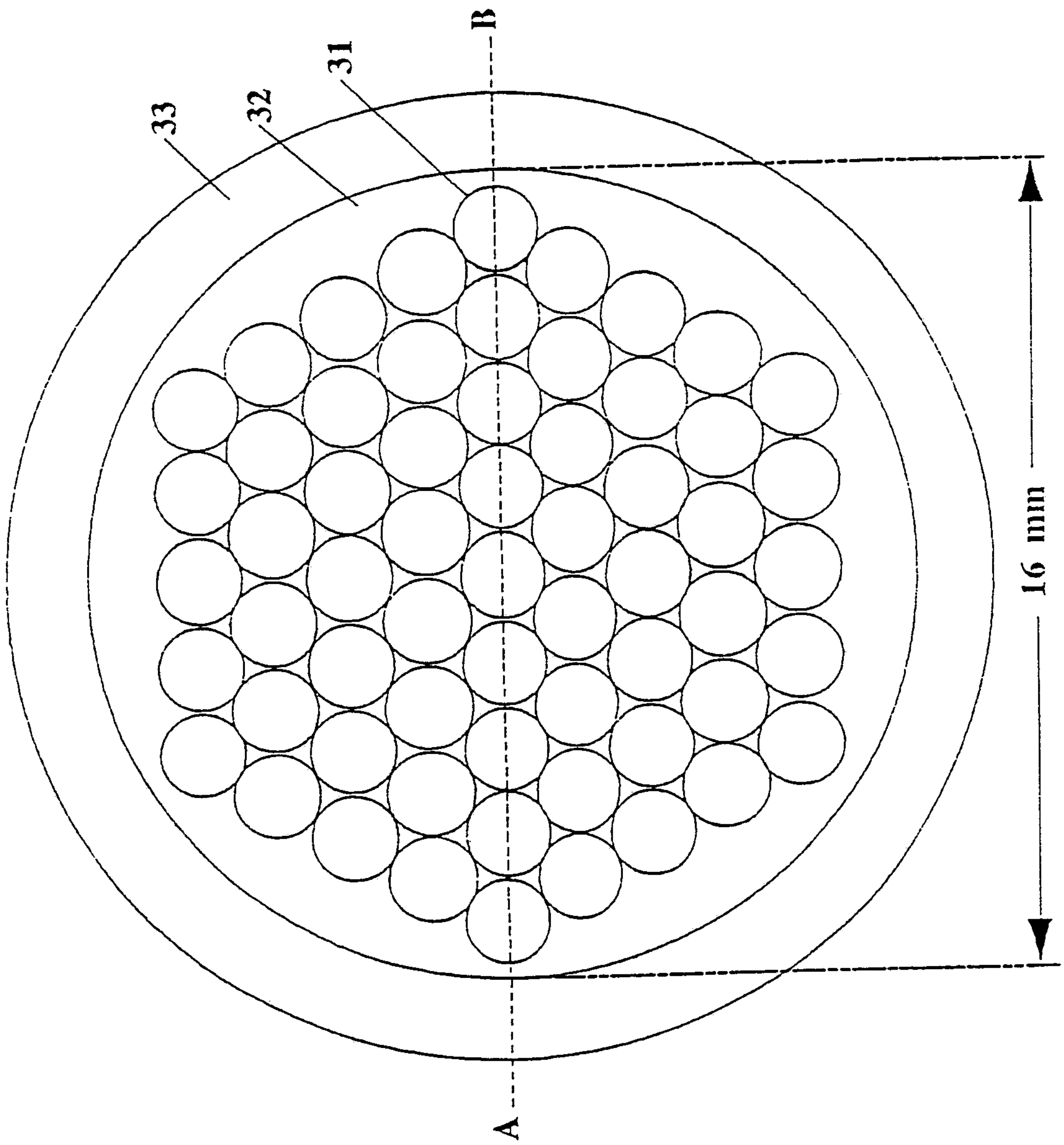


Figure 2

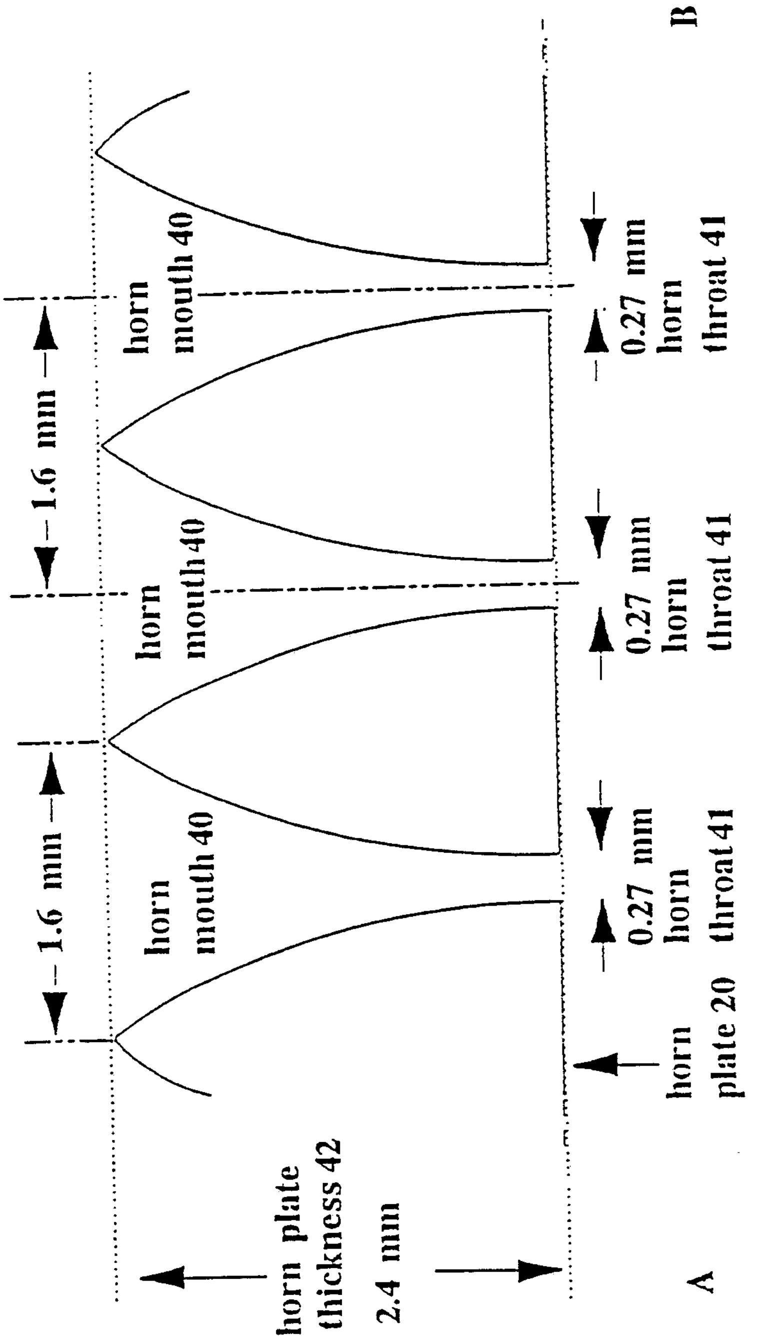

B
A
1.6 mm
1.6 mm
horn mouth 40
horn mouth 40
horn mouth 40
0.27 mm horn throat 41
0.27 mm horn throat 41
0.27 mm horn throat 41
horn plate 20
horn plate thickness 42
2.4 mm

Figure 3

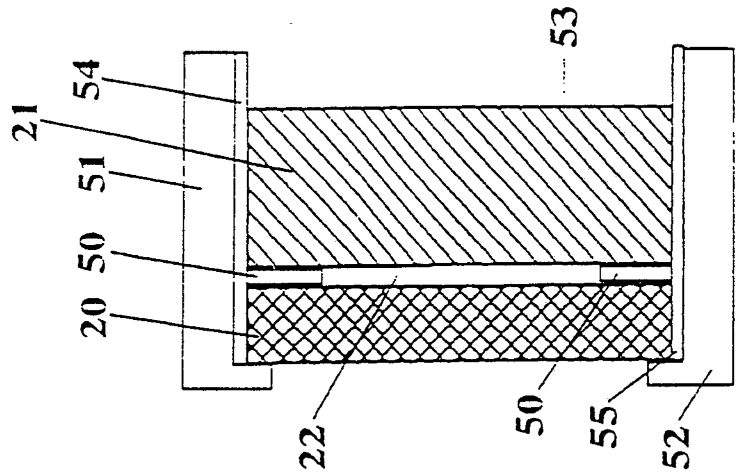
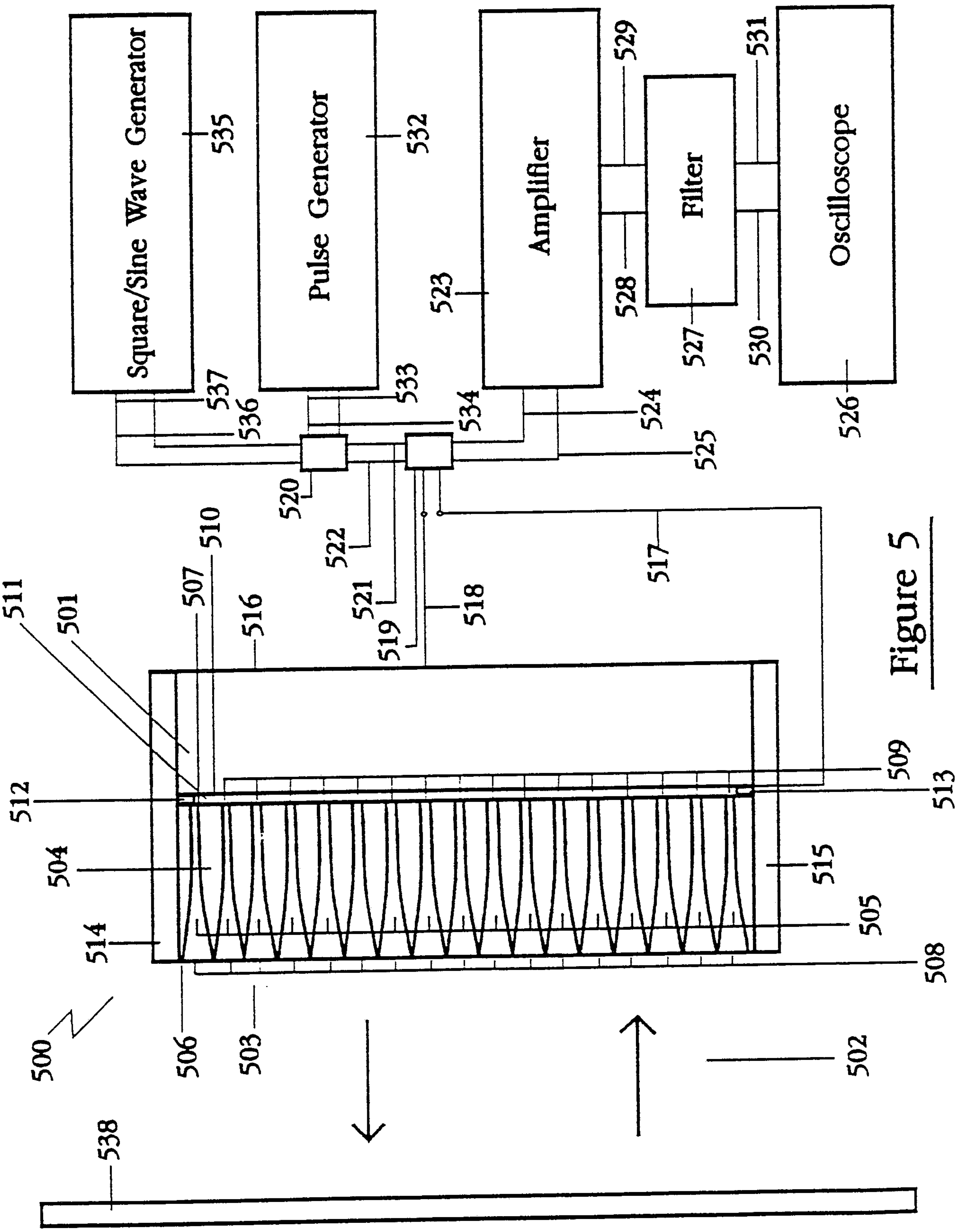


Figure 4


Square/Sine Wave Generator
Pulse Generator
Amplifier
Filter
Oscilloscope
500
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
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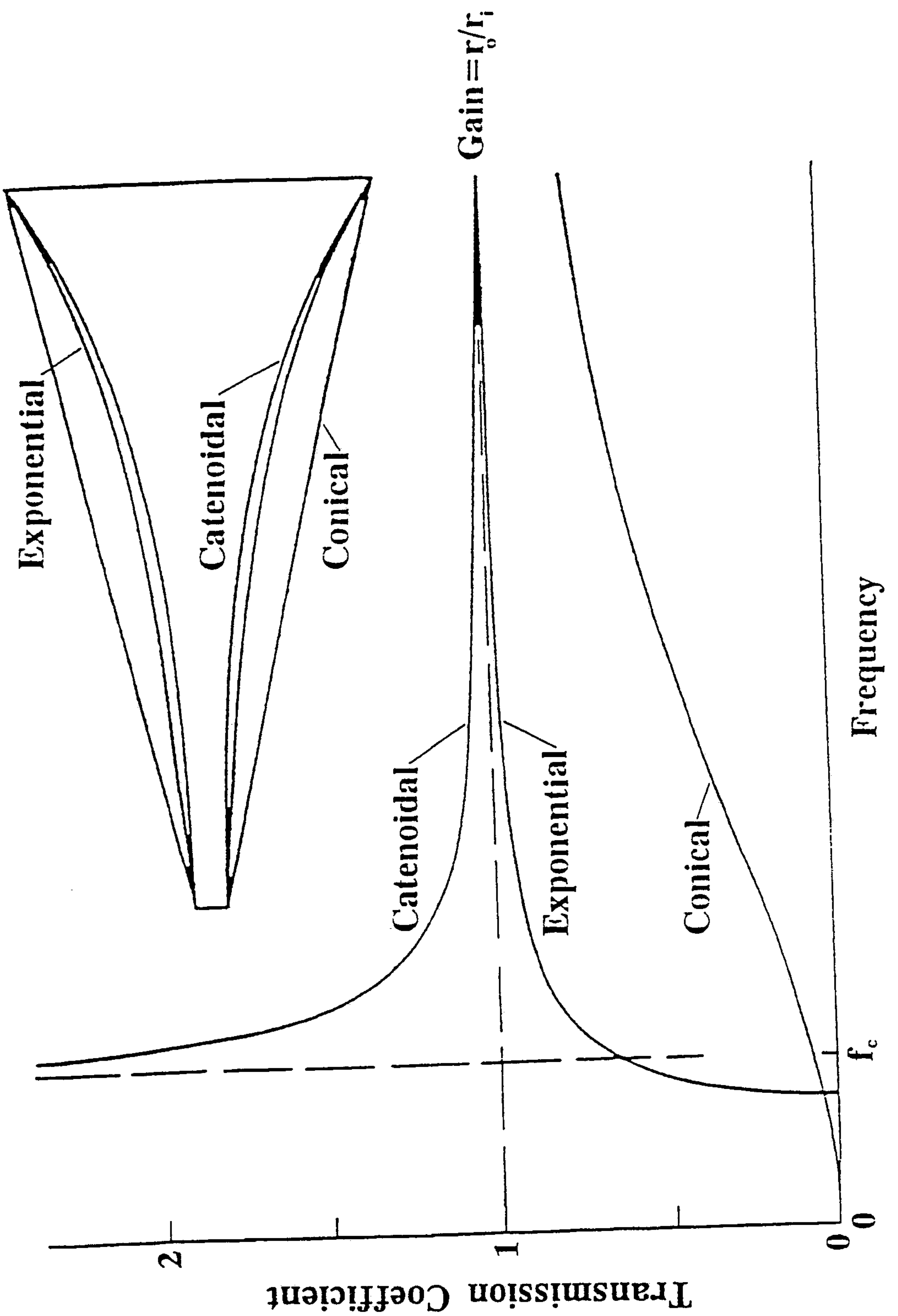
535
536
537
538

Figure 5



Gain=r_o/r_i
Exponential
Catenoidal
Conical
Catenoidal
Exponential
Conical
Frequency
f_c
0
0
1
2
Transmission Coefficient

Figure 6

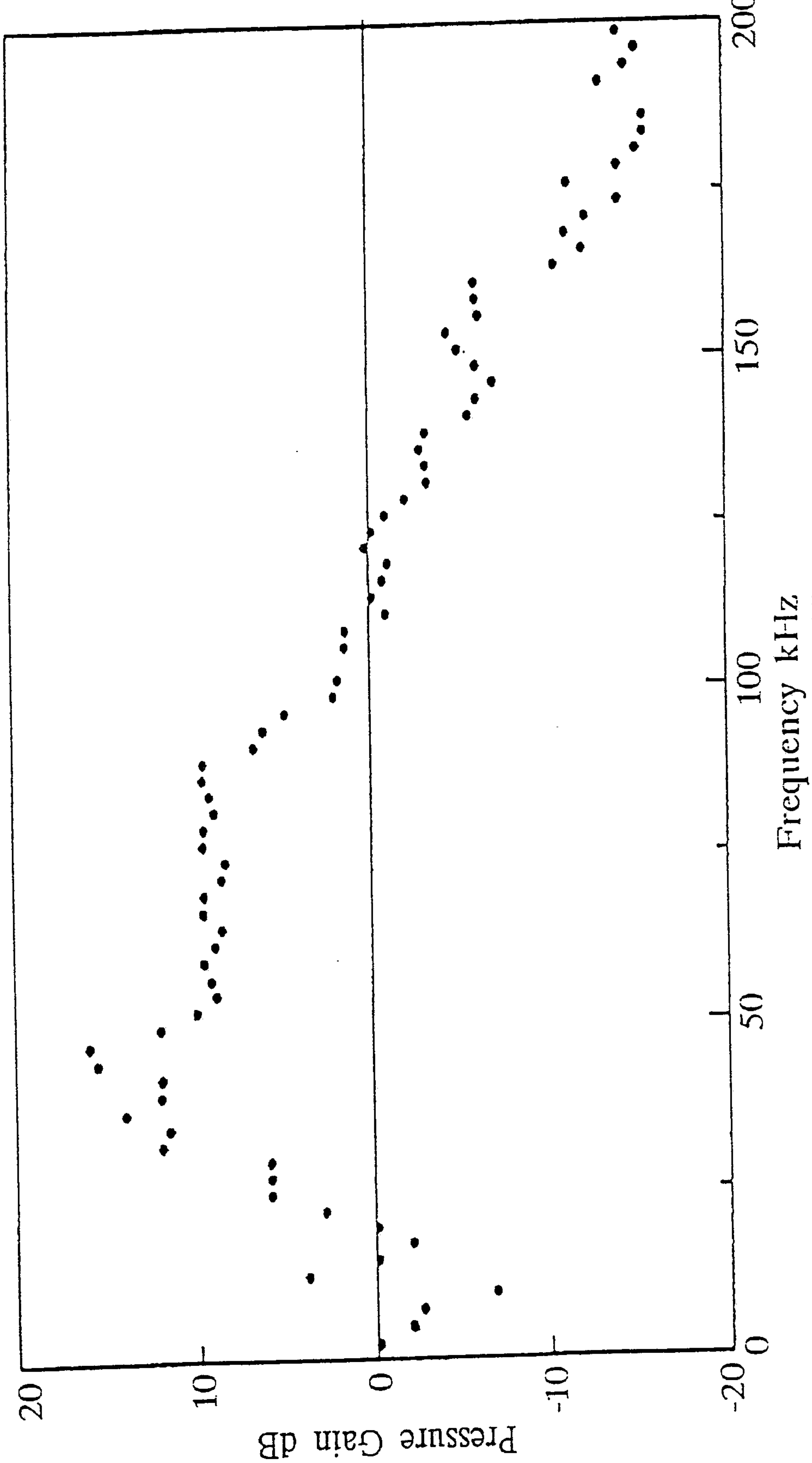


Figure 7

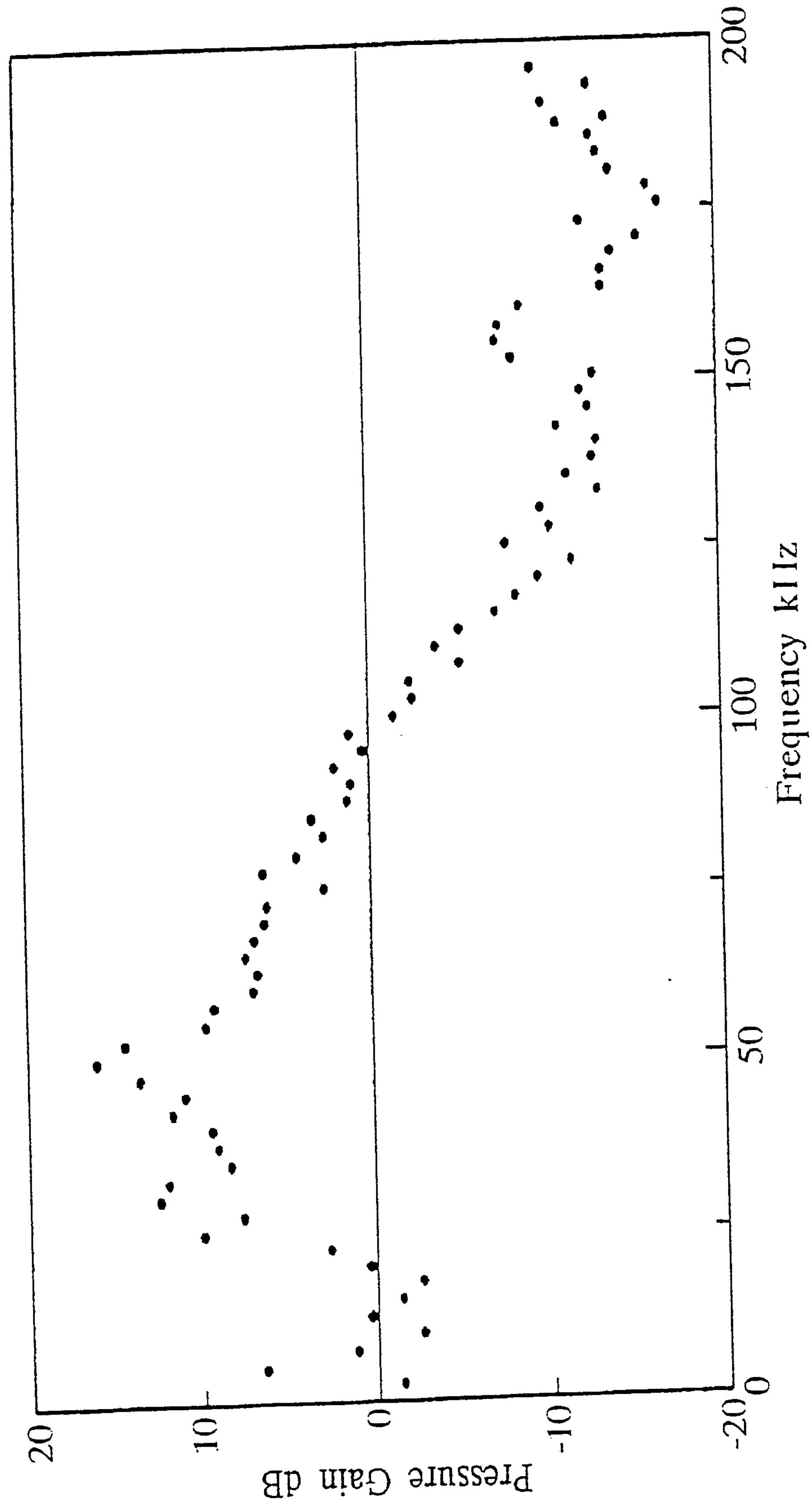
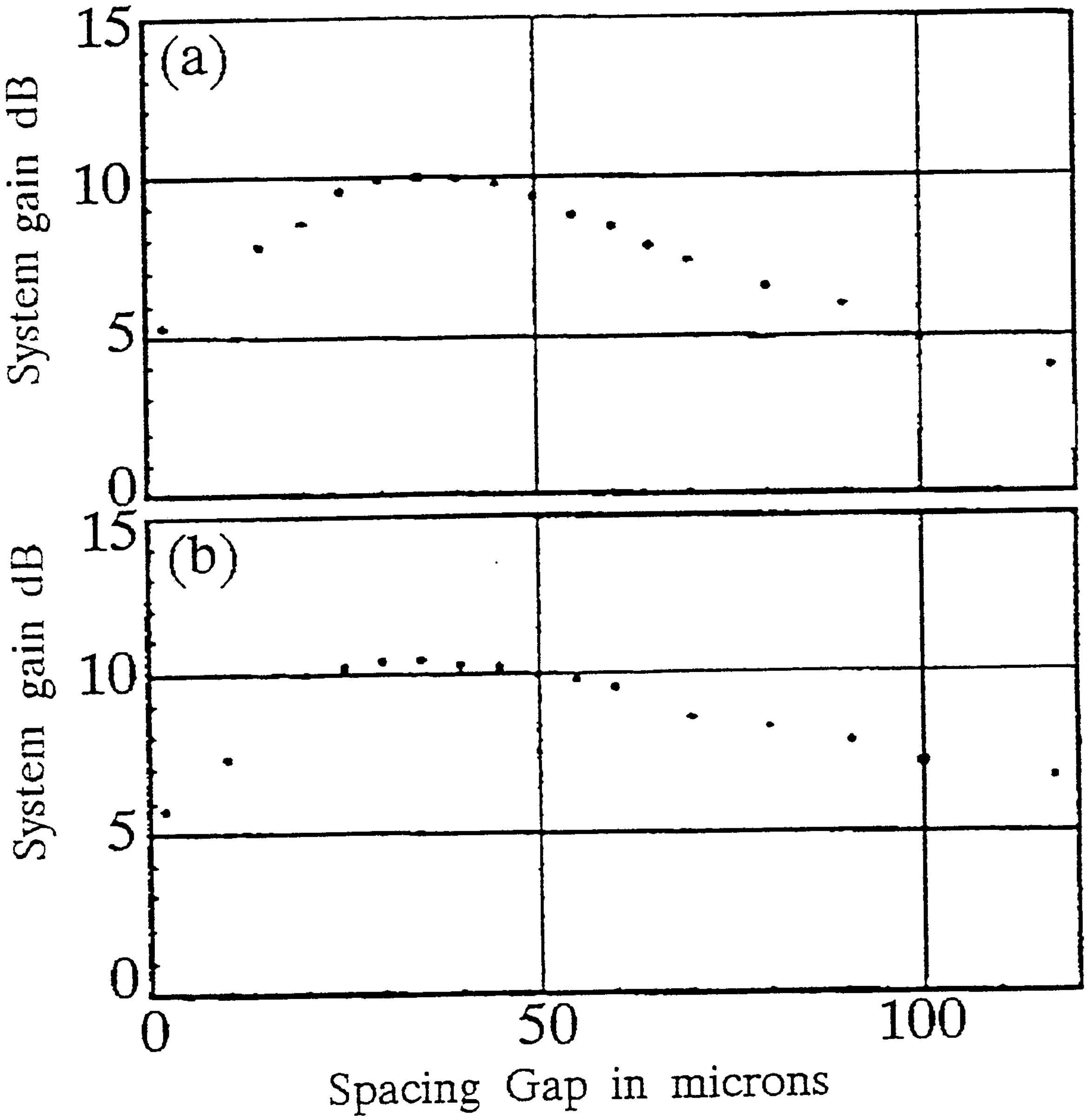


Figure 8



15
10
5
0
(a)
System gain dB
15
10
5
0
(b)
System gain dB
0
50
100
Spacing Gap in microns

Figure 9

INTERNATIONAL SEARCH REPORT

International Application No. PCT/AU 91/00206

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) 6

According to International Patent Classification (IPC) or to both National Classification and IPC

Int. Cl.[5] H04R 1/30, G10K 11/02

II. FIELDS SEARCHED

Minimum Documentation Searched 7

Classification System	Classification Symbols
IPC	H04R 1/30, G10K 11/02

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched 8

AU ; IPC as above

III. DOCUMENTS CONSIDERED TO BE RELEVANT 9

Category*	Citation of Document, 11 with indication, where appropriate, of the relevant passages 12	Relevant to Claim No 13
Y	US,A, 3852529 (SCHAFFT) 3 December 1974 (03.12.74) see column 1 lines 32-36	1-5, 7, 9-17, 19, 21-25
Y	Patents Abstracts of Japan, E-350, page 88, JP,A, 60-106294 (MATSUSHITA DENKI SANGYO K.K.) 11 June 1985 (11.06.85)	1-5, 7, 9-17, 19, 21-25
Y	US,A, 3584160 (JANSSEN) 8 June 1971 (08.06.71) see Fig. 1	1-5, 7, 9-17, 19, 21-25
Y	AU,B, 42329/89 (607085) (BRITISH GAS PLC) 5 April 1990 (05.04.90) page 1A line 12 - page 2 line 20	1-5, 7, 9-17, 19, 21-25

(continued)

* Special categories of cited documents: 10

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
27 August 1991 (27.08.91)	2 August 91
International Searching Authority	**Signature of Authorized Officer**
Australian Patent Office	a. W. Duke A.W. DUKE

FURTHER INFORMATION CONTINUED FROM THE SECOND SHEET

Y,P	AU,A, 46236/89 (MEGGITT LIMITED) 17 May 1990 (17.05.90) see abstract	1-5, 7, 9-17, 19, 21-25
A	GB,A, 1116358 (BLACKSTONE CORPORATION) 6 June 1968 (06.06.68)	

V. [] OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE 1

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1.[] Claim numbers ..., because they relate to subject matter not required to be searched by this Authority, namely:

2.[] Claim numbers ..., because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3.[] Claim numbers ..., because they are dependent claims and are not drafted in accordance with the second and third sentences of PCT Rule 6.4 (a):

VI. [] OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING 2

This International Searching Authority found multiple inventions in this international application as follows:

1. [] As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application.
2. [] As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:
3. [] No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim numbers:
4. [] As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

Remark on Protest

[] The additional search fees were accompanied by applicant's protest.

[] No protest accompanied the payment of additional search fees.

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL APPLICATION NO. PCT/AU 91/00206

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report	Patent Family Members		
AU 42329/89	DK 4751/89 JP 2177799	EP 361757	GB 2225426
AU 46236/89	WO 9005358		
US 3584160	DE 1904417	GB 1225098	
US 3852529	DE 2401132 IT 1008672	CA 988434 JP 49104619	FR 2213552 NL 7400200