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			GB 0547922 A	EP 2040483 A2
			EP 0984662 A2	WO 2018/047153 A1
			US 2293181 A	US 20160276992 A1
			US 20140027201 A1	
			US 10453438	
			US 10032445	
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(54) Title of the Invention: **Loudspeakers**
Abstract Title: **A sound-absorbing acoustic metamaterial used in a loudspeaker**

(57) The loudspeaker comprises an acoustic diaphragm 10 having front and rear surfaces, the acoustic diaphragm in use being driven to vibrate and radiate acoustic waves from its front surface in a forward direction A away from the loudspeaker and from its rear surface in a rearward direction.
A drive unit 20 is located to the diaphragm 16, and at least one tapered open duct 30 leads in a rearward direction away from the diaphragm. The at least one tapered open duct 30 has a cross-sectional area which decreases in a rearward direction.
Acoustic waves radiated from the rear surface of the diaphragm pass through at least a part. of the open duct before contacting a front surface of an acoustic rnetamaterial absorber 28 located generally to the rear of the duct.

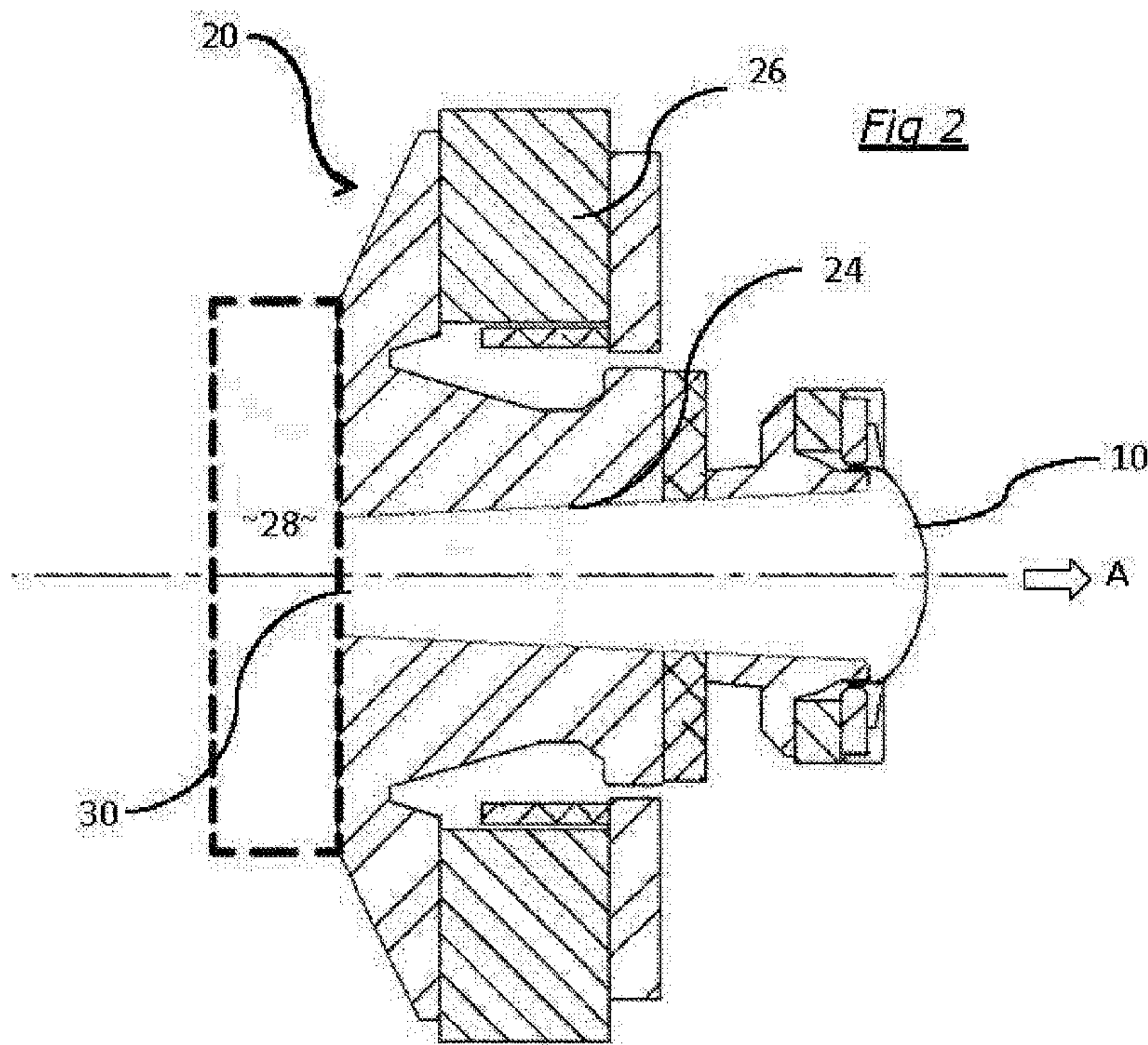


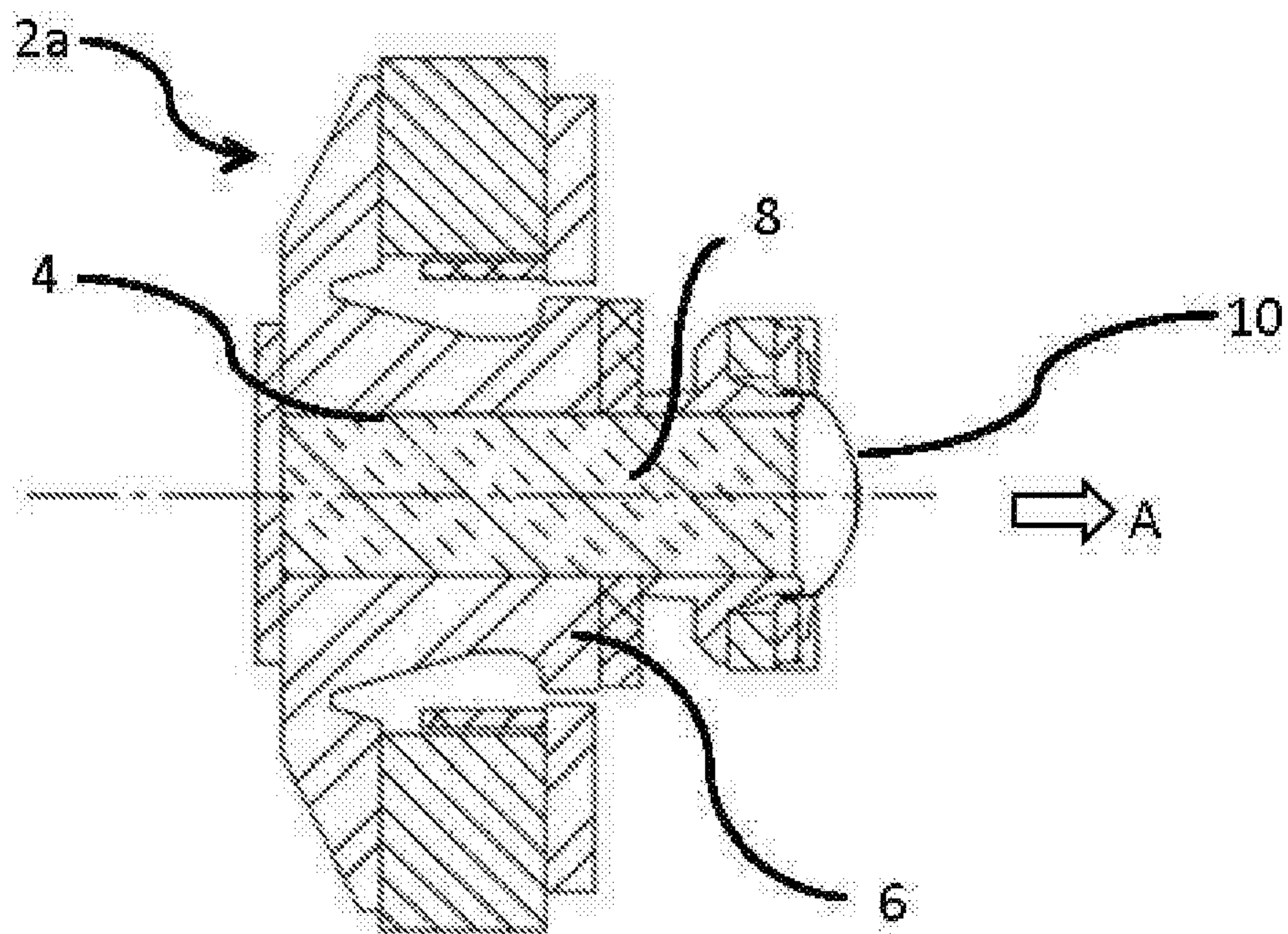
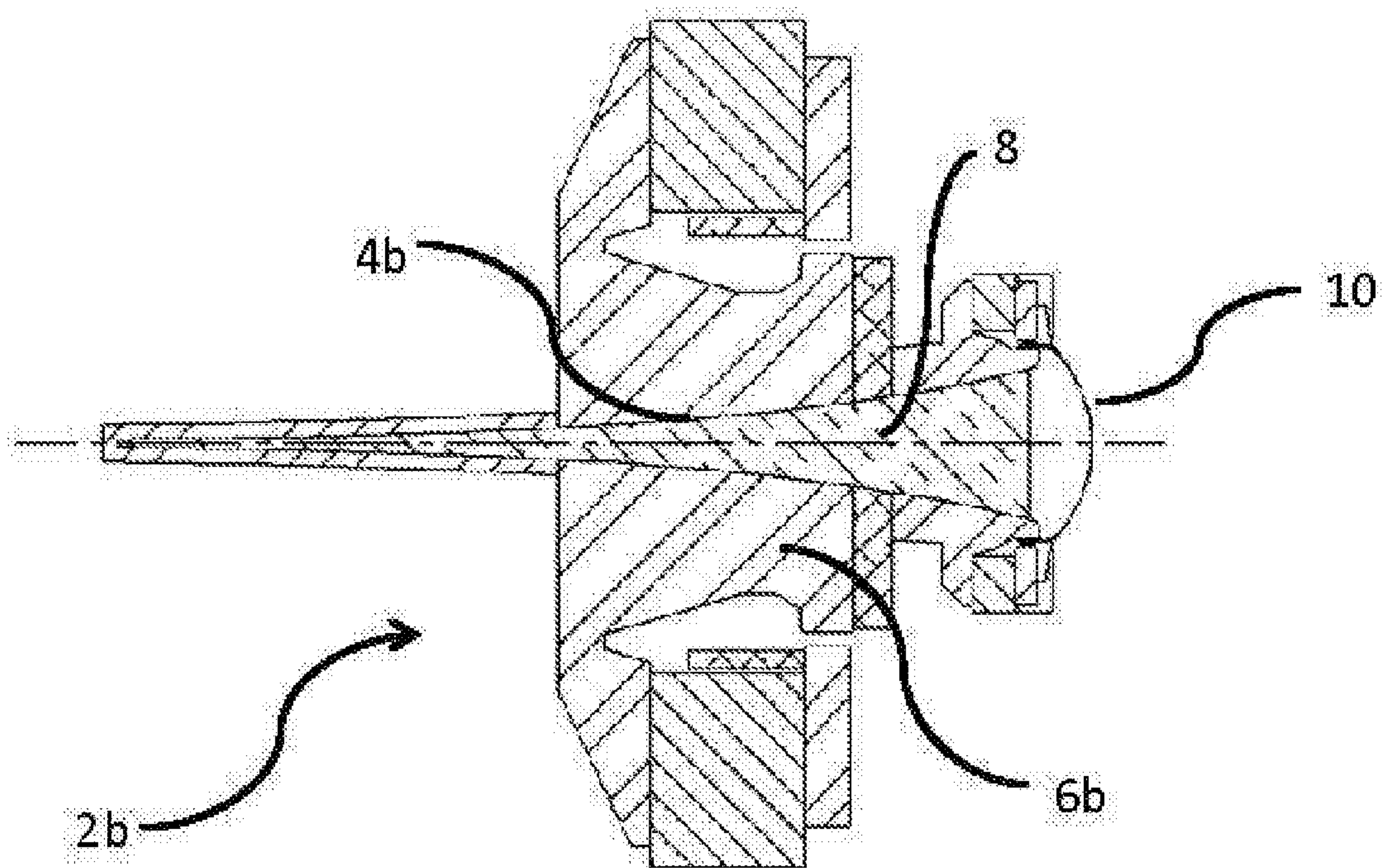
Fig 1aPrior ArtFig 1bPrior Art

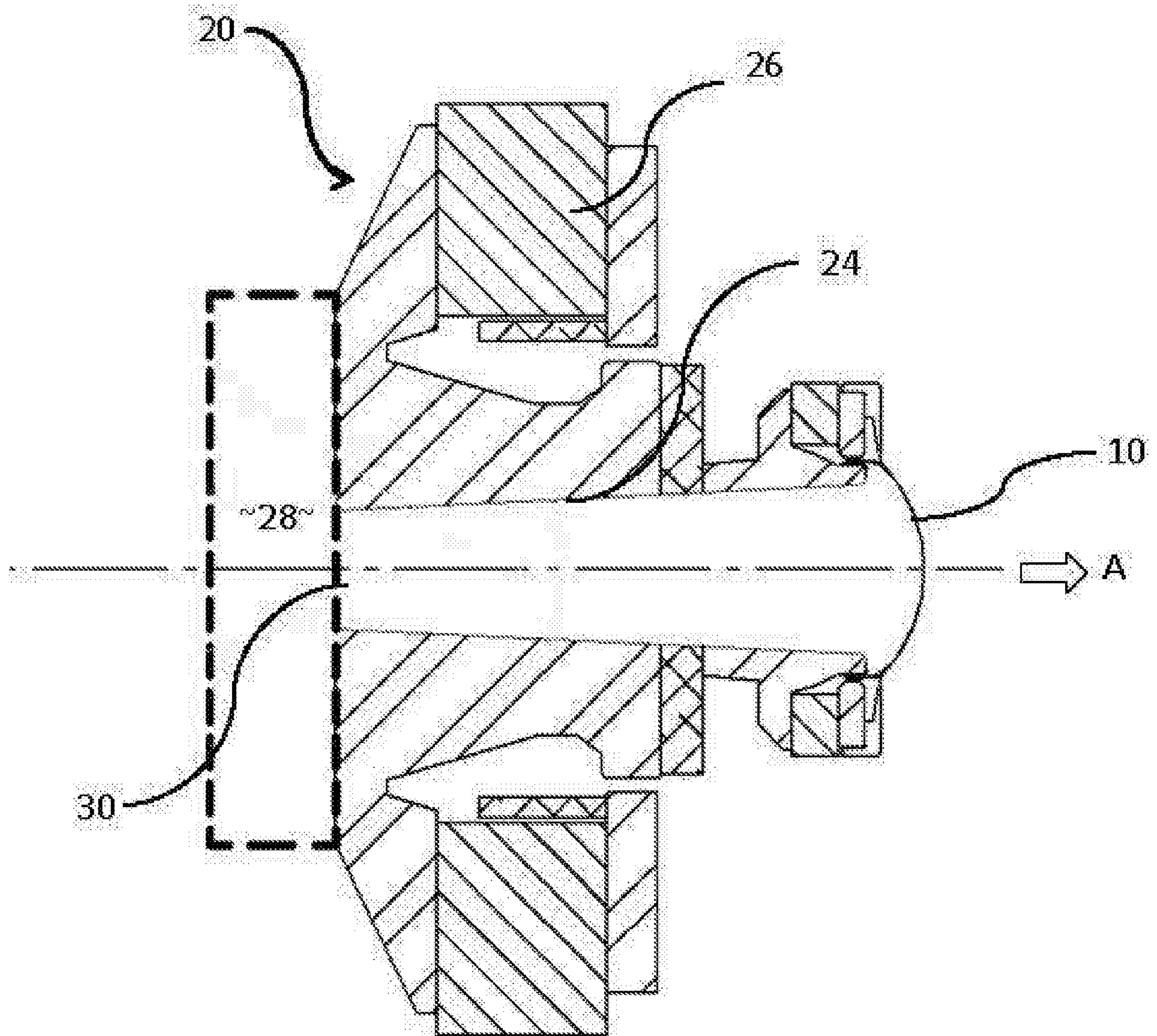
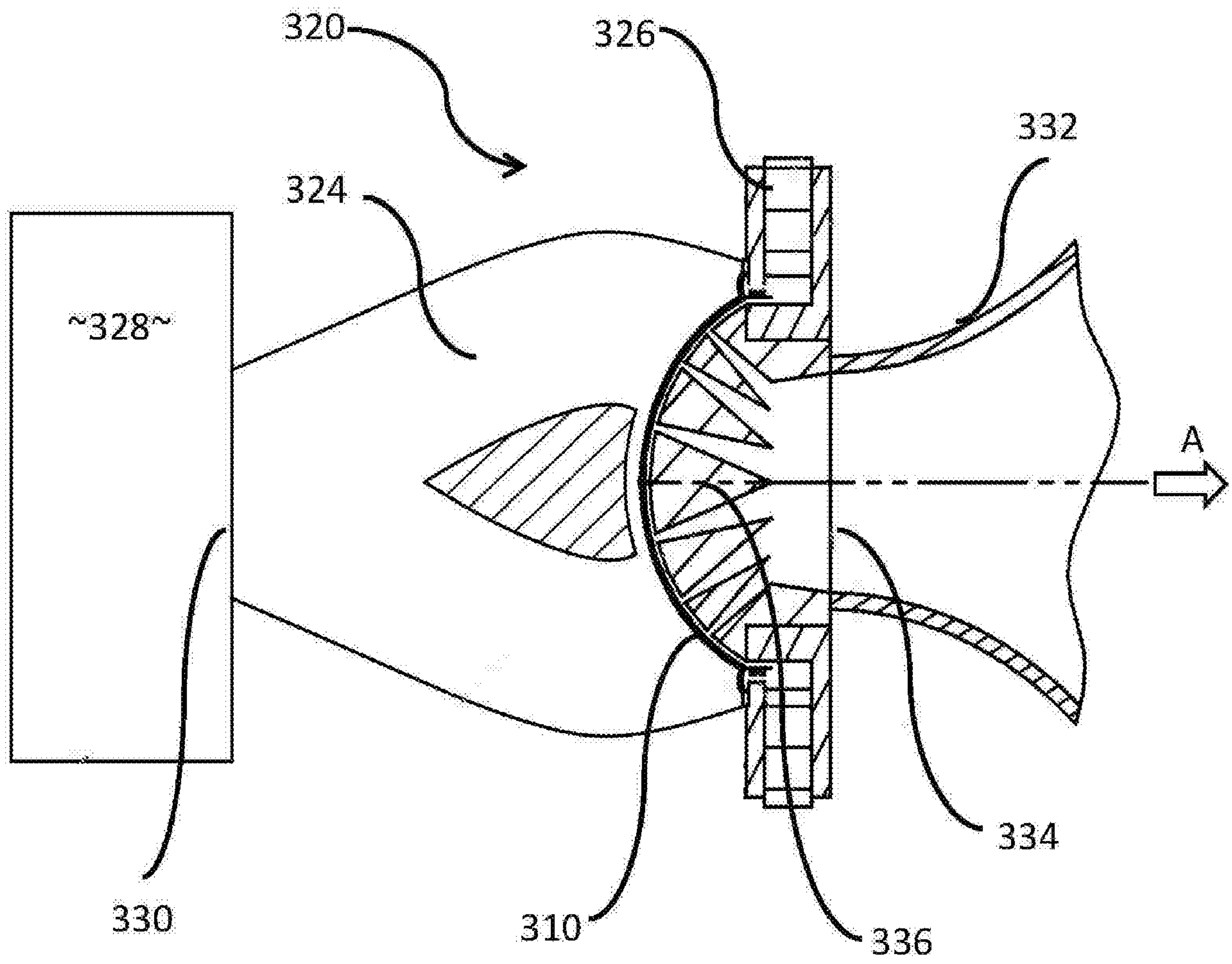
Fig 2

Fig 3



Loudspeakers

FIELD OF THE INVENTION

The present invention relates to loudspeakers.

BACKGROUND ART

The structure and operation of moving coil loudspeaker drive units is well known. A vibration diaphragm is attached to a coil of wire known as a voice coil, and the voice coil is placed in a magnetic field usually provided by one or more permanent magnets (together the voice coil and magnets being termed a motor or drive unit). When an alternating current is passed through the voice coil a force is induced in the voice coil, causing it to reciprocate and the diaphragm to vibrate and so to radiate acoustic waves. Acoustic waves are radiated from both sides of the diaphragm; the sound radiated from the front of the diaphragm is directed towards the listener, whereas the sound radiated from the rear of the diaphragm must be carefully treated if it is not to adversely affect the sound quality perceived by the user. In many cases, the loudspeaker is provided with an enclosure from which the front of the diaphragm projects, so that rear radiated sound is absorbed within the enclosure. For loudspeaker drivers operating in the midrange and high-frequency audio regions, from approximately 200Hz to 20kHz, the best possible scenario is that the rear radiated sound propagates totally unimpeded into the enclosure and is totally absorbed without reflection. This optimal situation would lead to the best possible sound quality with the driver free to operate without any influence from the enclosure.

A common approach to try and achieve this ideal is to provide an open duct directly behind the diaphragm, leading through or around the motor system, to allow the rear sound to propagate away from the loudspeaker diaphragm (as shown in our US5548657 for example). Figure 1a shows a section view of a prior art high frequency tweeter 2a from a coaxial driver using this approach, in this case having a large vent tube or duct 4 leading through the motor, or drive unit, 6 away from the rear of the diaphragm 10 (in this case having a 25.4mm diameter). The cross-sectional area of the duct 4 should be as large as possible for the rear sound to propagate unimpeded (the sound radiated from the front of the diaphragm 10 travels toward the direction of the listener, as shown by arrow A). In order to

absorb the rear sound and minimise reflection, the entire duct 4 is filled with an acoustically absorbent material 8, such as wadding or high density polyurethane foam. This simple approach has the advantage of allowing a relatively large volume rear enclosure, and this helps to reduce pressure behind the diaphragm 10 at low frequencies, but is quite poor at attenuating rear reflection and the example in Figure 1a reflects around 40% of the rear sound at 2kHz.

US2293181A describes a loudspeaker that attempts to achieve the above ideal using an exponentially tapering duct filled with lightweight porous wadding material. This style of midrange and high-frequency loudspeaker enclosure is now in wide use in high-quality loudspeakers. However, in order to achieve low reflection over a wide bandwidth the tapered duct must be long. In addition, the volume of air in the duct is smaller than the simpler arrangement of Figure 1a and this leads to a higher rear pressure at low frequencies, impeding the free movement of the diaphragm. Figure 1b shows a section through such a known high-frequency driver 2b from another coaxial driver (with a 25.4mm diameter diaphragm 10) using a 120mm long exponentially tapering duct 4b leading through the drive unit 6b to the rear enclosure. In use this duct 4b is again filled with a porous absorbent material 8, such as polyester fibre. A design such as this reflects approximately 30%, or -10dB, of the rear radiated sound at 2kHz, and is therefore an improvement over the design in Figure 1a in acoustic terms, but is significantly larger than the Figure 1a design.

There is a continuing need to provide loudspeakers which absorb rather than reflect a significant proportion of the rear radiated sound, whilst maintaining a small overall size.

SUMMARY OF THE INVENTION

The present invention is predicated on using acoustic metamaterials as the absorbing material, and on incorporating such materials in a design specifically tailored to reduce reflection of rear radiated sound in a small overall volume. A metamaterial is a material engineered to have a property that is not found in naturally occurring materials, in the present invention an acoustic metamaterial is a man-made material which has superior damping or vibro-acoustic characteristics compared to conventional damping materials. These improved characteristics comprise damping or absorbing sound or pressure to a greater extent than conventional absorbers, and/or over a greater variety or range of frequencies; these improved properties are often due to the structure of the metamaterial rather than its material

composition. Such structural metamaterials are made from assemblies of multiple elements fashioned from composite materials such as metals and plastics. The materials are often arranged in repeating patterns, and are at a scale that is smaller than the wavelengths of the phenomena they influence; in the present invention, acoustic wavelengths across the usual
5 audible frequency range, between about 20Hz and 20kHz. The precise shape, geometry, size, orientation and arrangement of the elements of acoustic metamaterials gives them their smart properties, capable of manipulating acoustic waves by blocking, absorbing, enhancing, or bending the waves. Structural acoustic metamaterials are known, for example from US 2014/0027201 and WO 2018/047153. Metamaterial absorbers
10 offer much higher absorption at comparable sizes to conventional absorbers, such as the tapered tube. For example the devices outlined in WO 2018/047153 have a length of about 11cm, and reflect (approximately) only 2% of the incident sound at 2kHz. Other, non-structural metamaterials comprise a plurality of active and/or mechanical components, such as a number of MEMs (Micro-Electro-Mechanical systems) diaphragms each with tuned mass,
15 stiffness and mechanical resistance, and such non-structural metamaterials provide an acoustic absorption of specific impedance. The present invention is not limited to structural metamaterials, but instead may be carried out using any kind of metamaterial.

A metamaterial absorber is typically composed of a number of narrow acoustical channels of various different lengths. The metamaterial absorbent surface is formed by closely
20 spaced walls forming ducts, or channels as we will refer to them here. These channels are usually sufficiently narrow for viscous effects of the air to dissipate acoustic energy. Often (as in WO2018047153A1) these channels are folded to create a compact overall structure. In most cases a significant portion of the acoustical dissipation comes from air viscosity in these narrow channels, and therefore it is important that the channels are extremely narrow to
25 attain optimum results. The manufacture of such an arrangement is complicated. In addition, the structural walls that form the channels through the metamaterial occupy volume and, in some arrangements, this can reduce the effectiveness of the absorber. A straightforward approach to improving existing designs would be to incorporate a metamaterial into a loudspeaker, by placing the metamaterial directly behind the diaphragm (e.g. so as to replace
30 the material 8 shown in Figures 1a and 1b with the same physical arrangement of metamaterial). The benefit of this approach is that the acoustical behaviour of the enclosure can be almost entirely dictated by the metamaterial. However, as can be appreciated from Figures 1a and 1b the space directly behind the diaphragm 10 is limited by the presence of

the drive unit 6a, 6b. This makes the design and manufacture of the metamaterial much more challenging due to practical limitations on minimum metamaterial wall thickness. In particular, since the structural walls of the metamaterial occupy volume and thus a proportion of the cross-sectional area of the duct 4a, 4b, this severely limits the effective open area that the metamaterial presents to the rear radiated sound, and consequently the path of the rear sound wave is significantly impeded. This issue is particularly severe if, in order to increase the viscous losses, extremely narrow metamaterial channels are used – because more channels require more walls, which take up a greater proportion of the cross-sectional area of the rearward-leading duct.

The present invention therefore provides a loudspeaker comprising: an acoustic diaphragm having front and rear surfaces, the acoustic diaphragm in use being driven so as to vibrate and radiate acoustic waves from its front surface in a forward direction away from the loudspeaker and from its rear surface in a rearward direction, a drive unit, and at least one open duct leading in a rearward direction away from the diaphragm, in which the at least one open duct has a cross-sectional area extending in the rearward direction, in which the cross-sectional area tapers or decreases along at least part of the rearward direction, and in which acoustic waves radiated from the rear surface of the diaphragm pass through at least a part of the open duct before contacting a front surface of an acoustic metamaterial absorber located generally to the rear of the duct, and to the rear of the decreasing cross-sectional area.

In such arrangements, the rear sound is channelled from the diaphragm to the metamaterial through a large area and low impedance duct with minimal or no porous acoustic wadding. This arrangement is very effective at allowing the majority of the rear-radiated sound to propagate to the metamaterial absorber, which in turn can be located further away from the diaphragm in an area where space is available, thereby allowing much more freedom over the metamaterial design and mechanical construction. There is also a subtlety to this arrangement that is not obvious on first examination. Although the metamaterial absorber can be designed to have extremely low reflection, this arrangement makes the effect of even a small reflection by the metamaterial much more problematic. Any reflection from the metamaterial will now occur at the interface between the duct and the metamaterial, the front surface of the metamaterial, which is now a significant rearward distance away from the diaphragm. The propagation time for the rear-sound to travel down the duct to the interface

and back to the diaphragm is typically several periods of the upper frequency range of the driver. This effect introduces irregularities into the driver diaphragm movement due to the reflective wave impinging on the diaphragm, and these irregularities can be severe even if the reflection from the metamaterial is a small percentage of the incident sound arriving at the metamaterial. It is therefore absolutely key to minimise any reflection from the front surface of the metamaterial at the interface between the duct and the metamaterial absorber. A significant proportion of the absorbent surface is formed by the walls separating adjacent channels, but these walls decrease the 'opening area' of the channels making it smaller than the 'opening area' of the driver duct* resulting in reflections. By aligning the channels with a surface normal or at an angle to the 'driver duct' aperture the total cross-sectional area of the channel apertures may be made to match the duct area, thereby greatly reducing reflections due to the wall thickness. (*The duct 'opening area' is the 'long-wavelength wavefront area' within an infinitely extending duct at the position of the opening). It is not always the case, however, that the metamaterial effective open area should match the duct open area. To get the best impedance match it is sometimes helpful to have a slight mismatch in the physical areas (to compensate for different acoustic materials or for viscosity in the meta-material).

In order to avoid acoustic reflection, the characteristic impedance of the wave travelling in the duct must match the acoustic impedance of the metamaterial absorber. Any fully enclosed and finite size acoustical absorber, including a metamaterial absorber, has zero absorption at very low frequencies. From this it follows that the real part of the acoustic impedance of the absorber will also be zero at very low frequencies. In addition, any fully enclosed, finite size acoustic absorber will have a low frequency impedance that has a negative imaginary part due to the acoustical compliance of the enclosed volume. A duct with constant cross-section, as shown in Figure 1a, carries a plane acoustical wave with a characteristic impedance that has zero imaginary part and a constant real part. Consequently a constant cross-section duct cannot minimise the impedance mis-match or the magnitude of the reflected sound. The characteristic impedance requirement, to have zero real part at low frequencies and a negative imaginary part, means that the duct necessarily must have a cross sectional area that reduces as the wave propagates from the diaphragm to the metamaterial absorber.

Accordingly, the acoustic impedance of the acoustic metamaterial absorber may substantially match the characteristic acoustic impedance of acoustic waves radiated from the

rear surface of the diaphragm at the point they contact the surface of the acoustic metamaterial absorber.

5 The acoustic metamaterial may be partially contained within the or each duct, or the or each open duct may have an opening at its rearward end, the front surface of the acoustic metamaterial absorber being located at this opening. Such arrangements effectively move the metamaterial absorber away from the rear of the diaphragm, so that the metamaterial is located behind the drive unit where there is more space and freeing up room immediately behind the diaphragm for other loudspeaker elements.

10 The drive unit and the at least one open duct may be located to the rear of the diaphragm and the at least one open duct may extend through the drive unit in a rearward direction, away from the diaphragm, with the front surface of the acoustic metamaterial absorber being located generally to the rear of the drive unit. Alternatively, the drive unit may be located outside and/or forwardly of the diaphragm; in this case, the open duct would not pass through the drive unit but would still extend rearwardly of the diaphragm, and the
15 metamaterial would be located at or adjacent the rearward end of the duct.

The or each open duct may taper conically towards the front surface of the acoustic metamaterial absorber, in a right or oblique cone. Additionally or alternatively the or each open duct might have walls which taper inwardly in a curve towards the front surface of the acoustic metamaterial absorber. There may be a plurality of open ducts, and each duct may
20 lead to a separate acoustic metamaterial absorber. The plurality of open ducts can be arranged in a matrix or in a ring and/or, where the plurality of open ducts is arranged in a ring, the ring can be circular. The or each open duct may have a constant cross-sectional shape, which may be circular. The or each open duct may contain sound absorbent material. The diaphragm can be a dome or conical diaphragm; in the latter case the duct(s) is/are preferably located outside
25 of the tweeter drive unit in an annular or ring-like arrangement, such as in our EP2952011, for example.

In another aspect, the invention also provides a method of designing a loudspeaker as described above in which one or more of the length, one or both end areas, the resonance frequency and the resonant strengths of the or each open duct are adjusted so as to allow
30 the acoustic impedance of the acoustic metamaterial absorber substantially to match the

characteristic acoustic impedance of acoustic waves radiated from the rear surface of the diaphragm at the point they contact the surface of the acoustic metamaterial absorber.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described by way of example and with reference to the
5 accompanying figures, in which;

Figures 1a and 1b show in cross-section prior art high frequency drivers from coaxial drivers;

Figure 2 shows an embodiment of a loudspeaker arrangement in accordance with the invention, and

10 Figure 3 shows a schematic view in cross-section of another loudspeaker arrangement in accordance with the invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Figure 1a shows a high-frequency driver with a 25.4mm diameter diaphragm using a large central vent tube/duct filled with dense acoustical wadding. Figure 1b shows a high-
15 frequency driver with a 25.4mm diameter diaphragm using a 120mm long, exponentially tapering duct.

Figure 2 shows in cross-section a tweeter 20 forming part of a coaxial driver with a highly effective arrangement according to this invention. The conical duct 24 through the drive unit 26 connecting the 25.4mm diameter diaphragm 10 to the front surface 30 of the
20 acoustic metamaterial 28 results in a spherical contracting acoustical wave with radius 146.4mm at the front surface 30 of the metamaterial 28. The characteristic acoustical impedance of this wave is a close match to the impedance of the metamaterial described in WO 2018/047153 when a design frequency of 600Hz is used. The impedance match in this case is not perfect and only over a limited bandwidth but it is enough that the reflection
25 issue is almost totally solved to the extent that it is not a limiting factor in the tweeter performance.

A tapering duct is also very practical for a number of reasons:

1. Commonly dome-shaped diaphragms are used on high-frequency units and the concave side tends to radiate the rear wave. This type of diaphragm can be made to generate a close to ideal spherical wave over a wide bandwidth when connected to an appropriate tapering duct (see for example US8094854B2)

5 2. The required entrance area of the metamaterial absorber is reduced by the tapered duct and this reduces the size of the metamaterial absorber fairly substantially.

3. The tapered duct occupies less space than a straight duct and makes it easier to accommodate this into a loudspeaker design where other parts are competing for space.

10 A conical duct is a good choice since it carries a spherical acoustic wave in a single parameter fashion, and consequently there is no diffraction and minimal reflection as the wave propagates in the duct. Other tapered ducts with curved walls could equally be used and provided the radius of the acoustical wave where the duct joins the metamaterial is correct an impedance miss-match could be largely avoided. In some cases such an
15 arrangement may give preferable results or a more practical geometry; for example, the part of the duct immediately behind the diaphragm could be enlarged so as to provide an acoustic volume before the duct begins to taper.

 In Figure 3 an alternative loudspeaker arrangement 320 is shown which is in accordance with the invention, in which the drive unit 326 is located forwardly and radially
20 outside the diaphragm 310. The diaphragm 310 is curved in the opposite direction to that shown in Figure 2, so that its concave surface radiates sound in the direction of arrow A towards the listener, this sound passing through passages in a phase plug 336, leaving the driver opening 334 and passing through acoustic horn 332. In this arrangement, the duct 324 extending rearwardly of the diaphragm 310 is initially curved in profile, and initially it enlarges
25 in cross-sectional area, before curving inwardly and tapering towards the metamaterial 328, the front surface of which 330 is located at the end of the duct 324.

 It will of course be understood that many variations may be made to the above-described embodiment without departing from the scope of the present invention. For example, the embodiment above is described as having one or more circular, conical ducts;
30 however, the invention applies equally to non-circular arrangements, such as oval, elliptical or race track shaped (figure of eight, or triangular/square/polygonal with rounded corners), or

any shape being symmetrical in one or two orthogonal directions lying in the general plane perpendicular to the front-rear axis A, as well as combinations of such arrangements and/or shapes. The duct(s) may be conical, with straight walls, or the walls may be curved (e.g. exponentially, elliptical, hyperbolic or parabolic). Conical ducts may be right cones or oblique
5 cones. There may be an annular arrangement of several ducts, which may be parallel, or arranged as a tapering or an enlarging right cone or oblique cone. Where several ducts are provided, there may be separate and/or different acoustic metamaterials provided at the rear end of each different duct. The metamaterial could intrude into a duct, such that the front surface of the metamaterial extends forwardly inside the duct, a short distance forward of its
10 rearward end; this might be for acoustic reasons, or to help accurately locate the metamaterial relative to the duct (such as where there are multiple ducts, the metamaterial might be shaped with protrusions to engage with the rearward ends of some or all of the ducts. Different types of metamaterials may be combined in an embodiment, and the multiple elements forming the metamaterial may repeat or they may be different in shape, dimension or structure. In the
15 drawn embodiment of Figure 2 there is an empty volume between the rear of the diaphragm 10 and the front surface of the metamaterial; this volume is formed from the volume of the conical duct 24 through the drive unit 26 and from the acoustic volume behind the diaphragm 10. In some embodiments it might be beneficial to enlarge the size of the empty volume, such as by increasing the size of the volume behind the diaphragm, and/or by enlarging the initial
20 part of the tapering duct, as in Figure 3. It may be that the initial part of the duct, immediately behind the diaphragm, increases in cross-sectional area for a short rearward direction before the duct reduces in cross-sectional area for the remainder of the rearward direction towards the metamaterial. The or each tapering duct may comprise portions which taper conically in combination with portions which taper in a curved profile.

25 Where different variations or alternative arrangements are described above, it should be understood that embodiments of the invention may incorporate such variations and/or alternatives in any suitable combination.

CLAIMS

1. A loudspeaker comprising:

- i. an acoustic diaphragm having front and rear surfaces, the acoustic diaphragm in use being driven so as to vibrate and radiate acoustic waves from its front surface in a forward direction away from the loudspeaker and from its rear surface in a rearward direction, and
- ii. a drive unit, and
- iii. at least one open duct leading in a rearward direction away from the diaphragm,

in which the at least one open duct has a cross-sectional area extending in the rearward direction, in which the cross-sectional area decreases along at least part of the rearward direction, and in which acoustic waves radiated from the rear surface of the diaphragm pass through at least a part of the open duct before contacting a front surface of an acoustic metamaterial absorber located generally to the rear of the duct, and to the rear of the decreasing cross-sectional area.

2. A loudspeaker according to Claim 1 in which the drive unit and the at least one open duct extend in a rearward direction, away from the diaphragm, the front surface of the acoustic metamaterial absorber being located generally to the rear of the drive unit.

3. A loudspeaker according to Claim 1 or Claim 2 in which the acoustic impedance of the acoustic metamaterial absorber substantially matches the characteristic acoustic impedance of acoustic waves radiated from the rear surface of the diaphragm at the point they contact the surface of the acoustic metamaterial absorber.

4. A loudspeaker according to any one of Claims 1, 2 or 3 in which the or each open duct has an opening at its rearward end, and in which the front surface of the acoustic metamaterial absorber is located at the opening.

5. A loudspeaker according to any preceding claim in which the or each open duct tapers conically towards the front surface of the acoustic metamaterial absorber.

6. A loudspeaker according to any preceding Claim in which the or each open duct has walls which taper inwardly in a curve towards the front surface of the acoustic metamaterial absorber.
7. A loudspeaker according to any preceding claim comprising a plurality of open ducts.
- 5 8. A loudspeaker according to Claim 7 in which each duct leads to a separate acoustic metamaterial absorber.
9. A loudspeaker according to Claim 7 or Claim 8 in which the plurality of open ducts is arranged in a matrix or in a ring.
- 10 10. A loudspeaker according to Claim 9 in which the plurality of open ducts is arranged in a ring.
11. A loudspeaker according to Claim 10 in which the ring is circular.
12. A loudspeaker according to any preceding claim in which the or each open duct has a constant cross-sectional shape.
13. A loudspeaker according to Claim 11 in which the shape is circular.
- 15 14. A loudspeaker according to any preceding claim in which the at least one open duct comprises an annular duct.
15. A loudspeaker according to any preceding claim in which the or each open duct contains sound absorbent material.
- 20 16. A loudspeaker according to any preceding claim in which the diaphragm is a dome or conical diaphragm.
- 25 17. A method of designing a loudspeaker according to any preceding claim in which one or more of the length, one or both end areas, the resonance frequency and the resonant strengths of the or each open duct are adjusted so as to allow the acoustic impedance of the acoustic metamaterial absorber substantially to match the characteristic acoustic impedance of acoustic waves radiated from the rear surface of the diaphragm at the point they contact the surface of the acoustic metamaterial absorber.



Application No: GB1919144.4

Examiner: Peter Easterfield

Claims searched: 1 to 17

Date of search: 5 May 2020

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
Y	1-17	US 10453438 B1 (GRIFFIN et al) see fig 2A
Y	1-17	US 2016/276992 A1 (VILERMO et al) see fig 9
Y	1-17	US 10032445 B1 (LINCH et al)
Y	1-17	US 2014/027201 A1 (ISLAM et al)
Y	1-17	WO 2018/047153 A1 (ACOUSTIC METAMATERIALS GROUP)
Y	1-17	EP 2040483 A2 (DICKIE) see figs 4-20
Y	1-17	EP 0984662 A2 (BOSE) see fig 1
Y	1-17	GB 2324928 A1 (B&W)
Y	1-17	GB 2290672 A (B&W)
Y	1-17	GB 547922 A (STANDARD TELEPHONES)
Y	1-17	US 2293181 A (INT STANDARD ELECTRIC CORP)

Categories:



X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^X :

Worldwide search of patent documents classified in the following areas of the IPC

G10K; H04R

The following online and other databases have been used in the preparation of this search report

WPI, EPODOC, Patent Fulltext

International Classification:

Subclass	Subgroup	Valid From
H04R	0001/28	01/01/2006
G10K	0011/162	01/01/2006