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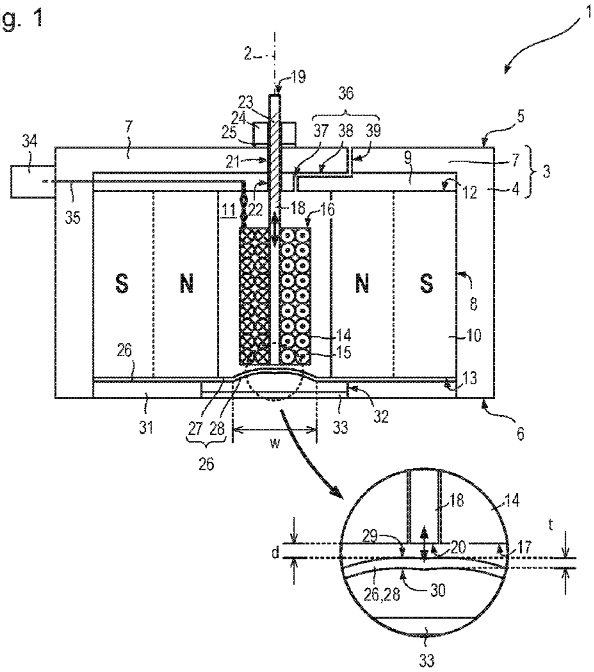
(54) Title: ULTRASONIC TRANSDUCER

Fig. 1



(57) Abstract: An ultrasonic transducer (1) is disclosed. The transducer comprises a magnetic core (18) which extends along a central axis (2) to a distal end (20), a solenoid (14) wound around the magnet core, an annular permanent magnet (10) disposed around the solenoid and a transverse conductive foil (26) in front of the distal end of the magnetic core. The magnetic core is moveable along the central axis.

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Ultrasonic transducer

Field

The present invention relates to an ultrasonic transducer, in particular an electromagnetic flexural ultrasonic transducer.

Background

Vibration characteristics of conventional fluid-coupled ultrasonic transducers, such as air-coupled piezoelectric ultrasonic transducers, piezoelectric micromachined ultrasonic transducers (PMUTs), and flexural ultrasonic transducers (FUTs), are typically governed by resonance modes of either piezoelectric ceramics or elastic plates used in their construction. Flexural ultrasonic transducers are usually made by bonding a piezoelectric disc to a membrane, which vibrates at one of its mechanical resonant frequencies. These piezoelectric-type devices require the active element to be physically bonded to the membrane and are, by their nature, narrow band devices, although they can be activated at a number of different, discrete frequencies.

Wide frequency band response is highly desirable for various applications including ultrasonic communication, material characterization, and non-destructive evaluation. A wider bandwidth means reliable energy transmission over a sufficiently large frequency range, where the characteristics of a test subject can be investigated efficiently through the simultaneous transmission and detection of ultrasound waves. With a wideband ultrasonic transducer, its ultrasonic signal is much shorter in the time domain and, therefore, it is simpler to perform time-of-flight ultrasonic range measurements to measure distance with improved accuracy. Moreover, it is possible to generate more complex forms of transmitting signals using a coded excitation technique to improve the signal-to-noise ratio (SNR) and the resolution of ultrasonic imaging systems.

Attempts to improve bandwidth performance of fluid-coupled ultrasonic transducers have been made including introducing further mechanical and electrical damping, multi-frequency piezoelectric arrays, exploiting the non-resonant vibration of films, and using microelectromechanical systems (MEMS). However, these approached tend to suffer problems due to a compromise between bandwidth, frequency-response, sensitivity, directivity, cost, complexity, robustness and intrinsic safety of the transducers in various applications.

T. Eriksson *et al.*: "*Experimental Evaluation of Three Designs of Electrodynamic Flexural Transducers*", Sensors, volume 16, 1363 (2016), which is incorporated herein by reference, describes an electromagnetically-driven flexural transducer comprising a thin, aluminium, front plate which is actuated electrodynamically by a spiral coil and a steel back plate.

Summary

According to a first aspect of the present invention there is provided an ultrasonic transducer comprising a magnetic core which extends along a central axis to a distal end, a solenoid wound around the magnet core, an annular permanent magnet disposed around the solenoid and a transverse conductive foil in front of the distal end of the magnetic core. The magnetic core is moveable along the central axis.

Thus, separation (or "lift-off") between the distal end of the magnetic core and the conductive foil can be varied for a given input power level and so allow an optimum sensitivity to be found. The position of the magnetic core may then be locked.

The magnetic core may take the form of a powdered-metal core, for example, comprising or consisting of powdered iron or Permalloy, a ferrite core or other core comprising a material having a high relative permeability (*e.g.*, $\mu_r > 10$).

The magnetic core may take the form of a rod. The magnetic core may be rotatable around the central axis. The magnetic core may include a threaded portion. The solenoid may be fixedly attached to the magnetic core such that the solenoid moves with the rod.

The annular permanent magnet may be radially magnetized. The annular permanent magnet may be axially magnetized. An axially-magnetized permanent magnet may still generate a radial magnetic field. The annular permanent magnet may be multi-piece or comprise a plurality of separate, angularly-spaced permanent magnets.

The solenoid may comprise turns of wire stacked along the central axis.

The conductive foil has a thickness, t, which may be of between 1 μm and 100 μm, preferably between 5 μm and 15 μm. A portion of the conductive foil may curve towards the distal end of the magnetic core. The conductive foil may comprise or consist of aluminium. The conductive foil may comprise a fixed, outer perimeter portion and a central portion. The outer perimeter may be supported or fixed to the permanent magnet. The outer perimeter portion is fixed via elastic support(s). For example, an annular elastic layer may be interposed between the permanent magnet and the outer portion of the foil. Additionally or alternatively, an (additional) annular elastic layer may be interposed between the outer portion and an annular cap. The central portion may be configured to be resilient. For example, the central portion may curve towards the distal end of the magnetic core. The central portion may have a diameter, *w*, much greater than the thickness. The diameter may be greater than 1 mm, preferably between 5 mm and 10 mm.

The ultrasonic transducer may comprise a case having a lumen which houses at least a portion of the magnetic core, the solenoid, the annular permanent magnet and the conductive foil. The case may include a through hole from outside the case to inside the case. The magnetic core may be movable with respect to the case.

The case may include a backplate proximate to or abutting a blind end of the case. The backplate may comprise or consist of a ferromagnetic material.

The case may comprise or consist of a non-ferromagnetic material.

The conductive foil may be interposed between the permanent magnet and an annular cap forming a central hole. The central hole may be filled with a rigid mesh. The mesh may comprise or consist of a non-ferromagnetic material.

According to a second aspect of the present invention there is provided a method of operating the ultrasonic transducer of the first aspect comprising moving the magnetic core along the central axis.

The method may further comprise applying a time-varying electrical signal to the solenoid. This can be used to generate an ultrasonic signal.

The method may further comprise measuring a time-varying electrical signal generated by the solenoid. This can be used to measure an ultrasonic signal.

The method may comprise operating the transducer at a pressure above 10 bar (1,000 kPa) or above 100 bar (10,000 kPa). The transducer may be formed exclusively of materials which have respective relevant critical temperatures, *e.g.*, a glass transition temperature, a melting point, or (for permanent magnets) a Currie temperature, and, thus, the method may comprise operating the transducer at a temperature above 100 °C.

Brief Description of the Drawings

Certain embodiments of the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic side view of an electromagnetically-actuated, flexural ultrasonic transducer;

Figure 2 is a plot of measured pressure signal against time for a first comparative example;

Figure 3 is a plot of measured pressure signal against time for a second comparative example; and

Figure 4 is a plot of measured pressure signal against time for the transducer shown in Figure 1.

Detailed Description of Certain Embodiments

Referring to Figure 1, an electromagnetically-actuated, flexural ultrasonic transducer 1 (herein also referred to as a "wideband electromagnetic dynamic ultrasonic transducer" or WEMDUT and herein after simply referred to as a "ultrasonic transducer") is shown. The transducer 1 may be used to generate and/or to measure ultrasonic waves in a medium (not shown), such as air.

The ultrasonic transducer 1 is generally cylindrical about a central axis 2 and comprises a case 3 which takes the form of a blind-ended cylinder. The case 3 consists of a cylindrical wall 4, which extends between first and second ends 5, 6 (herein also referred to as the "back" and "front" respectively), and a blind end plate 7 (or "backwall" of the case) at the first end 5. The case 3 defines a lumen 8.

The case 3 houses, in the lumen 8, a disk-shaped backplate 9, which abuts the backwall 7. The backplate 9 is made from a ferromagnetic material, such as ferromagnetic stainless steel. The case 3 is preferably made from a non-ferromagnetic material, such as brass, aluminium or non-ferromagnetic stainless steel, for providing mechanical protection and electromagnetic shielding. The case 3, however, may be formed from a ferromagnetic material, in which case, the backplate 9 may be omitted.

The case 3 houses, in the lumen 8, an elongated annular permanent magnet 10, which defines an inner or central lumen 11. The permanent magnet 10 is preferably radially magnetised (*i.e.*, perpendicularly to the direction of the central axis 2). The permanent magnet 10 may, however, be axially magnetised (*i.e.*, along the direction of the central axis 2) between first and second ends 12, 13. The permanent magnet 10 may be assembled from two or more pieces (not shown) or take the form of a plurality of angularly-spaced bar magnets (not shown).

The case 3 also houses, in the central lumen 11, an elongated cylindrical solenoid 14 comprising wire 15 wound around and stacked along the central axis 2, the solenoid 14 having first and second ends 16, 17. The solenoid 14 is mounted on an axially-moveable magnetic core rod 18 having a first end 19 and a second, distal end 20 (herein also referred to as the "back" and "front" respectively). The magnetic core rod 18 may take the form of powdered-metal core, for example, formed of powdered iron or Permalloy, or a ferrite core. The solenoid 14 may be fixed to the rod 18 and so moves together with the rod 18. The rod 18 may be moved manually or by a motor (not shown). The rod 18 may sit proud of the solenoid 14, *i.e.*, the distal end 20 of the rod 18 may extend beyond the plane of the end 17 of the solenoid 14.

The rod 18 passes through a central threaded through hole 21 in the backwall 7 and a central threaded through hole 22 in the backplate 9. The rod 18 includes a threaded potion 23 proximate the first end 19. A locking nut 24 is mounted on the rod 18 and a spring washer 25 is interposed between the locking nut 24 and backwall 7. The locking nut 24 can be used to secure the rod 18 in place along its longitudinal axis once a suitable position is found.

A protective cap (not shown), for example, in the form of blind-ended cylinder formed of a non-ferromagnetic material such a non-ferromagnetic stainless steel, may cover the end plate 7, distal end of the rod 18 and the locking nut 24.

The case 3 houses a thin, generally disk-shaped aluminium foil 26 comprising a flat, annular portion 27 and a central portion 28 having first and second faces 29, 30. The central portion 28 is preferably concave. The foil 26 generally extends transversely to the central axis 2. The foil 26 passes in front of the distal end 20 of the core 18. The foil 26 has a thickness, *t*, which is between 1 µm and 100 µm, preferably between 5 µm and 15 µm. The central potion 28 of the foil 26 has a diameter, *d*, which is of the order of millimetres, for example, between 5 mm to 10 mm. The concave (or "domed") shape of the central portion 28 of the foil 26 can help to increase compliance. The aluminium foil 26 is interposed between the permanent magnet 10 and an annular cap 31 having a central hole 32 which is fitted (*i.e.*, filled) with a rigid mesh 33.

The central portion 28 of the foil 26 can be flat, *i.e.*, not concave. However, a flat foil tends to be more sensitive to residual stress, which can influence the vibration frequency and the bandwidth of the transducer. Moreover, the distribution and the strength of residual stress in the foil can change during assembly. Thus, after the foil 26 is fixed or clamped in position in the transducer, the distribution of stress can be adjusted to be more uniform by changing the shape of the central portion 28 of the foil 26, for example, to be dome-shaped, using a suitable mechanical method, such as indenting.

The central portion 28 of the foil 26 need not be dome-shaped, but can have another, resilient shape, for example, including concentric fold(s) or having a corrugated shape. A dome-shaped or other resilient structure can help to reduce the influence of the clamped edge (which defines a rigid boundary condition producing a strong reaction force leading to a resonant-like narrowband vibration behaviour) on the vibration of the foil, so that a broader frequency bandwidth can be achieved.

A dome-shaped foil can change the radiation-pattern of the ultrasonic field, so that a better directivity performance can be achieved.

The annular cap 31 comprises a ferromagnetic material, such as ferromagnetic stainless steel. Being ferromagnetic, the backplate 9 and annular cap 31 can help to enhance the static magnetic field generated by the permanent magnet 10, thereby increasing sensitivity. An additional, non-ferromagnetic annular cap (not shown) may be provided in front of the ferromagnetic annular cap 31. The rigid mesh 33 may take the form of a plate perforated with an array of holes (not shown). The mesh 33 is gas permeable so that air (and thus ultrasonic waves in the air) can pass through the mesh 33. The mesh 33 may comprise a non-ferromagnetic material such as plastic or a non-ferromagnetic material. Other forms of protective structure can be used instead of the rigid mesh 33. For example, the protective structure may take the form of a cage covered by a sponge. In some embodiments, a protective structure need not be used, *i.e.*, there is no mesh 33 or other protective structure.

The diameter of the central hole 32 of the cap 31 can be the same as the diameter of the central lumen 11. However, the central hole 32 of the cap 31 may be larger or smaller. Changing the diameter of the central hole 32 changes the effective working area of the foil 26 which can be used to adjust of the range of the working frequency, the efficiency and the radiation pattern of the transducer.

Respective additional elastic layers (not shown), for example, formed from rubber, can be introduced between the foil 26 and the magnet 10 and/or between the foil 26 and the cap 31 to change the rigid boundary condition of the foil 26 into a flexible boundary condition which can help to broaden bandwidth of the transducer 1.

The foil 26 passes in front of the distal end 20 of the core 18. The first face 27 of the concave portion 28 of the aluminium foil 26 and the distal end 20 of the magnetic core 18 are separated by a gap, d (which is herein also referred to as "lift-off"), which can be varied. As mentioned hereinbefore, the rod 18 can be moved to adjust lift-off to optimise the sensitivity of the transducer 1 for a given power. Once a suitable lift-off has been found, then rod 18 may be locked in place.

The ultrasonic transducer 1 includes an electrical connector 34 to which a cable (not shown) can be connected for supplying an excitation signal (not shown) and receiving a measured signal (not shown). The electrical connector 34 is connected to the solenoid 14 via a pair of wires 35.

The ultrasonic transducer 1 includes a venting passage 36 between the outside of the case 3 and the inner lumen 11. In particular, the backwall 7 and backplate 9 include respective through holes 37, 38 connected by a passage 39 which provides fluid communication between the through holes 37, 38 and which may take the form of, for example, a routed channel in the backplate 9. If a protective cap (not shown) is used, then the protective cap also has a venting passage.

The ultrasonic transducer 1 can be assembled without an adhesive or potting compound (such as epoxy resin) which has a glass-transition temperature or a melting temperature below 100 °C. For example, the components may press-fit into the case 3, be crimped and/or be secured for example using high-temperature (>100 °C) sintering.

The ultrasonic transducer 1 can have one or more advantages. By using a solenoid 14 (as opposed to, for example, a flat pancake coil), the ultrasonic transducer 1 can be simpler to manufacture and, since the solenoid 14 is able to generate a larger magnetic field, can be more sensitive. By being able to vary lift-off, a suitable lift-off for a given power level and/or for a given foil can be found which can help to increase sensitivity. Using a thin, dome-shaped aluminium foil 26 can help to reduce the influence of the rigid boundary condition on the vibration of the foil thereby helping to provide a broader frequency response of the transducer. A thick (e.g. > 250 μm), flat plate tends to restrict the vibration response of the transducer to a relatively narrow bandwidth, largely determined by flexural resonances of the plate whose reaction force of the vibration is primarily provided by the rigid boundary formed between the plate and the permanent magnet. Using venting can help operation at higher pressures, for example, greater than 100 bar (10,000 kPa), and/or varying pressures.

Referring still to Figure 1, operation of the ultrasonic transducer 1 will now be described.

An alternating current (not shown) is applied to the solenoid 14 and an eddy current (not shown) is induced in the aluminium foil 26. The interaction between the eddy current (not shown) with the in-plane static magnetic field (not shown) generated by the permanent magnet 10 generates a Lorentz force, resulting in an out-of-plane oscillation of the foil 26. The thickness, *t*, of the foil 26is much smaller than its lateral dimensions thereby resulting in a broadband frequency vibration response. According to Maxwell's equations and the Lorentz's force law, the out-of-plane vibration of the foil 26 in the in-plane static magnetic field experiences an additional Lorentz force, preventing vibration of the foil 26, functioning as an eddy current brake converting kinetic energy into heat. This self-adaptive drag force results in an even broader bandwidth of the transducer 1. By adjusting the distance, d, between the magnetic core 18 and the aluminium foil 26, an optimum and stable static lift-off distance d can be achieved at different input power levels, leading to optimized transducer sensitivity.

No soldering point, conductive wire, ceramic disc, epoxy or any additional component materials are in contact with the foil 26 of the transducer 1. As a result, significantly improved consistency, in terms of transducer performance, can be achieved with lower cost, more suitable for mass production. Moreover, the foil-only structure means that no additional mass or rigidity is introduced, such that its transduction efficiency in different fluids and bandwidth are improved. The vibration of the foil 26 generates an annularly-shaped acoustic source (although other shapes of acoustic source may be generated), whose resultant acoustic field exhibits such characteristics including near-field distance, far-field radiation pattern, beam spread angle and side lobes, which can all be adjusted through varying the materials, structures and/or dimensions of the magnetic core 18, the solenoid 14 and the permanent magnet 10. This can help provide significantly greater flexibility, which means that the ultrasonic transducer can be used in a wide range of applications.

The ultrasonic pressure signals of a commercial-available air-coupled ultrasonic transducer (herein referred to as the "first comparative example"), the device ultrasonic transducer in Eriksson *et al. ibid.* (herein referred to as the "second comparative example"), and the ultrasonic transducer 1 are measured and compared.

Referring to Figures 2, 3 and 4, the transducers are excited by wideband signals with a frequency bandwidth ranging from 0 to 200 kHz. The duration of the signal from the ultrasonic transducer 1 is only approximately 0.022 ms, whilst the duration of the signals from the other two transducers are greater than 0.75 ms.

The wideband feature of the ultrasonic transducer 1 results in a much shorter, simpler form of ultrasonic signal, enabling a high-accuracy and high-resolution ultrasonic measurement to be carried out in various fluid-coupled applications.

Modifications

It will be appreciated that various modifications may be made to the embodiments hereinbefore described. Such modifications may involve equivalent and other features which are already known in the design, manufacture and use of ultrasonic transducers and component parts thereof and which may be used instead of or in addition to features already described herein. Features of one embodiment may be replaced or supplemented by features of another embodiment.

For example, the conductive foil need not be formed from aluminium. Another conductive, non-magnetic material, such beryllium or a suitable metal alloy, may be used which has a comparable or higher conductivity, a comparable or higher compliance and/or a comparable or lower density than aluminium. The conductive foil may be formed from a ferromagnetic material, such as stainless steel, nickel alloy, or amorphous steel. This can allow operation using the Lorentz force, the magnetostriction force and the magnetization force.

Although claims have been formulated in this application to particular combinations of features, it should be understood that the scope of the disclosure of the present invention also includes any novel features or any novel combination of features disclosed herein either explicitly or implicitly or any generalization thereof, whether or not it relates to the same invention as presently claimed in any claim and whether or not it mitigates any or all of the same technical problems as does the present invention. The applicants hereby give notice that new claims may be formulated to such features and/or combinations of such features during the prosecution of the present application or of any further application derived therefrom.

Claims

1. An ultrasonic transducer comprising:
a magnetic core which extends along a central axis to a distal end;
a solenoid wound around the magnet core;
an annular permanent magnet disposed around the solenoid; and
a conductive foil passing in front of the distal end of the magnetic core;
wherein the magnetic core is moveable along the central axis.

2. The ultrasonic transducer of claim 1, wherein the solenoid comprises turns of wire stacked along the central axis.

3. The ultrasonic transducer of claim 1 or 2, wherein the annular permanent magnet is radially magnetized.

4. The ultrasonic transducer of claim 1 or 2, wherein the annular permanent magnet is axially magnetized.

5. The ultrasonic transducer of any one of claims 1 to 4, wherein the conductive foil has a thickness, *t*, of between 1 µm and 100 µm.

6. The ultrasonic transducer of claim 5, wherein the thickness, *t*, is between 5 µm and 15 µm.

7. The ultrasonic transducer of any one of claims 1 to 6, wherein a portion of the conductive foil curves towards the distal end of the magnetic core.

8. The ultrasonic transducer of any one of claims 1 to 7, wherein the conductive foil comprises aluminium.

9. The ultrasonic transducer of any one of claims 1 to 8, wherein the conductive foil comprises a fixed, outer perimeter portion and a central portion.

10. The ultrasonic transducer of claim 9, wherein the outer perimeter portion is fixed via elastic support(s).

11. The ultrasonic transducer of any one of claims 1 to 10 comprising a case having a lumen which houses at least a portion of the magnetic core, the solenoid, the annular permanent magnet and the conductive foil.

12. The ultrasonic transducer of claim 11 wherein the case includes a through hole from outside the case to inside the case.

13. A method of operating the ultrasonic transducer of any one of claims 1 to 12 comprising:
moving the magnetic core along the central axis.

14. The method of claim 13, further comprising:
applying a time-varying electrical signal to the solenoid.

15. The method of claim 13 or 14, further comprising:
measuring a time-varying electrical signal generated by the solenoid.

16. The method of any one of claims 12 to 15, comprising:
operating the transducer at a pressure above 10 bar (1,000 kPa).

17. The method of any one of claims 12 to 16, comprising:
operating the transducer at a temperature above 100°C.

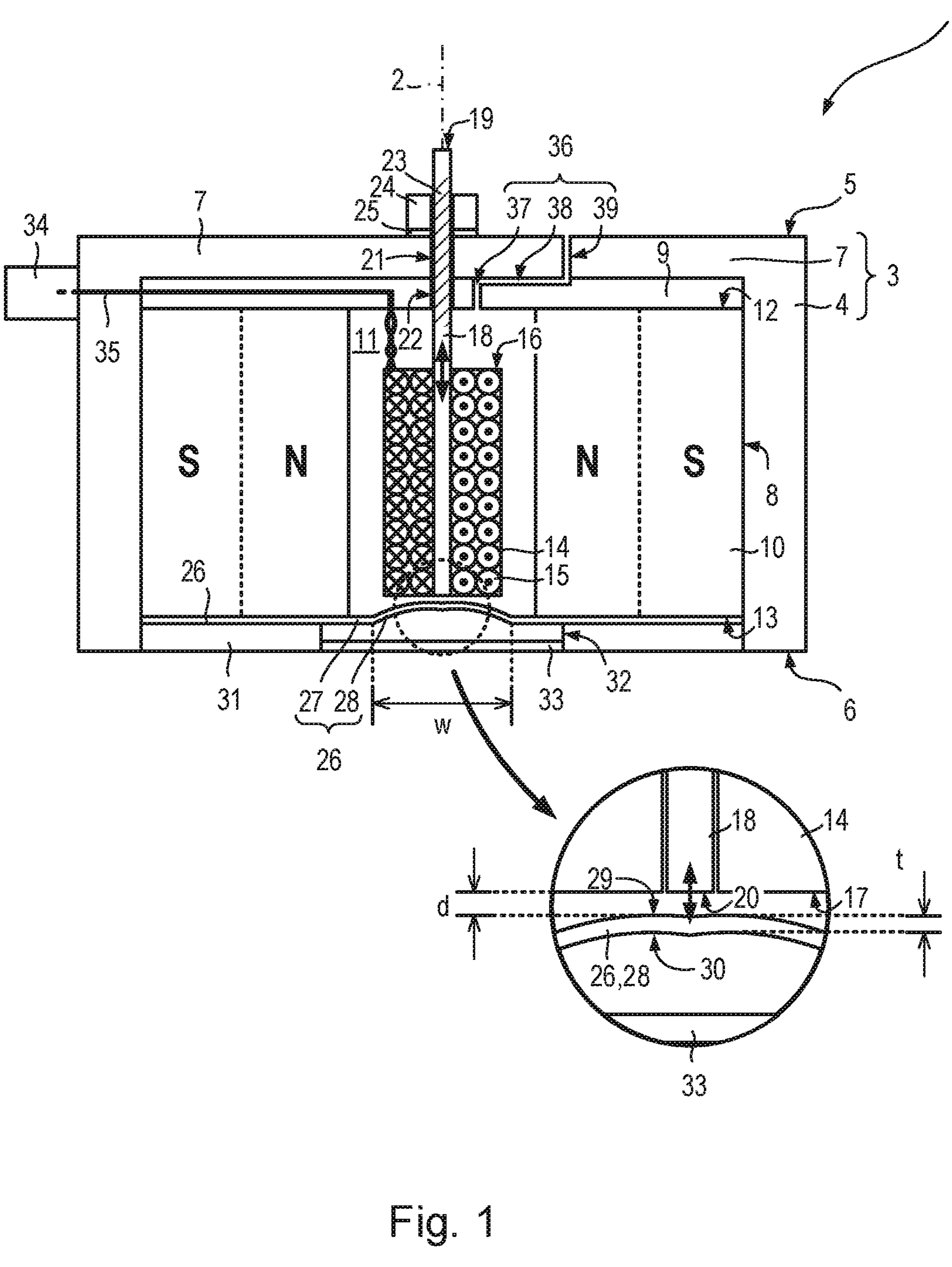
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Fig. 1

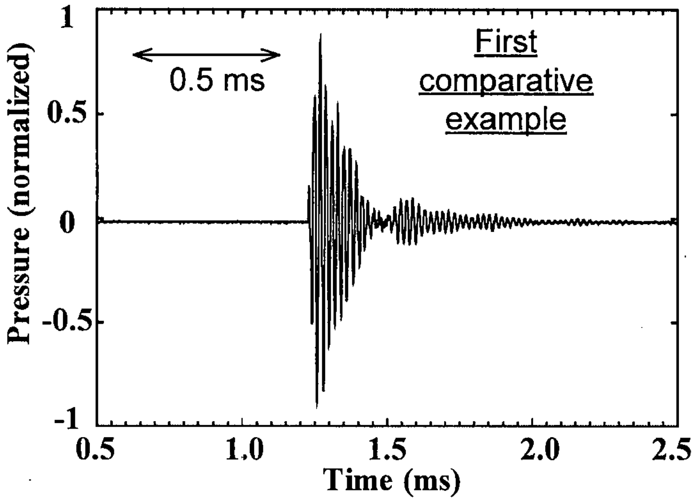

Fig. 2

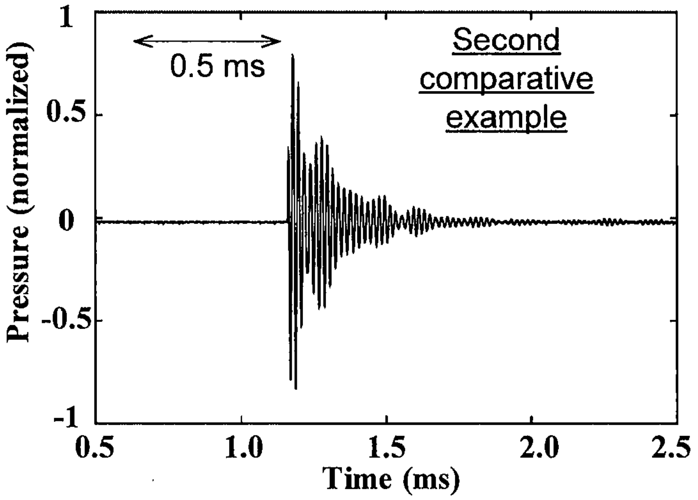

Fig. 3

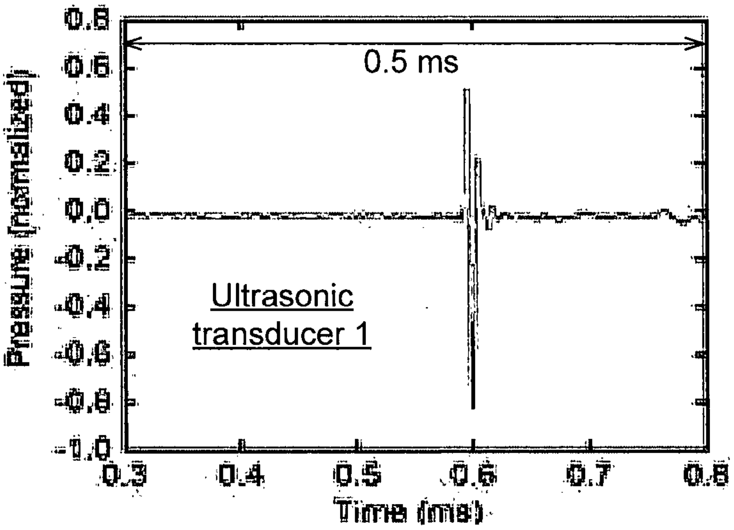

Fig. 4

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2019/051995

A. CLASSIFICATION OF SUBJECT MATTER

INV. B06B1/04

ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G10K B06B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	TOBIAS ERIKSSON ET AL: "Experimental Evaluation of Three Designs of Electrodynamic Flexural Transducers", SENSORS, vol. 16, no. 9, 25 August 2016 (2016-08-25), page 1363, XP055634182, DOI: 10.3390/s16091363 abstract figure 1c -----	1-17
Y	US 6 684 681 B1 (ZOMBO PAUL [US]) 3 February 2004 (2004-02-03) column 3, line 42 - line 45 figure 1 ----- -/--	1-17

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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

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

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"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

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Date of the actual completion of the international search 22 October 2019	Date of mailing of the international search report 31/10/2019
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Hippchen, Sabine

2

International application No
PCT/GB2019/051995

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	paragraph [0034] paragraph [0045] figure 5 -----	1,2,5-17
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A	column 1, line 23 - line 28 -----	1-16

INTERNATIONAL SEARCH REPORT

Information on patent family members

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