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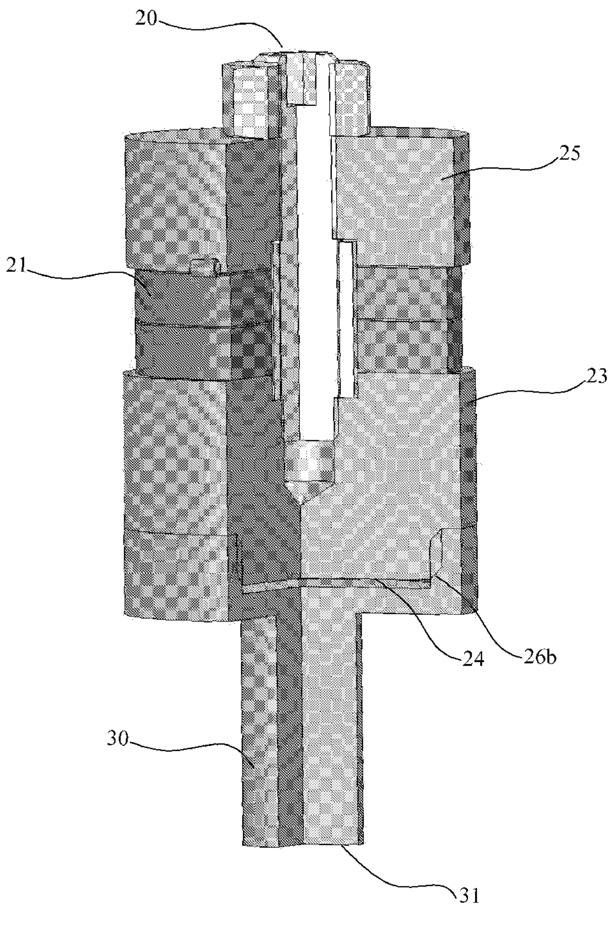

(57) Abstract: The present invention relates to a device for producing ultrasonic longitudinal acoustic vibrations in a user element, comprising at least one electro-acoustic transducer (20), the piezoelectric ceramics (21) of which vibrate in a radial mode, and an intermediate element (30), which is placed between the transducer and the user element, and is firmly attached on one side to the distal face of the transducer in a contact area (26b) localized around a vibration amplitude anti-node of the distal face and on the other side, to the user element through a planar end surface, any point of the end surface, being driven by a homogenous vibration orthogonal to said surface.

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DEVICE FOR PRODUCING ULTRASONIC VIBRATIONS

The invention relates to the general technical field of devices and methods for generating ultrasound.

GENERAL PRESENTATION OF THE PRIOR ART

Devices and methods for generating ultrasound have already been proposed.

These devices generally comprise an ultrasound «producing element», associated with a «user element» which transmits the ultrasonic waves to a substrate for a given technical effect: welding, cleaning, destruction of cells or even cutting soft foodstuffs.

The user elements, their shapes and their characteristics depending on the substrate and on the sought-after technical effect are well known to one skilled in the art, as well as the ultrasound producing elements.

Generation of power ultrasonic waves is currently performed from piezoelectric ceramics or more specifically from electro-acoustic transducers 20 of the «*Langevin triplet*» type.

An electro-acoustic transducer allows high frequency electric energy from an electronic generator 10 to be transformed into mechanical vibrations.

With reference to Fig. 1a, an electro-acoustic transducer comprises two piezoelectric ceramics mounted and pre-stressed between two cylindrical metal parts 23, 25: the «*horn*» 23 positioned under both ceramics 21, and the «*countermass*» 25 positioned on both ceramics 21.

It will be understood subsequently that when a part A is mentioned as being *«on»* a part B, the latter may directly be on the part B, or may be located above the part B, and separated from said part B by one or more intermediate parts.

It will also be understood that when a part A is mentioned as being *«on»* a part B, the latter may cover the whole surface of the part B, or a portion of said part B.

Piezoelectric ceramics 21 are generally disc-shaped with small thickness relatively to their diameter, or torus-shaped with a rectangular or similar section.

The different types of electro-acoustic power transducers are widely described in books such as *«Modern Ceramic Engineering of Richerson»*, Marcel Dekker Inc., page 284, fig. 7.24, or *«High Intensity Ultrasonics of Brown and Goodman»*, Iliffe Books Ltd 1965, or even in the book Crowford Engineering of Frederick and Co.

These transducers are used in the industry, mainly for welding thermoplastics, or for cleaning complex parts in optics, electronics or even in mechanics.

The electro-acoustic transducers as described above may use two distinct vibrational modes of piezoelectric ceramics:

- the mode producing alternating changes in their thickness (a so-called *«ceramic thickness»* mode) and
- the mode producing alternating changes in their diameter (a so-called *«ceramic planar»* or *«planar»*, or *«radial»* mode).

The so-called thickness vibrational mode of piezoelectric ceramics 21 generates longitudinal vibrations in the horn 23 so that each point of the planar distal face 24 of the horn 23 - i.e. the face opposite to the face of the horn facing the ceramic - is driven by a homogenous vibration orthogonal to said face 24

This mode allows high intensity longitudinal vibrations to propagate through devices vibrating in resonance with the electro-acoustic transducer and the associated generator 10, generically called «*ultrasonic horns*» and attached to the distal face 24 of the horn 23, the contact being made over the whole extent of said distal face, according to the prior art.

In this case, the piezoelectric ceramics are powered by a generator providing an electric signal with a narrow passband width (100 or 200 Hz) and which is centered on a frequency which should be away from the resonance eigenfrequency of the piezoelectric ceramics in their radial vibrational mode.

The so-called ceramic thickness vibrational mode is used in most industrial applications of power ultrasound such as for example welding, spraying, destruction of cells or even cutting of soft foodstuffs such as «foie gras».

It is well known to one skilled in the art that the dimensions of such electro-acoustic power transducers 20 using the so-called ceramic thickness vibrational mode, vary in an inversely proportional way to the frequency used.

In practice, the length of this type of electro-acoustic transducer 20 is of the order of a half wavelength whereas its diameter will be considerably smaller than a quarter of a wavelength in order to avoid superposition of a transverse vibration to the preferential vibrational mode, superposition of both vibrations may result in the destruction of the ceramics.

Thus, beyond 40 kHz, the diameter of the ceramics is considerably reduced which significatively limits the admissible power, so that, for example, at 80 Hz, this diameter is about 15 mm with a permanent operating output power limited to about 20 Watts.

A drawback of such devices is therefore the fact that they are unsuitable for transmitting significative output power, i.e. of the order of a minimum of 100 Watts, at frequencies higher or equal to 60 kHz, to a user element and cannot therefore be used in the case of industrial applications requiring such power/frequency pairs.

The second vibrational mode of piezoelectric ceramics, a so-called planar or radial mode, is obtained by selecting their dimensions, as well as the piezoelectric characteristics of their material, so that their eigenfrequency, according to this vibrational mode, is equal to that of the generator.

One skilled in the art knows that, in the case of toric ceramics, this eigenfrequency F is given by the following formula:

F = C / (Dext - Dint),

wherein:

- C is the radial vibration coefficient of the material used,
- Dext is the outer diameter of the ceramics,
- Dint is the inner diameter of the ceramics.

The dimensions of the electro-acoustic transducers, the ceramics of which vibrate in a planar or radial mode, may be much larger than those of transducers for which the ceramics vibrate in the thickness mode, at equal frequency, because of their respective vibrational modes.

Thus, it is current to find for example electro-acoustic transducers for which the ceramics vibrate in a planar mode, with an eigenfrequency of 100 kHz, having piezoelectric ceramics with a diameter of the order of 40 mm and allowing a considerably larger power level than that of transducers of the same frequency but operating in the ceramic thickness mode.

This vibrational mode of the ceramics generates flexural vibrations at the distal face 24 of the horn 23. Thus, this type of transducer is specifically intended for setting into vibration, according to the flexure mode, large planar surfaces particularly sought for ultrasonic cleaning.

In this case, several electro-acoustic transducers are generally directly attached to the cleaning tank, or adhesively bonded inside an immersible sealed casing, via the whole of their distal end face 24 of the horn 23 in order to transmit to the liquid contained in the tank, the ultrasonic vibratory energy required for the ultrasonic cleaning process.

The electro-acoustic transducers are then electrically connected in parallel in order to form an assembly having a wide and very flattened electro-acoustic impedance curve versus frequency and electrically powered by a frequency sweep generator, covering a wide band of frequencies (several kHz) around the target frequency.

One skilled in the art who is aware of the need existing in industry for generating longitudinal ultrasonic vibrations in a user element at frequencies higher than or equal to 60 kHz and at powers larger than or equal to 100 Watts on the one hand and, of the existence of electro-acoustic transducers on the other hand, the ceramics of which vibrate in the so-called planar or radial mode and the distal face in the flexural mode, and which are capable of operating at such power/frequency pairs, is then led to pose the following problem: how to use such transducers for generating the thereby sought longitudinal ultrasonic vibrations?

An object of the invention is to provide a solution to this problem.

PRESENTATION OF THE INVENTION

For this purpose, provision is therefore made for using the capacity of electro-acoustic transducers 20, as described above and for which the piezoelectric ceramics 21 vibrate in a so-called planar or radial mode and the distal face 24 in a flexural mode, of transmitting high power at the sought frequencies.

The flexural mode is a mode with deformation of the material, well known to one skilled in the art, in which the distal face bends in response to a stress.

The flexural mode vibration of the distal face 24 of the transducer is well illustrated by Figs. 1b and 1c.

As an example, the transducer illustrated in Figs. 1 is calculated in order to vibrate at 80 kHz in this ceramic vibrational mode, the diameter of its cylindrical horn 23 is 41 mm.

The curve of Fig. 1d illustrates the vibrational amplitude of each point of the distal face 24 of the horn 23 versus its distance from the centre of the face.

This curve brings out the fact that the flexural vibration of the distal face has two amplitude anti-nodes, located at the centre and at the outer edge of said face, respectively; both of these anti-nodes are separated by an amplitude node located on a circle concentrical with said face and with a diameter of about 26 mm.

The central amplitude anti-node is much more marked than the peripheral amplitude anti-node.

In the vicinity of each anti-node, the amplitude curve is flattened, so that in a small area 26 around each anti-node, the amplitude is constant in a first approximation.

Thus, in a disc 26a concentrical with the distal face, with a diameter of about 6 mm, the amplitude in any point is larger than 90% of the amplitude at the central anti-node; in this case, the ratio of the disc radius 26a to the radius of the distal face is 3/20.5 = 14.6%.

Also, in a crown 26b concentrical with the distal face, located at its periphery and with a width of about 2.5 mm, the amplitude in any point is larger than 90% of the amplitude at the peripheral anti-node; in this case, the ratio of the width of the crown 26b to the radius of the distal face is 2.5/20.5 = 12.2%.

Both of these ratios are located between 10 and 15%.

A first aspect of the device according to the invention consists of using this particular characteristic for recovering the vibratory energy produced by the transducer via at least one of these areas where the vibration is homogenous and of strong amplitude in a first approximation.

A firm connection will then be placed between one of these areas 26a or 26b on the one hand, and, either an intermediate element 30 or directly a user element 40, 50 on the other hand.

This allows the desired longitudinal vibrations to be generated in the user element, at the desired power/frequency pairs and thus provides the sought solution to the posed problem.

By associating several electro-acoustic transducers 20 and several intermediate elements 30 if necessary, it is notably possible with the present invention to produce in a user element (part 40 or assembly of parts 50) for which the vibration eigenfrequency is tuned on that of the transducers, high intensity longitudinal vibrations required for reaching, in the case of high frequencies larger than or equal to 60 kHz, the output power level required for industrial applications such as spraying, welding, machining, processing of liquids, cutting, etc.

Other preferred but non-limiting aspects of the device according to the invention are the following:

- the vibration eigenfrequency in the radial mode of the piezoelectric ceramics 21 of the transducer and the vibration eigenfrequency of the intermediate element 30 are tuned on the same ultrasonic frequency F;

- the transducer 20 is then connected to a generator 10 capable of producing an electric AC signal with a narrow passband width and comprised between 100 and 300 Hz around said ultrasonic frequency F;

- in a first embodiment, an intermediate element 30 is firmly attached to the transducer by the contact area 26a localized at the centre of the distal face; this intermediate element may comprise a metal cylindrical bar intended to come into contact with the user element 40, 50 via the planar end surface 31, which is driven in every point by a homogenous vibration orthogonal to the surface;

- in a second embodiment, the intermediate element 30 and the horn 23 of the piezoelectric transducer are made in a single piece;

- in a third embodiment, the intermediate element 30 and the user element 40 are made as a single piece, so that the user element 40 is directly and firmly attached to the transducer by the contact area 26a localized at the centre of the distal face;

- in a fourth embodiment, the intermediate element 30 is firmly attached to the transducer by the contact area 26b localized at the periphery of the distal face; this intermediate element may comprise a metal cylinder including a recess, the face 32 of the cylinder including the recess intended to be set facing the face 24 of the electro-acoustic transducer, so as to allow both opposite faces 32 and 24 to freely vibrate without mutual contact;

- in a fifth embodiment, a plurality of electro-acoustic transducers 20 are associated with the intermediate element 30; this intermediate element may for example be in the shape of a thick disc at the periphery of which the transducers are firmly attached and regularly spaced out, the axes of the transducers being orthogonal to the axis of the disc and the end surface 31 being parallel to the axis of the disc.

Other preferred aspects of the device according to the invention are the following:

- the ultrasonic frequency F is between 20 kHz and 400 kHz, preferentially 40 kHz and 200 kHz, and even more preferentially between 80 kHz and 200 kHz,

- the ultrasonic power delivered by the generator 10 is between 50 and 10,000 Watts,

- at least one end face 31 of the intermediate element 30 is planar, the vibrations in any point of this face being homogenous and orthogonal to said end face,

- the transducer is positioned in a sealed chamber in which a coolant gas or liquid flows,

- the device further comprises a user element comprising a part 40 or an assembly of parts 50 positioned at the end face 31 of the intermediate element 30.

According to a first alternative, the user element 40 comprises a ultrasonic horn formed with a cylindrical rod 41.

According to a second alternative, the user element 50 comprises a velocity transformer 52, and/or a cylindrical rod 51, and/or a ultrasonic horn 54, 58, 59.

In a preferred but non-limiting case, the different components of the user element 40, 50 taken separately, have a vibration eigenfrequency tuned on that of the generator 10.

According to a third alternative, the applied ultrasonic horn 53 comprises an axial bar 57 around which is laid out a radial crown 56 positioned around the bar 57 orthogonally to the axis of the bar. The bar vibrates longitudinally and the crown radially, the outer radius of the crown 56 being determined so that it comprises a first quarter wavelength, and then an integral number of half-wavelengths in the radial vibrational mode of the crown 56 at frequency F.

The vibration of the surface 55 which forms the outer edge of the crown 56 for example allows a liquid to be sprayed, so that atomization devices may be produced. In such a case, the device according to the invention may advantageously in part be located inside a sealed enclosure 61, penetration being performed at a node 511 of the vibration. Such a device for example allows molten metal alloys to be atomized, the thereby formed droplets giving, by cooling in the enclosure, metal powders with narrow particle size distribution.

According to a fourth alternative, the intermediate element 30 is in the shape of a crown at the periphery of which a plurality of transducers 20 are firmly attached and regularly spaced out, the axes of the transducers being orthogonal to the axis of the crown and the surface 31 is formed by a portion of the crown. The user element 40 is an axisymmetrical hollow tube, the axis of which is the same as that of the crown, the length of which is selected so that it vibrates in resonance at frequency F and which is firmly attached to the surface 31. The tube may preferentially be in two portions 45 and 46, on either side of the crown 30.

The invention also relates to a method for producing longitudinal ultrasonic acoustic vibrations comprising the steps of:

- converting an electric AC signal into radial mechanical vibrations of piezoelectric ceramics which are the components of an ultrasonic transducer,

- transforming radial mechanical vibrations of the ceramics into flexural vibrations of the distal face of the transducer,

- using the vibratory energy of the distal face of the transducer for generating longitudinal mechanical vibrations in a user element via an intermediate element.

PRESENTATION OF THE FIGURES

Other features, objects and advantages of the present invention will become further apparent from the description which follows, which is purely illustrative and non-limiting and should be read in view to the appended drawings wherein:

- Fig. 1a illustrates a schematic perspective view of an electro-acoustic transducer of the «Langevin triplet» type from the prior art;
- Figs. 1b and 1c illustrate in a sectional view, an operating model in the so-called radial or planar excitation mode of piezoelectric ceramics, in both positions with maximum amplitude which are in opposite phase, of the electro-acoustic transducer illustrated in Fig. 1a;
- Fig. 1d shows the amplitude of vibration of each point of the distal face of the electro-acoustic transducer illustrated in Fig. 1a, versus its distance from the axis of revolution;
- Figs. 2-13 illustrate different embodiments of the device according to the invention.

DESCRIPTION OF THE INVENTION

As described earlier, the dimensions of the electro-acoustic transducers excited according to the second excitation mode of their piezoelectric ceramics, i.e. the ceramics of which vibrate in a planar (or radial) mode, may be much larger than those of transducers excited according to the first mode, i.e. the ceramics of which vibrate in the thickness mode.

However and as illustrated in Figs. 1b and 1c, an electro-acoustic transducer, the ceramics of which vibrate in a planar (or radial) mode, produces a flexural vibration of the distal face 24 of the horn 23 - i.e. the face opposite to the face of the horn facing the ceramic.

Now, this does not allow a user element (part 40 or assembly of parts 50) attached to said distal face 24 to be set into vibration in the longitudinal mode, according to the same methods as those which are used in the case of ceramics vibrating in the thickness mode, and even less to transmit to it a significant useful ultrasonic output power. This is true even when the vibration eigenfrequency of the user element (part 40 or assembly of parts 50) is tuned on that of the transducer 20.

Indeed, it is known to one skilled in the art that in order that such a significant ultrasonic output power be transmitted to the user element (part 40 or assembly of parts 50), vibrating in the longitudinal mode, each point of the distal planar face 24, which is at the interface between the horn 23 (source of the vibrations) and the element (part 40 or assembly of parts 50) using the vibrations, should vibrate in a homogenous way and orthogonally to the distal face 24.

In order to find a remedy to this drawback, the invention proposes a device for producing ultrasonic acoustic vibrations as illustrated in Figs. 2-13.

This device comprises:

- at least, one electro-acoustic transducer 20, as illustrated in Fig. 1a and including a pair of piezoelectric ceramics 21, the ceramics of which 21 vibrate in the radial mode and the distal face 24 in the flexural mode, as illustrated in Figs. 1b and 1c,

- a user element 40, 50,

- an intermediate element 30, which is placed between the transducer 20 and the user element 40, 50 and is firmly attached on one side, to the distal face 24 of the transducer 20 in a contact area 26 localized around a vibration amplitude anti-node of the distal face 24 and, on the other side, to the user element 40, 50 through its planar end face 31, every point of the end surface 31 being driven by a homogenous vibration orthogonal to said surface.

With reference to Fig. 2a, an embodiment of the device according to the invention is illustrated.

In this embodiment, the device comprises a generator 10, an electro-acoustic transducer 20, and an intermediate element 30.

The generator 10 allows an electric AC signal of ultrasonic frequency F to be generated.

The generator 10 is electrically connected to the electro-acoustic transducer 20 in a way known to one skilled in the art.

The electro-acoustic transducer 20 is of the «Langevin triplet» type.

This transducer 20 includes two contiguous piezoelectric ceramics 21a, 21b.

Both ceramics 21a, 21b are positioned between a first metal part 23 - designated as horn hereafter - firmly attached to one 21a of the two ceramics, and a second metal part 25 - designated as countermass hereafter - firmly attached to the other ceramic 21b.

In the embodiment illustrated in Fig. 2a, the horn 23, the countermass 25 are of a cylindrical shape, and both ceramics 21a, 21b of a toric shape with a rectangular section. However, the horn 23, the countermass 25, and/or the ceramics 21a, 21b may have shapes other than those illustrated in Fig. 2a.

The ceramics 21a, 21b are capable of vibrating in the radial mode. More particularly, the piezoelectric characteristics of the material making up the ceramics and the dimensions of the ceramics 21a, 21b are selected so that the frequency F of the generator 10 corresponds to their resonance frequency (or eigenfrequency) in the radial vibrational mode.

The vibration of the ceramics 21a, 21b in the radial mode induces flexural vibrations at the distal face 24 of the horn 23.

In the embodiment illustrated in Figs. 1a-1d, the distal face 24 of the horn 23 comprises two vibration anti-nodes: a central anti-node 26a, localized at the centre of the distal face 24, and a peripheral anti-node 26b, localized at the periphery of the distal face 24.

Within the scope of the present invention, by «*vibration anti-node*» is meant a region of the distal face 24 where the displacement amplitude of the distal face 24 of the horn 23 is maximum when the ceramics 21 vibrate in the radial mode.

The central anti-node 26a and the peripheral anti-node 26b are separated by a nodal region of the distal face 24 corresponding to a circle, as illustrated in Figs. 1b-1d.

In the embodiment illustrated in Fig. 2a, the intermediate element 30 is firmly attached to the horn 23 in a contact area 26a with the shape of a disc concentric with the distal face 24 and therefore localized at the central anti-node of said face.

Advantageously, the radius of this contact area is between 10% and 15% of the radius of the distal face 24 so that, according to Fig. 1d, the amplitude of the vibration in any point of said area is larger than 90% of the amplitude of the vibration at the centre.

The intermediate element 30 illustrated in Fig. 2a consists of a metal cylindrical bar coaxial with the horn 23, the material and the dimensions of which have been selected to that it has a vibrational eigenmode in the longitudinal mode, which resonates at frequency F.

It is attached to the horn 23 via a small cylinder coaxial with the bar, the section of which has the same dimension as the contact area 26a and the height is about 1 mm; this arrangement allows the contact between both parts to be limited to the desired contact area 26a.

The means for attaching the intermediate element 30 to the horn 23 may be of any nature known to one skilled in the art such as: screwing, welding, adhesive bonding, crimping, reinforcement …

In a particular non-limiting embodiment of the invention, the intermediate element 30 and the horn 23 are in a single piece.

The intermediate element 30 moreover comprises a planar end face 31. This end face corresponds to the face of the intermediate element 30 opposite to the contact area between the intermediate element 30 and the horn 23.

A user element 40, 50 may be attached to the end face 31 of the intermediate element 30.

The operating principle of the device illustrated in Fig. 2a is the following.

The generator 10 generates an electric AC signal with an ultrasonic frequency F which sets the piezoelectric ceramics 21a, 21b of the transducer 20 into vibration.

The ceramics vibrate in the radial mode.

This vibrational mode of the ceramics 21 induces alternating changes in their diameters which excite the vibration of the horn 23 in a flexural mode at its distal face 24.

The intermediate element 30, which is firmly attached to the horn 23 at the contact area 26a located at the central anti-node of the distal face 24 is excited by the vibration of said horn 23.

The amplitude of the vibration of the distal face 24 in the contact area is quasi-homogenous, since in every point of said area, the amplitude is between 90% and 100% of the amplitude at the centre of the area. This allows the intermediate element 30 to be set into vibration at frequency F according to its longitudinal eigenmode, so that any point of its end face 31 is then driven by a homogenous vibration orthogonal to said face.

Any user element 40, 50 attached to the end face 31 may then be set into vibration in the longitudinal mode at frequency F, from the moment that it has been designed for doing this according to the prior art.

Thus, the invention proposes a device for producing homogenous longitudinal vibrations which may be used in most industrial applications such as welding, spraying and industrial cutting, with which a significant output power larger than or equal to 100 Watts may be transmitted.

With reference to Fig. 2b, another embodiment of the device according to the invention is illustrated.

In this particular embodiment, the intermediate element 30 is integrated to the user element 40, which in this case is a ultrasonic horn of the prior art; as for the remainder, the device is identical with the one shown in Fig. 2a.

With reference to Fig. 3, another embodiment of the device according to the invention is illustrated.

In the case shown by Fig. 3, the contact area 26 between the horn 23 and the intermediate element 30 is located at the peripheral anti-node of the distal face 24.

The intermediate element 30 and the horn 23 are two distinct parts attached by screwing, welding, adhesive bonding, crimping, or reinforcement or still any other means known to one skilled in the art providing a rigid connection between the horn 23 and the intermediate element 30.

The intermediate element 30 comprises a first metal cylinder with a diameter substantially equal to the diameter of the horn 23, and intended to be in contact with the horn 23 at the peripheral anti-node of the distal face 24, the contact area 26b being crown-shaped.

Advantageously, the width of this crown is between 10% and 15% of the radius of the distal face 24, so that, according to Fig. 1d, the amplitude of the vibration in any point of said area is larger than 90% of the amplitude of the vibration at the periphery.

The first cylinder comprises a recess, the depth of which is provided to be sufficient so that the distal face 24 of the horn 23 and the opposite face 32 of the intermediate element 30 may freely vibrate in their respective modes without touching each other elsewhere as in the contact area 26b. This provides decoupling of the vibrations of both of these faces which vibrate in opposite phase relatively to each other.

More generally, the geometry of the intermediate element 30 is selected so that the contact between the intermediate element 30 and the horn 23 only occurs at the retained contact area 26 when the device is operating, so as not to disturb the vibration of both parts according to their resonant eigenmode.

The material (for example aluminum, titanium, …) of the intermediate element 30 is selected, and its geometry is calculated, so that it enters into vibration in resonance at the same frequency F and that the planar end face 31 of the intermediate element 30 is driven in every point by a homogenous vibrational movement, orthogonally to said end face 31.

The operating principle of the embodiment illustrated in Fig. 3 is similar to the one of the embodiment illustrated in Fig. 2.

The generator 10 generates an electric AC signal with an ultrasonic frequency F which sets the ceramics into vibration in a radial mode.

The vibration of ceramics 21a, 21b excite the vibration of the horn 23 in a flexural mode at its distal face 24.

The intermediate element 30, which is firmly attached to the horn 23 at the contact area 26b localized at the peripheral anti-node of the distal face 24, is excited by the vibration of said horn 23.

The amplitude of the vibration of the distal face 24 in the contact area is quasi-homogenous, since in every point of said area, the amplitude is between 90% and 100% of the amplitude at the centre of the area. This allows the intermediate element 30 to be set into vibration at frequency F according to its eigenmode, so that every point of its end face 31 is then driven by a homogenous vibration orthogonal to said face.

With reference to Fig. 4, another embodiment of the device according to the invention is illustrated.

In this embodiment, the intermediate element 30 comprises a circular plate and at least a cylindrical protrusion extending towards the outside of the plate, and concentric with the axis of revolution of the plate, the end of the protrusion forming the planar end face 31 of the intermediate element 30 intended to receive the user assembly.

The material and the geometrical characteristics of the plate are carefully selected so that it has a resonant vibrational eigenmode at frequency F so that the circular plate vibrates in the radial mode and the protrusion 31 vibrates in the longitudinal mode in opposite phase (through the Poisson effect) according to the prior art, as for example described in US Patent 3,696,259 as of 03.10.1972.

A plurality of identical transducers 20 is associated with the plate via contact areas 26a located at the central anti-node of the distal face 24 of each transducer 20.

These transducers 20 are attached to the outside of the plate and protrude radially, so that the axis of revolution of the plate is orthogonal to the axis of revolution of the transducers 20.

The transducers 20 are regularly spaced out around the plate, and connected to the same generator 10 so that all the transducers vibrate in phase at the frequency F of the generator.

Of course, the geometry of the intermediate element 30 of Fig. 4 is determined so that the contact operating between the intermediate element 30 and each transducer 20 only occurs at the retained contact area 26, i.e. at the central anti-node or the peripheral anti-node of the distal face 24 of the horn 23 of each electro-acoustic transducer 20.

Thus, the horns 23 of the electro-acoustic transducers will vibrate at their distal face 24 in phase in the flexural mode; via the contact areas 26 where the vibration is homogenous, they will excite the vibration of the plate in its eigenmode, so that it will itself be driven by a radial vibration.

The operating principle of the embodiment illustrated in Fig. 4 is the following.

The generator 10 generates an electric AC signal with an ultrasonic frequency F which sets the ceramics of the transducer 20 into vibration in the radial mode.

The vibrations of the ceramics 21, 21b excite the vibration of the horn 23 of each transducer 20 in a flexural mode at its distal face 24.

The intermediate element 30, which is attached to the horn 23 of the transducers at the central anti-node

26a or the peripheral anti-node 26b of the distal faces 24 is excited by the vibrations of the horns 23.

The vibrations of the horns 23 induce contraction and expansion of the plate, the latter inducing contraction and expansion of the protrusion in opposite phase (Poisson effect). Thus, the plate vibrates radially and the protrusion vibrates longitudinally at the same frequency.

In fact, the end surface 31, to which the user assembly 40, 50 is firmly attached, allows this assembly to be set into vibration in the longitudinal mode.

With the embodiment shown in Fig. 4, it is possible to obtain particularly high acoustic output power, by putting the electro-acoustic transducers 20 in parallel, which all operate in phase.

The intermediate element 30 illustrated in Fig. 4 thus simultaneously achieves:

- placing several electro-acoustic transducers 20 in parallel, vibrating in phase,
- transforming the vibrational mode of the piezoelectric transducers 20 into a radial mode of the plate,
- transforming the radial vibrational mode of the plate into a longitudinal mode at the end face 31,
- transforming the amplitude of the vibrations.

By opportunely selecting the number of electro-acoustic transducers and their geometry, it is thereby possible to cover a range of frequencies from 20 to 400 kHz and a power range from 50 to 10,000 Watts.

With reference to Fig. 5, another embodiment of the device according to the invention is illustrated.

In this embodiment, the device according to the invention illustrated in Fig. 2a is positioned in a sealed chamber 60 in which a coolant gas or liquid flows.

Indeed, the electro-acoustic transducer (the case of Figs. 2 and 3), or the electro-acoustic transducers (case of Fig. 4) release heat when operating, which causes increase of their temperature.

This increase in temperature of the transducers may lead to their destruction.

To find a remedy to this drawback, the electro-acoustic transducer(s) may be placed inside a cooling chamber 60, the cooling means being provided by a flow of air, of gas or water, flowing in the latter case in a sealed jacket, or even by any other conceivable means.

In the case of Fig. 5, cooling is provided by a flow of compressed air entering through the aperture 601 and exiting through the aperture 602.

The output junction of the device according to the invention and of the cooling chamber 60 is achieved in an amplitude node 33 of the vibration of the intermediate element 30.

According to principles well known to one skilled in the art, it is possible to then firmly attach to the end face 31, a user element (part 40 or assembly of parts 50), which will be set into ultrasonic vibration at the same frequency as the previous parts, the vibrations generated in the portion in contact with the end face 31 being longitudinal and propagating in the user element (part 40 or assembly of parts 50) with planes of equal phase, at least in its initial portion.

The connections between the horn 23 and the intermediate element 30 on the one hand and between the intermediate element 30 and the user element (part 40 or assembly of parts 50), on the other hand, may be achieved according to the prior art by any suitable means such as screwing, welding, adhesive bonding, crimping, reinforcement or further by any other suitable mechanical means providing a rigid connection.

In this respect, an alternative of the connecting mode between two consecutive parts consists of producing them as a single piece, in the same block of material.

Without the present invention being limited to the following cases, the user element (part 40 or depending on the case, each part forming the assembly of parts 50) may be preferentially selected so that it has a vibration eigenfrequency tuned on the eigenfrequency F common to the generator 10, to the electro-acoustic transducer 20 and to the intermediate element 30, the thereby composed assemblies forming a whole which vibrates in resonance at frequency F of the electric signal delivered by the generator 10.

The user element (part 40 or assembly of parts 50) may comprise a ultrasonic horn, or a cutting blade, or a sprayer or an ultrasonic reactor, or further any other assembly which resonates depending on the targeted application: welding, machining, cutting, spraying, treating liquids and solid/liquid mixtures such as homogenization, dispersion, disintegration, destruction of biological cells, degassing.

Subsequently, the present invention advantageously finds application in all the industrial applications of power ultrasound and notably in welding, machining, cutting, spraying, cleaning, sieving, treatment of liquids, etc…

Other features and advantages of the present invention will become apparent upon reading the description detailed hereafter of a certain number of particular embodiments of the present invention.

Figs. 6-8 relate to the setting of simple ultrasonic horns in vibration.

Fig. 6 illustrates a ultrasonic horn 40, the geometry of which may be adapted to any particular use. It comprises a cylindrical bar 41 with a circular section which is firmly attached to the end face 31 of the intermediate element 30.

The invention allows propagation in the cylindrical bar 41 of longitudinal ultrasonic vibrations which propagate along the generatrix of the cylindrical bar with planes of equal phase.

Fig. 7 applies a user assembly 50, consisting of a velocity transformer 52 also commonly called a booster by one skilled in the art - and of a ultrasonic horn 58, which may for example be used for stirring/homogenizing a liquid; both ends of the booster 52 are connected to the other elements of the user assembly in the vicinity of displacement amplitude anti-nodes of the vibration.

Fig. 8 applies a user assembly 50, consisting of a velocity transformer or booster 52 and of a ultrasonic horn 59, which may for example be used for cutting soft or brittle materials (“foie gras", "mille-feuille” pastry, etc.).

Figs. 9-11 relate to devices for spraying liquid substances or solid/liquid mixtures according to the invention.

Fig. 9a applies a device for setting a user assembly 50 into vibration, successively comprising a cylindrical rod 51 attached to the planar end face 31 of the intermediate element 30 and with a length equal to an integer multiple of half-wavelengths (longitudinal vibrational mode), a velocity transformer 52 or booster and a spraying ultrasonic horn 53.

The ultrasonic horn 53 which is illustrated in detailed in Fig. 9b, includes a disc 56 and axisymmetrical cylindrical outgrowths 57 concentric with the axis of the disc 56 and extending on either side of the latter.

The material and the geometry of the ultrasonic horn 53 are selected so that the cylindrical outgrowths 57 vibrate longitudinally in resonance at the frequency of the generator 10 and the disc 56 vibrates radially in resonance at the same frequency.

The radius of the disc is thus determined specifically so that at frequency F, the radial vibration driving it, comprises a first quarter wavelength and then an integral number of half-wavelengths.

The outer face 55, which forms the edge of the disc 56, is driven by a vibration orthogonal to said outer face 55, which allows the liquid to be sprayed by this outer face 55 homogenously and in an industrially productive way.

European Patent EP 0 588 609 describes such a ultrasonic horn 53.

The radius of the disc 56 may, in particular embodiments of the present invention, be more or less significant, from the moment it allows said disc 56 to vibrate radially in resonance at the frequency F of the generator and that, by this very fact, the vibration driving it comprises a first quarter-wavelength and then an integral number of half-wave-lengths.

Fig. 10 applies the spraying assembly of Fig. 9 mounted inside a sealed enclosure 61, in which any suitable atmosphere may be established from the points of view of composition, temperature and pressure, with the purpose of forming an atomization device of the spray cooling type or of the spray drying type, or even of any other type.

In the case of Fig. 10, the penetration of the device according to the invention inside the sealed enclosure 60 is performed at an amplitude node 511 of the vibration of the cylindrical rod 51. With the sprayer of Fig. 10, in which a cold gas flow is established, it is for example possible to produce fine metal alloy powders which have a narrow particle size spectrum by spray cooling.

This metal alloy brought beforehand to a temperature above its melting point, is sprayed inside the sprayer in fine droplets.

These droplets then cool when falling inside the enclosure and solidify producing the sought powders.

As an example, an assembly according to Figs. 9 and 10, and operating at 80 kHz, with a rated power of 350 Watts, will be described in detail hereafter.

This assembly comprises an electro-acoustic transducer 20, equipped with two ceramics 21 with outer 38 mm/inner 12 mm diameters and with a thickness of 6 mm, excited in the so-called radial or planar mode.

This transducer 20 is connected via an intermediate element 30 to a straight cylindrical coupling rod 51 of diameter 15 mm, made in a titanium alloy TA6V with a length corresponding to 6 half-wavelengths, i.e. 300 mm.

This assembly further comprises a booster 52, with a ratio of 2.25, so that a peak-to-peak vibration of the order of 2-6 microns may be obtained at its attachment point (vibration anti-node) at the spraying ultrasonic horn 53.

The spraying ultrasonic horn is of the type disclosed by Fig. 9b and vibrating in resonance with the assembly described earlier.

With this assembly it is possible to produce a spherical powder of fusible tin-based metal alloy with an average diameter of the order of 30 microns under an alloy flow rate of the order of 100 kg/h.

The device illustrated in Fig. 11 applies a user element 50 successively comprising a cylindrical rod 51 attached to the planar end face 31 of the intermediate element 30, a booster 52 and a spraying ultrasonic horn 54 including a cylindrical bar with a circular section, the free face 55 of which (i.e. the most distant from the transducer 20) allows a liquid to be sprayed.

A sheath 62 surrounds the user element 50, which penetrates into the sheath at an amplitude node 511 of the vibration of the cylindrical rod 51.

With this sheath 62, it is possible to feed the liquid to be sprayed on the ultrasonic horn 54 via an orifice 63.

With reference to Fig. 12, another embodiment of the device according to the invention is illustrated with which a tubular ultrasonic reactor may be formed.

In this embodiment, the intermediate element 30 is ring-shaped.

A plurality of identical transducers 20 are associated with the ring via contact areas 26a located at the central anti-node of the distal face 24 of each transducer 20.

These transducers 20 are attached to the outside of the ring and protrude radially, so that the axis of revolution of the ring is orthogonal to the axes of revolution of the transducers 20.

The transducers 20 are regularly spaced out around the ring, and connected to the same generator 10, so that all the transducers vibrate in phase at the frequency F of the generator.

Two tubes 45 and 46 are attached on either side of the ring 30 to the crowns 31 internal to the ring, tubes which may in a preferential but non-limiting embodiment, be integrated with the ring 30 into a single piece.

The materials and the geometrical characteristics of the ring 30 and of the tubes 45, 46 forming together the user element 40, are selected so that at frequency F, the ring vibrates in resonance in the radial mode and the tubes in the longitudinal mode.

The operation of the device according to the invention illustrated in Fig. 12 is then the following.

The transducers 20 vibrate in phase at the frequency F delivered by the generator and set the ring 30 into vibration in the radial mode.

By the Poisson effect of the ring, the tubes 45 and 46 are set into vibration in the longitudinal mode.

A liquid which flows within the tubes then receives ultrasonic energy.

Finally, Fig. 13 applies an ultrasonic reactor, set into vibration by electro-acoustic transducers 20 and their intermediate elements 30.

European Patent EP0567579 discloses such an ultrasonic reactor, consisting of a tubular metal body 43 and of an annular bulge 42 in the median portion of the tube 43, each vibrating in resonance at the same ultrasonic frequency.

Fig. 13 according to the present invention repeats the general diagram disclosed by this document: it comprises a tubular metal body 43 and the annular bulge 42 made in a single piece 40.

In the particular case illustrated by Fig. 13, only two transducers 20 are illustrated, but a plurality of transducers also distributed around the annular bulge 42 may also be applied.

The connection between each electro-acoustic transducer 20 and its associated intermediate element 30 is positioned, in the case of Fig. 13, at the peripheral amplitude anti-node 26b, but it may also be located at the central amplitude anti-node 26a.

The reader will appreciate that many modifications may be brought to the invention as described above without materially departing from the teachings of the present document. For example, the distal face 24 of the electro-acoustic transducer may comprise more than two vibration anti-nodes, the contact area, the radius (case of a central disc) or the width (case of a peripheral crown) of which was shown to be preferably between 10% and 15% of the radius of the distal face, may be smaller or larger.

Finally, the shape of the intermediate element 30 may vary. For example, the cylinder including the recess as illustrated in Fig. 3 may include notches at its outer wall.

CLAIMS

1. A device for producing longitudinal ultrasonic acoustic vibrations in a user element (40, 50), comprising at least one electro-acoustic transducer (20), including a pair of piezoelectric ceramics (21),

characterized in that

the piezoelectric ceramics (21) of the transducer vibrate in the radial mode and its distal face (24) in the flexural mode,

an intermediate element (30) is placed between the transducer (20) and the user element (40, 50),

the intermediate element is firmly attached on one side to the distal face (24) of the transducer (20) in a contact area (26) localized around a vibration amplitude anti-node of the distal face (24),

the intermediate element (30) is attached, on the other side, to the user element (40, 50) through its planar end face (31),

and any point of the end face (31) is driven by a homogenous vibration along a direction orthogonal to said face.

2. The device according to claim 1, characterized in that the electro-acoustic transducer (20) and the intermediate element (30) are in a single piece.

3. The device according to claim 1, characterized in that the intermediate element (30) on the one hand, and the user element (40) or a portion of the user assembly (50) on the other hand, are in a single piece.

4. The device according to any of claims 1 to 3, characterized in that the contact area (26) is localized at the centre (26a) of the distal face (24) of the transducer (20).

5. The device according to claim 4, characterized in that the radius of the contact area (26a) is between 10 and 15% of the radius of the distal face (24) of the transducer (20).

6. The device according to any of claims 1 to 3, characterized in that the contact area (26) is localized at the periphery (26b) of the distal face (24) of the transducer (20).

7. The device according to claim 6, characterized in that the width of the contact area (26b) is between 10 and 15% of the radius of the distal face (24) of the transducer (20).

8. The device according to claim 6, characterized in that the intermediate element (30) comprises a metal cylinder including a recess, the face of the cylinder including the recess, being intended to be facing the electro-acoustic transducer.

9. The device according to any of claims 1 to 8, characterized in that the extent of the contact area (26) is such that at each of its points, the amplitude of the vibration is larger than 90% of the amplitude at the anti-node around which the contact area (26) is located.

10. The device according to any of claims 1 to 9, characterized in that it comprises a plurality of electro-acoustic transducers (20) associated with the intermediate element (30),

the intermediate element (30) being disc-shaped and the transducers (20) being regularly spaced out and firmly attached to the periphery of the latter,

the axes of the transducers being orthogonal to the axis of the disc

and the end surface 31 being parallel to the disc.

11. The device according to any of claims 1 to 10, wherein the transducer(s) (20) is(are) connected to a generator (10) of an electric AC signal of ultrasonic frequency F, the vibration eigenfrequency in the radial mode of the piezoelectric ceramics (21) of the transducer and the eigenfrequency of the intermediate element (30) being tuned on the ultrasonic frequency F of the generator (10) and the passband of said generator being of a width between 100 and 300 Hz around the frequency F.

12. The device according to claim 11, characterized in that the ultrasonic frequency F is between 20 kHz and 400 kHz, preferentially 40 kHz and 200 kHz, and even more preferentially between 80 kHz and 200 kHz.

13. The device according to any of claims 11 or 12, characterized in that the ultrasonic power delivered by the generator (10) is between 50 and 10,000 Watts.

14. The device according to any of claims 1 to 13, characterized in that the transducer(s) (20) is(are)

positioned in a sealed chamber (60) in which a coolant gas or liquid flows.

15. The device according to any of claims 1 to 14, characterized in that the user assembly (50) comprises a velocity transformer (52) and/or a cylindrical rod (51) and/or a ultrasonic horn (53).

16. The device according to any of claims 1 to 15, characterized in that the user element (40) or each part of the user assembly (50) taken separately, has an eigenfrequency tuned on the ultrasonic frequency F of the generator (10).

17. The device according to claim 16, characterized in that

the user assembly (50) comprises at least one ultrasonic horn (53) consisting of an axial bar (57) around which is arranged a radial crown (56), positioned around the bar (57) orthogonally to the axis of the bar,

the bar (57) vibrates longitudinally and the crown radially, the outer radius of the crown (56) being determined so as to comprise a first quarter-wavelength, and then an integral number of half-wavelengths in the radial vibrational mode of the crown (56) at frequency F.

18. The liquid spraying device according to claim 17, characterized in that the liquid is sprayed by the vibration of the surface (55) located on the outer edge of the crown (56).

19. The device according to any of claims 11 to 16, which may be used as a modular unit of an ultrasonic reactor, wherein

the disc-shaped intermediate element (30) is a crown recessed in its centre,

the surface (31) is in two portions which are located on either side of the element (30), respectively, and themselves have the shape of an inner crown concentric with the element (30),

the user element (40) is a tube in two portions (45) and (46), each attached to one of the two portions of the surface (31), respectively, a tube for which the characteristics are selected so that it enters into resonance in the longitudinal vibrational mode, at frequency F.

20. A method for producing longitudinal ultrasonic acoustic vibrations comprising the steps of:

- converting an electric AC signal into radial mechanical vibrations of piezoelectric ceramics which are the components of an ultrasonic transducer,

- transforming the radial mechanical vibrations of the ceramics into a flexural vibration of the distal face of the transducer,

- using the vibratory energy of the distal face of the transducer for generating longitudinal mechanical vibrations in a user element by means of an intermediate element, the intermediate element being firmly attached on one side to the distal face of the transducer in a contact area localized around a vibration amplitude anti-node of the distal face.

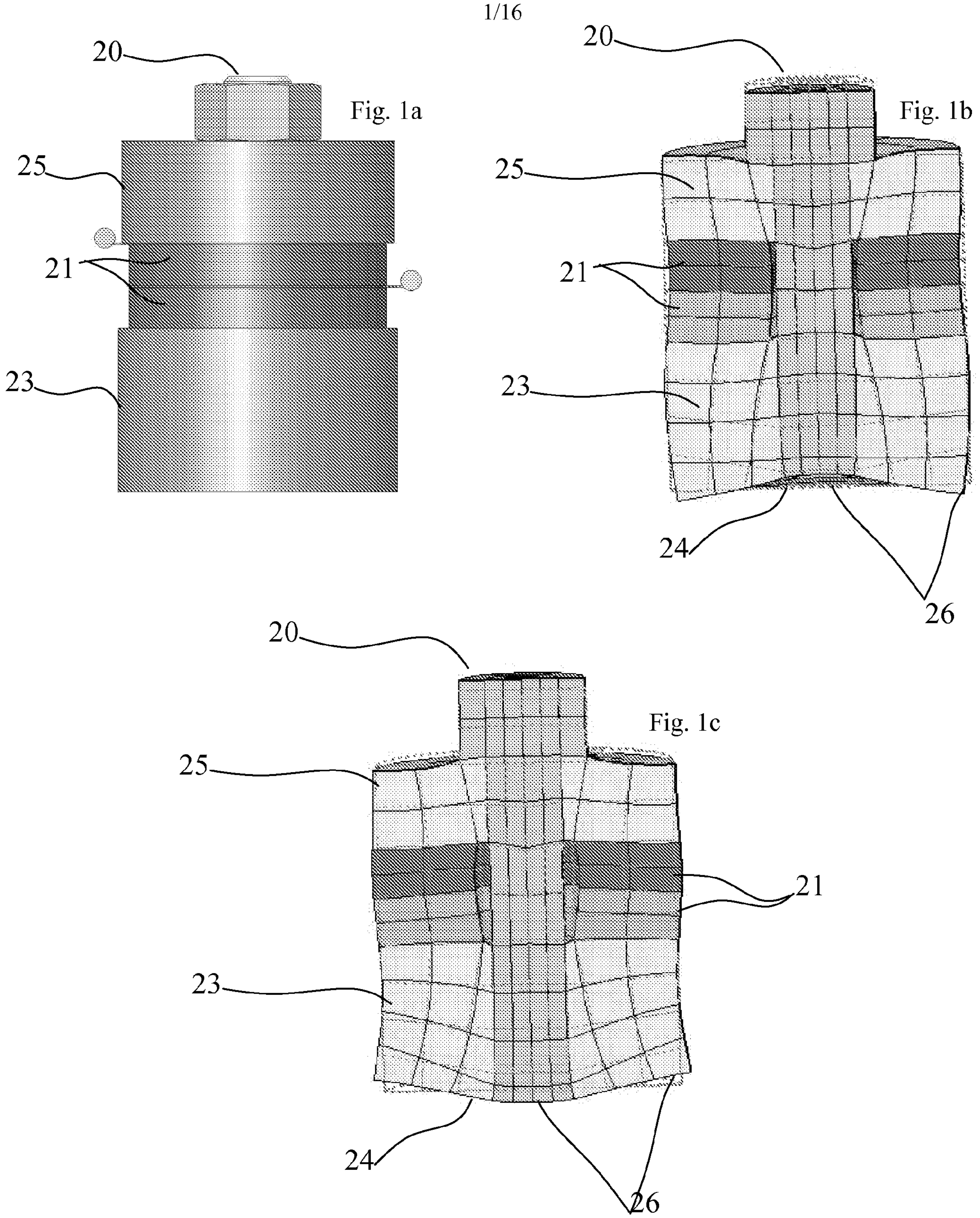

FIG. 1a-b-c

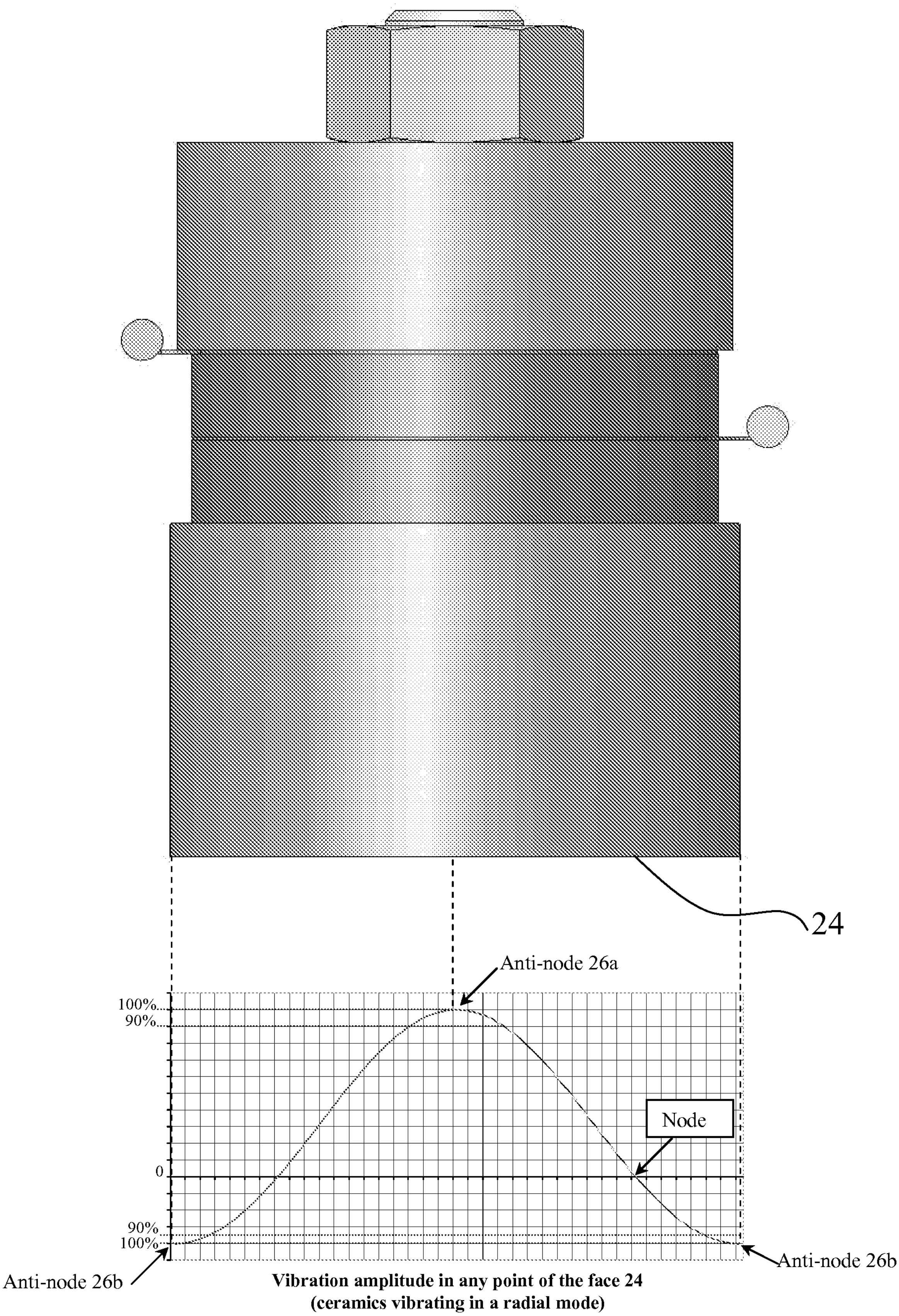
24
Anti-node 26a
100%
90%
Node
0
90%
100%
Anti-node 26b
Anti-node 26b
Vibration amplitude in any point of the face 24
(ceramics vibrating in a radial mode)

FIG. 1d

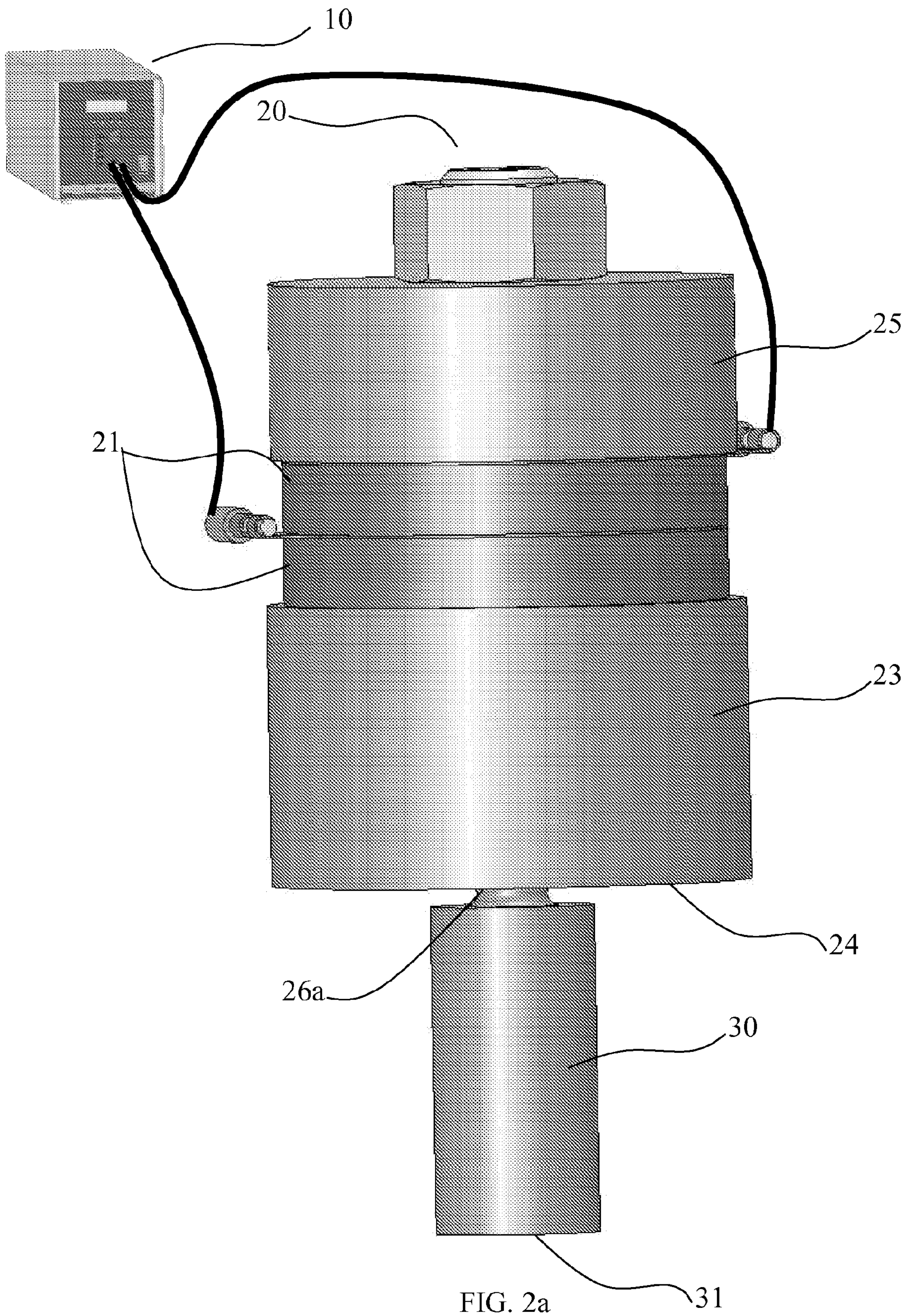

FIG. 2a

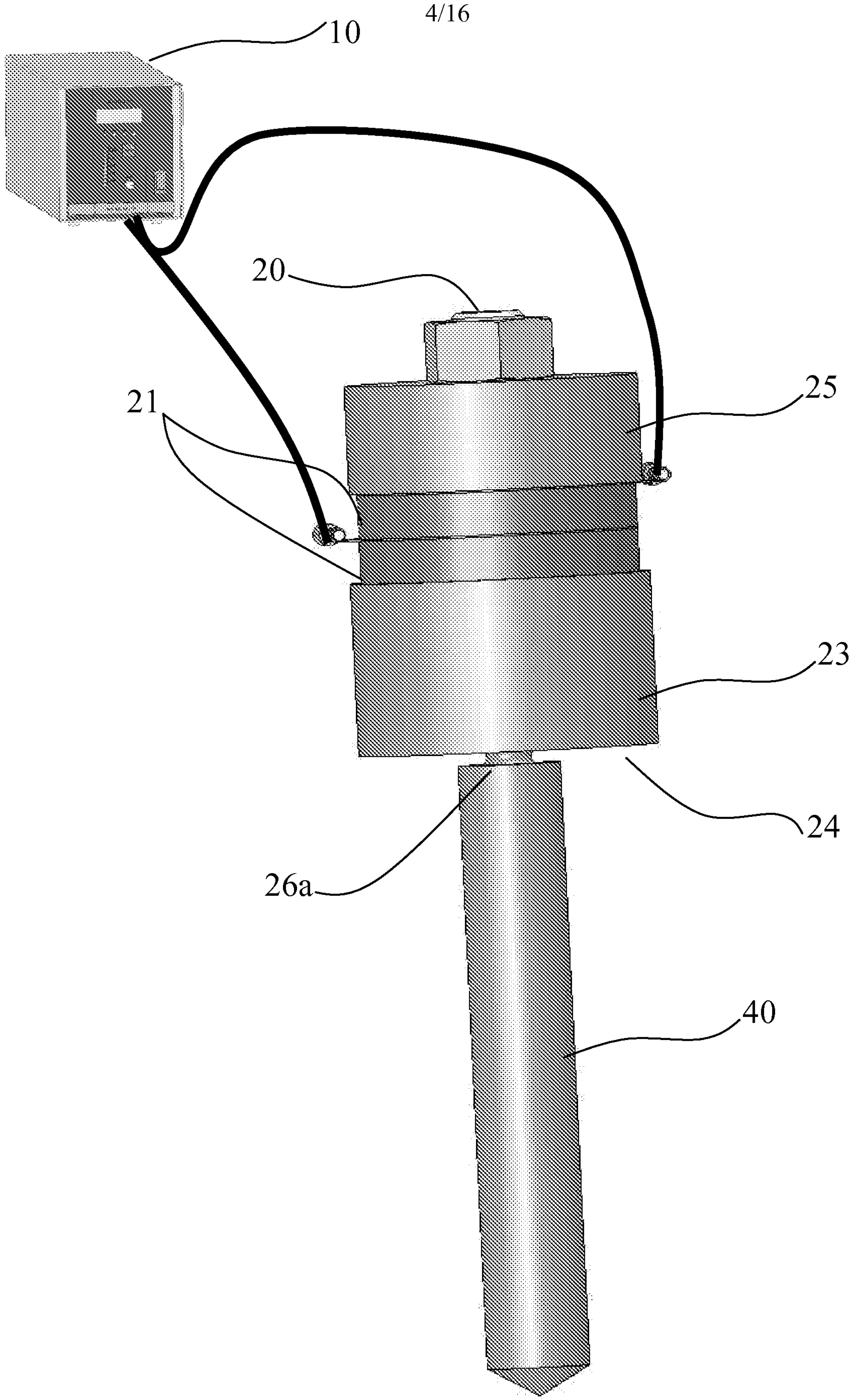

FIG. 2b

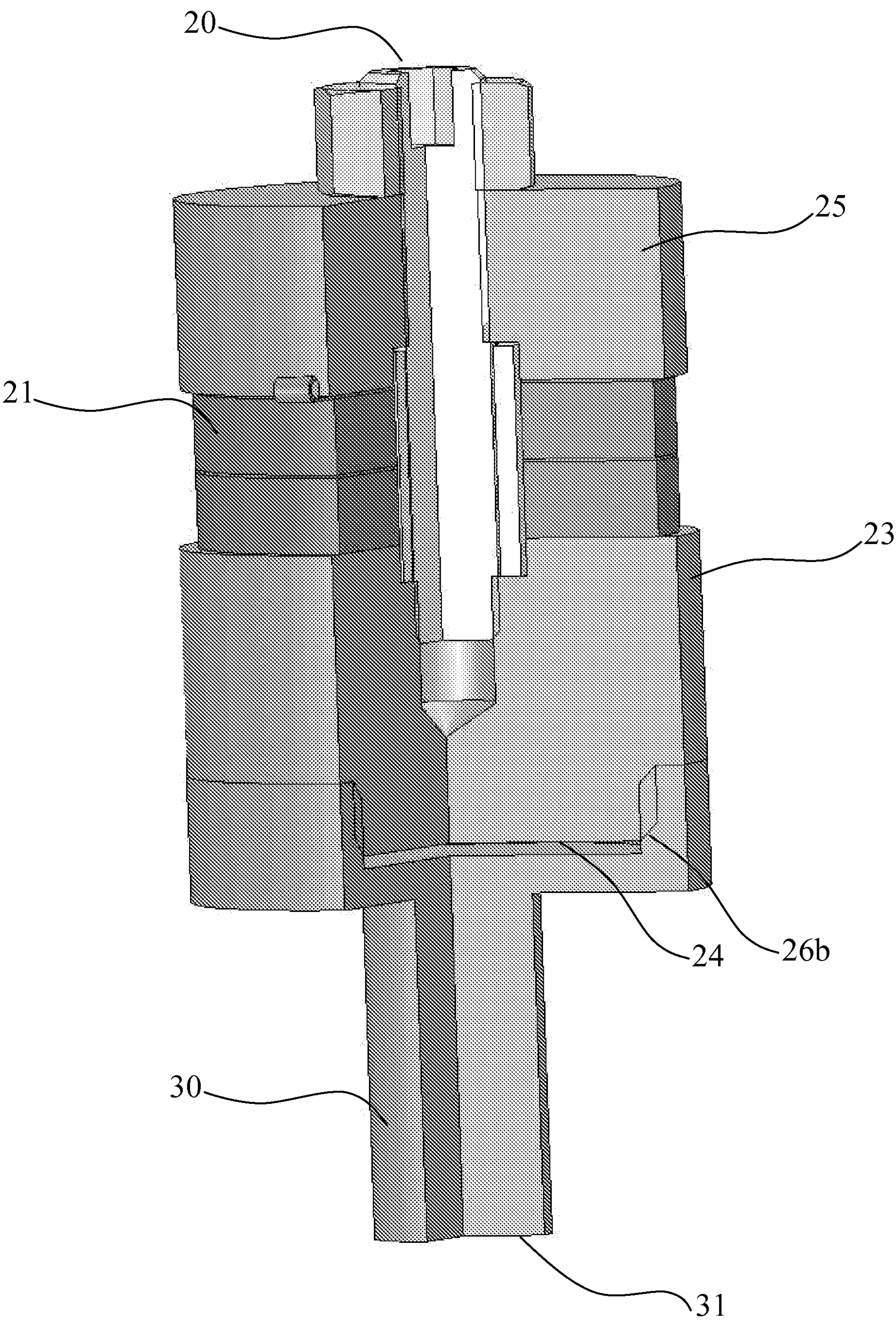

FIG. 3

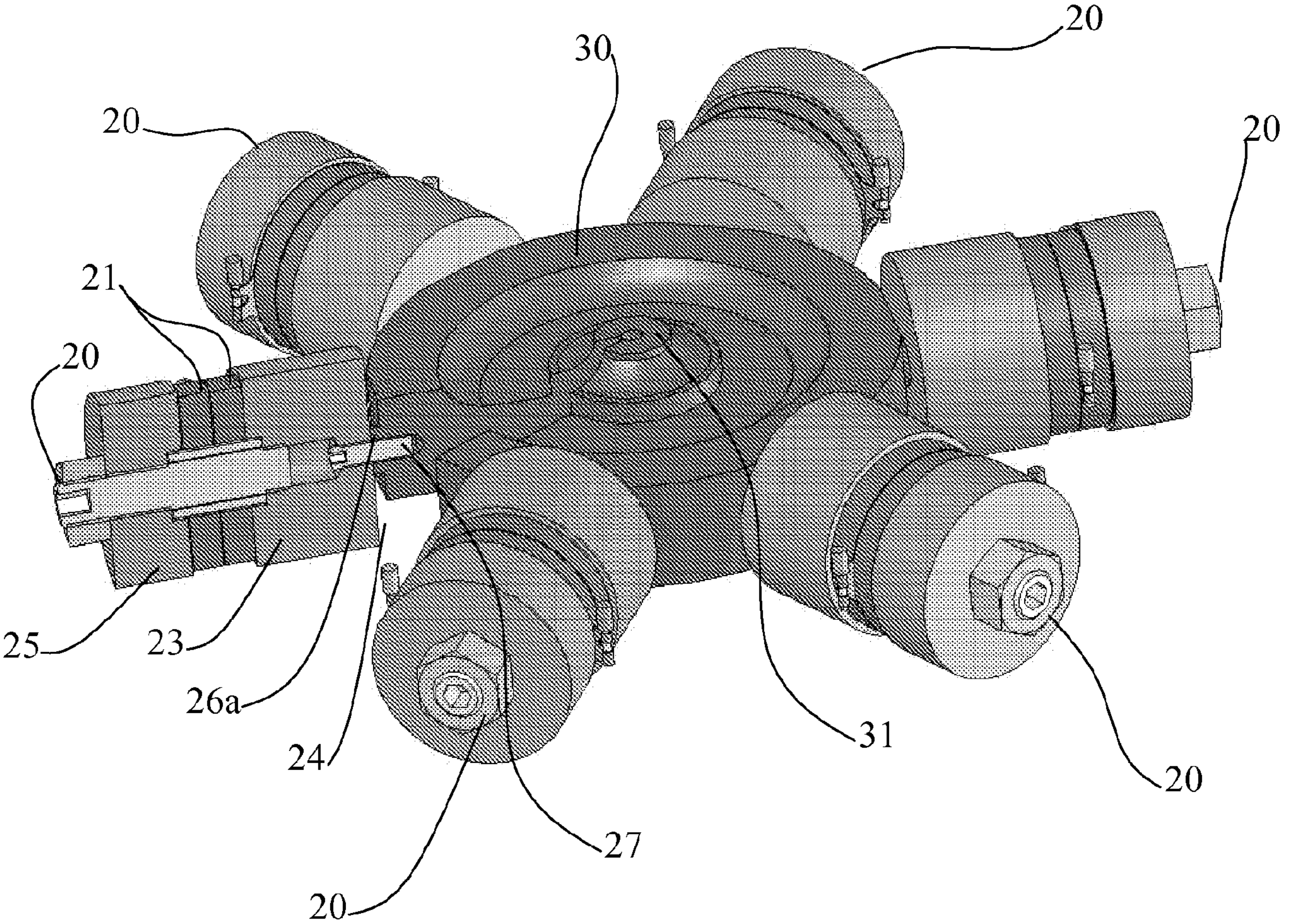

FIG. 4

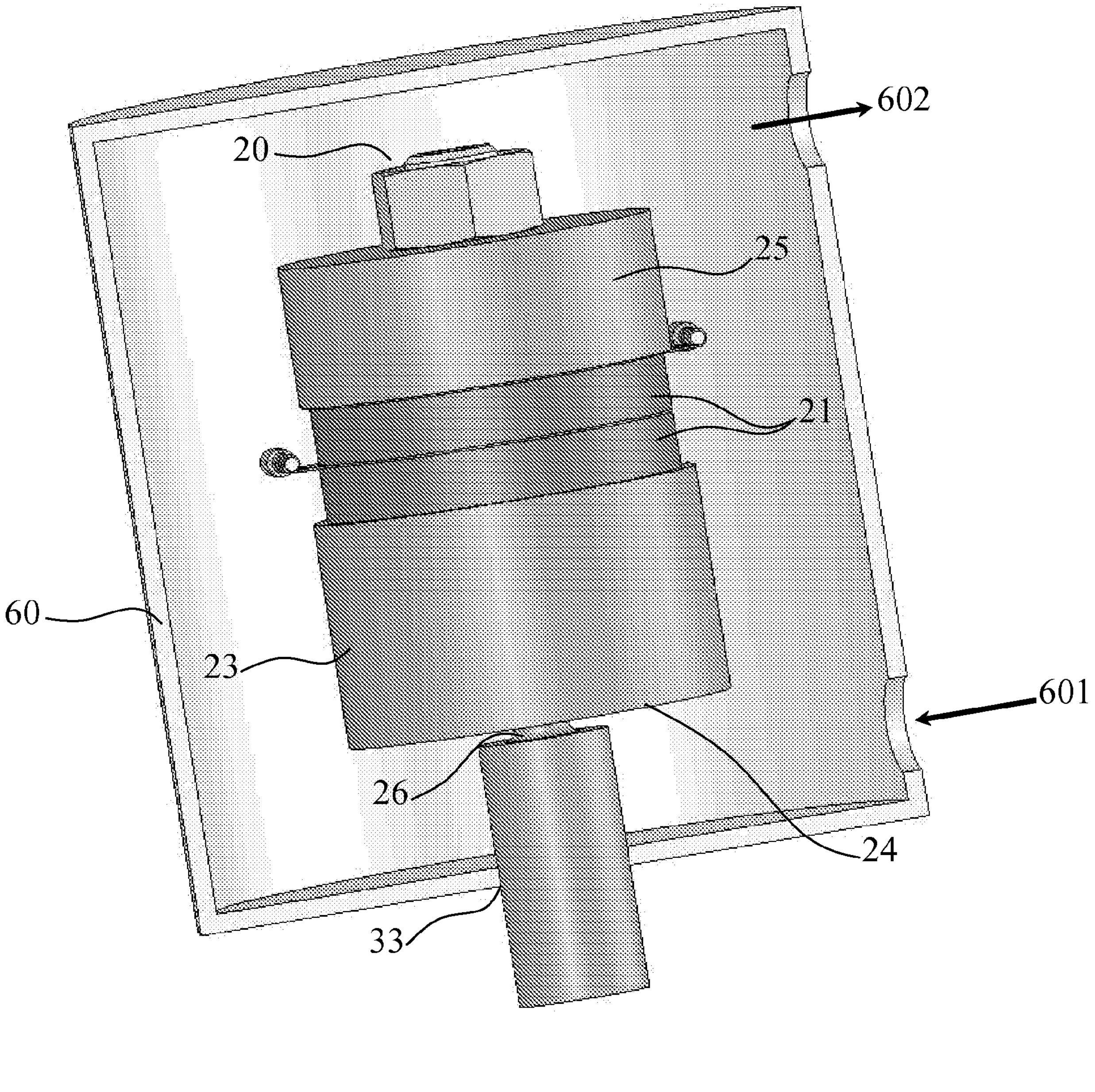

FIG. 5

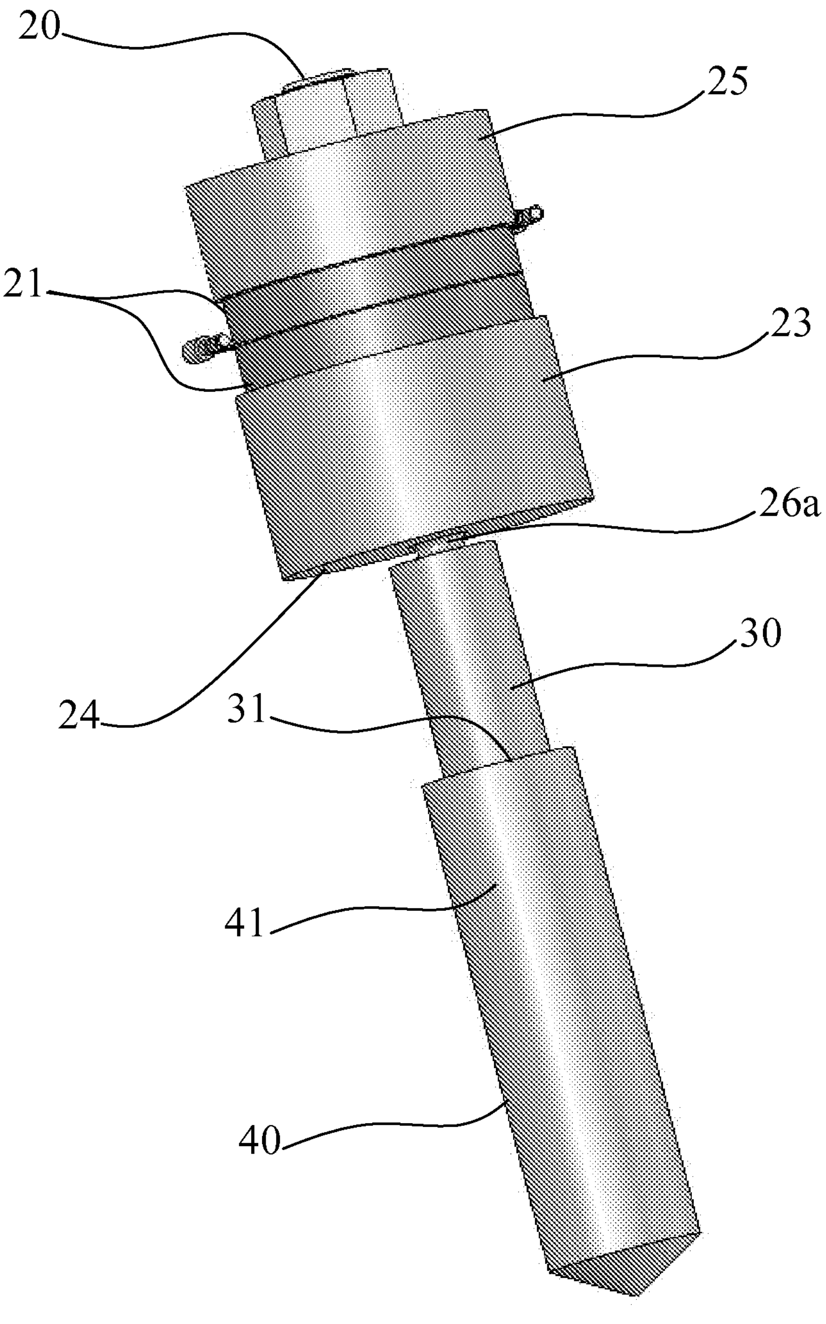

FIG. 6

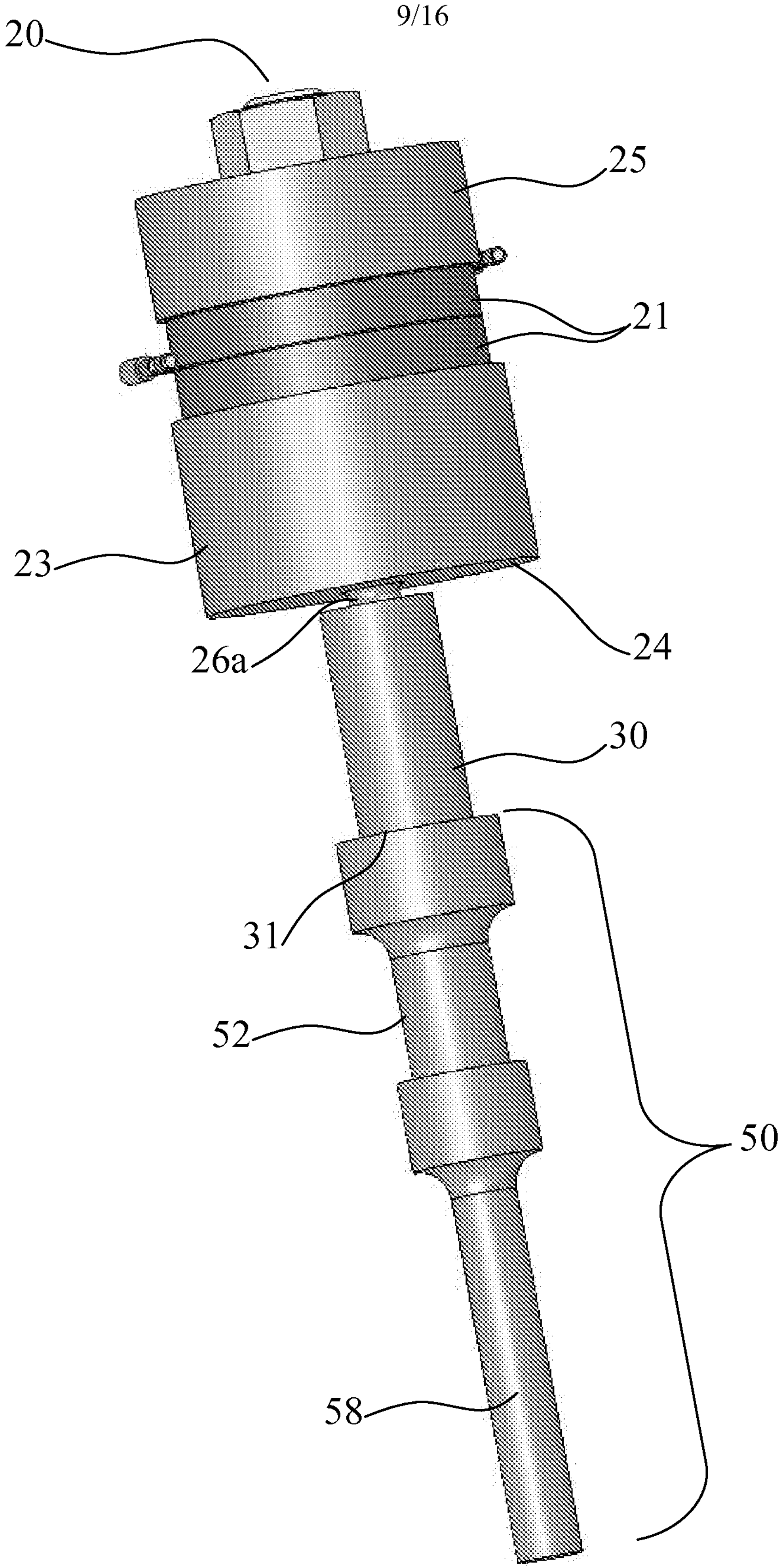

FIG. 7

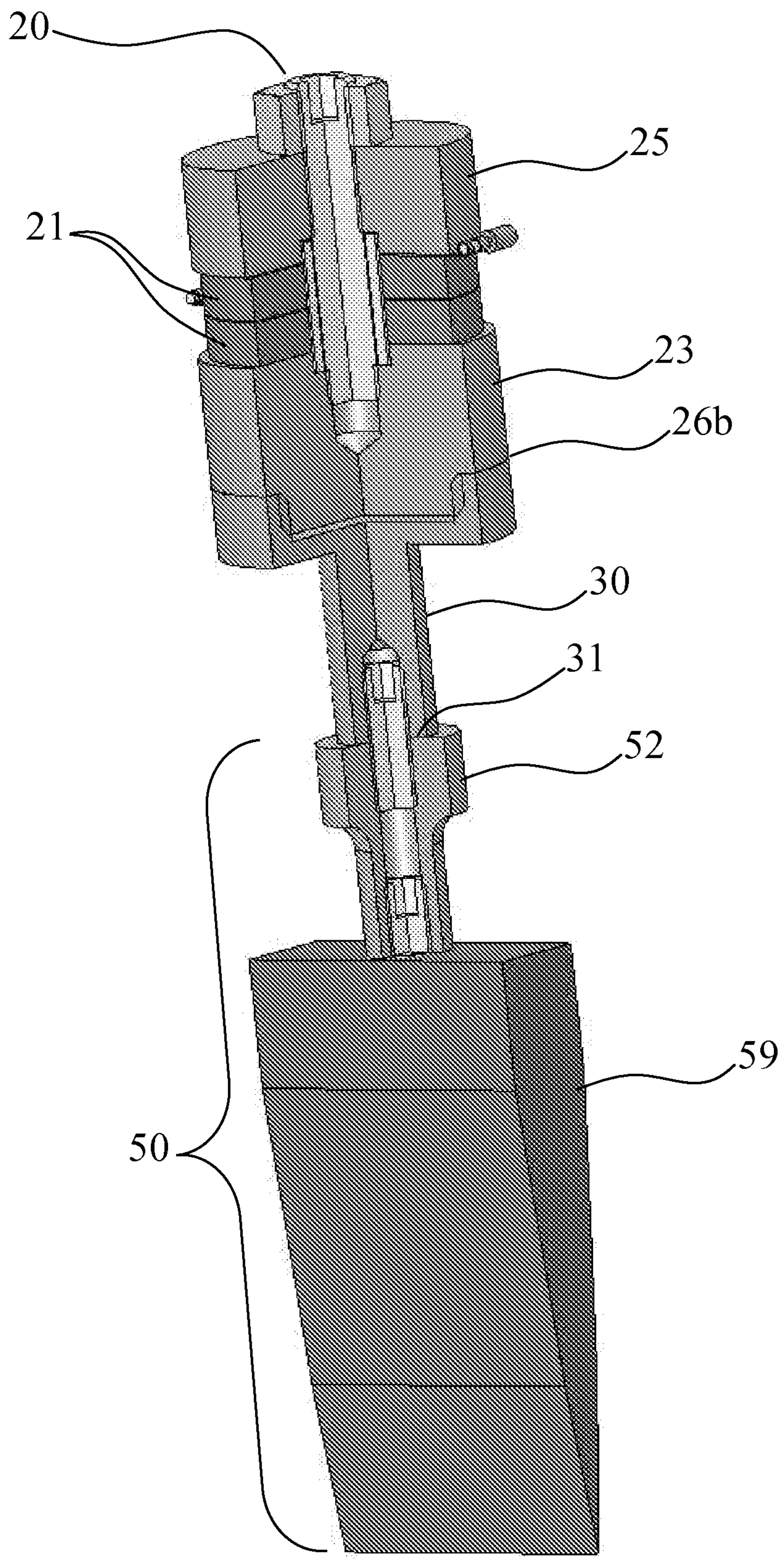

FIG. 8

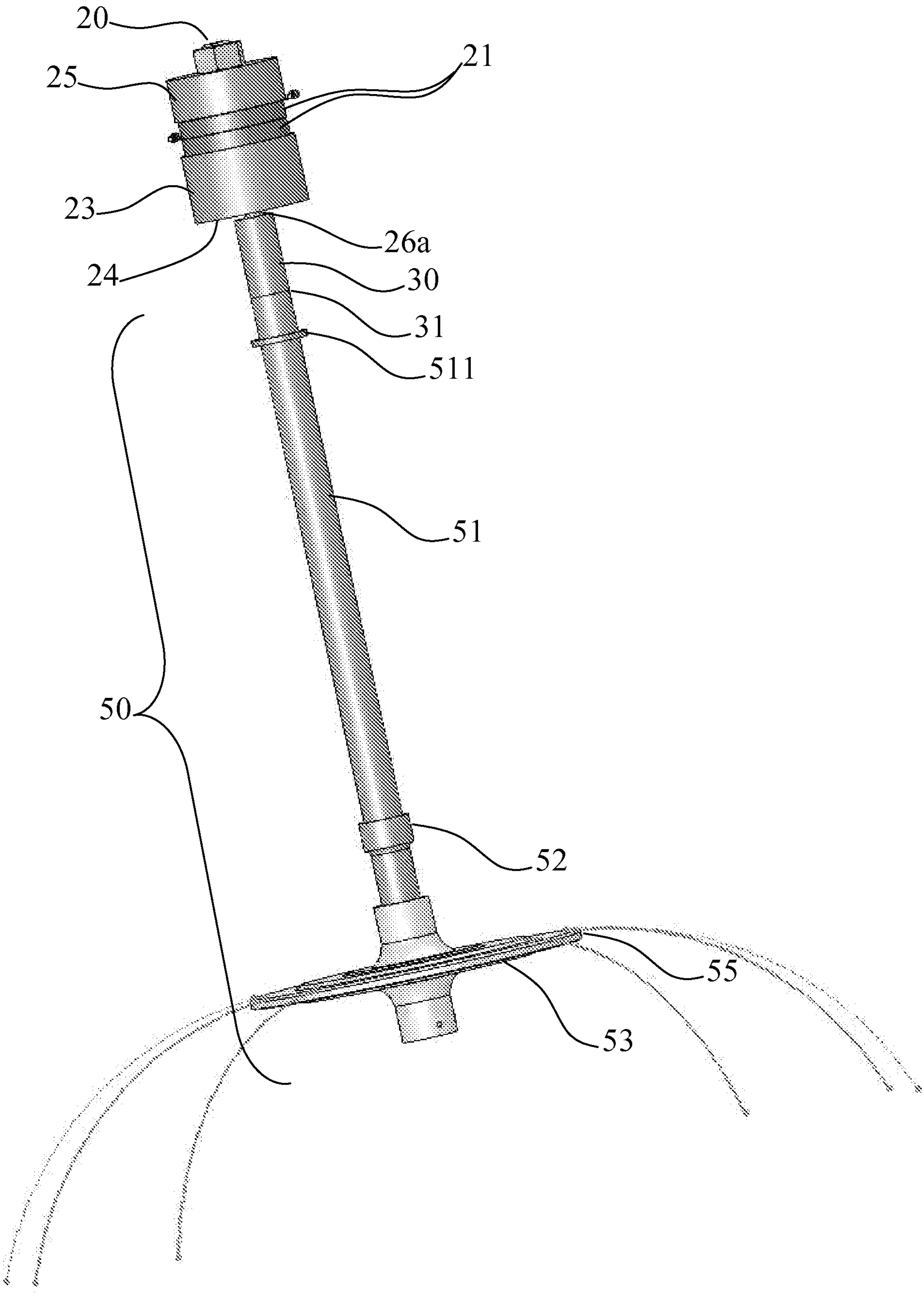

FIG. 9a

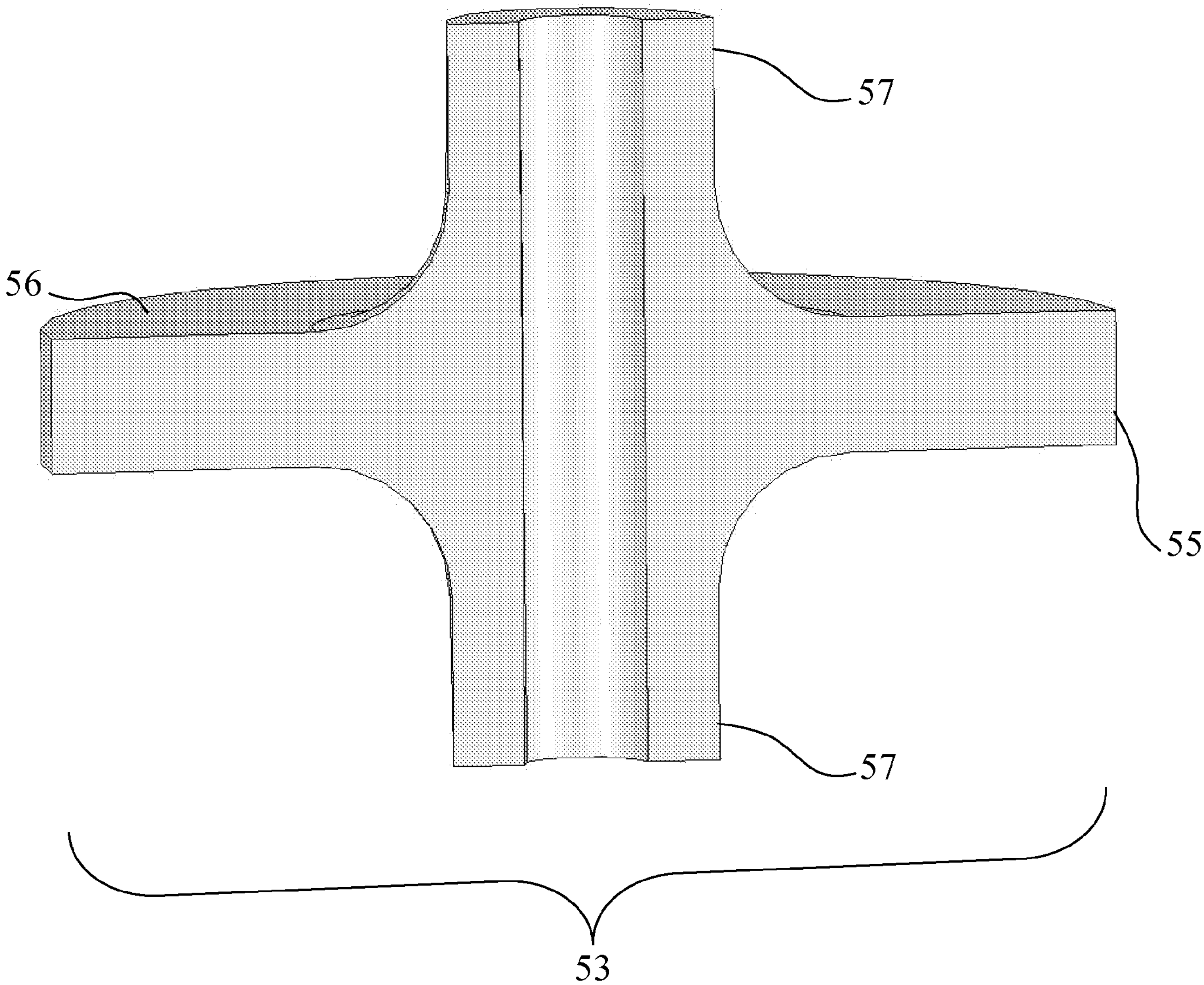

FIG. 9b

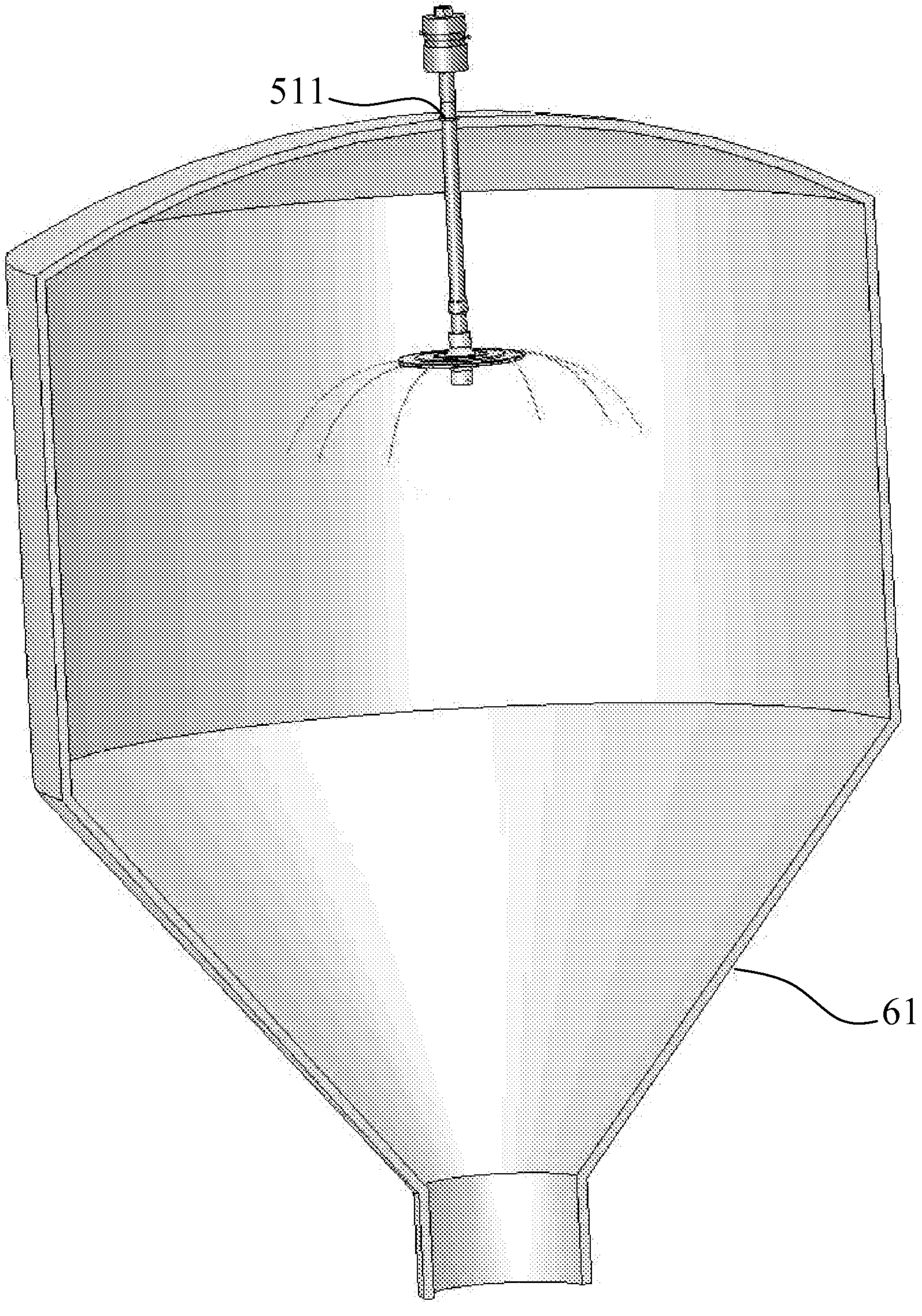

FIG. 10

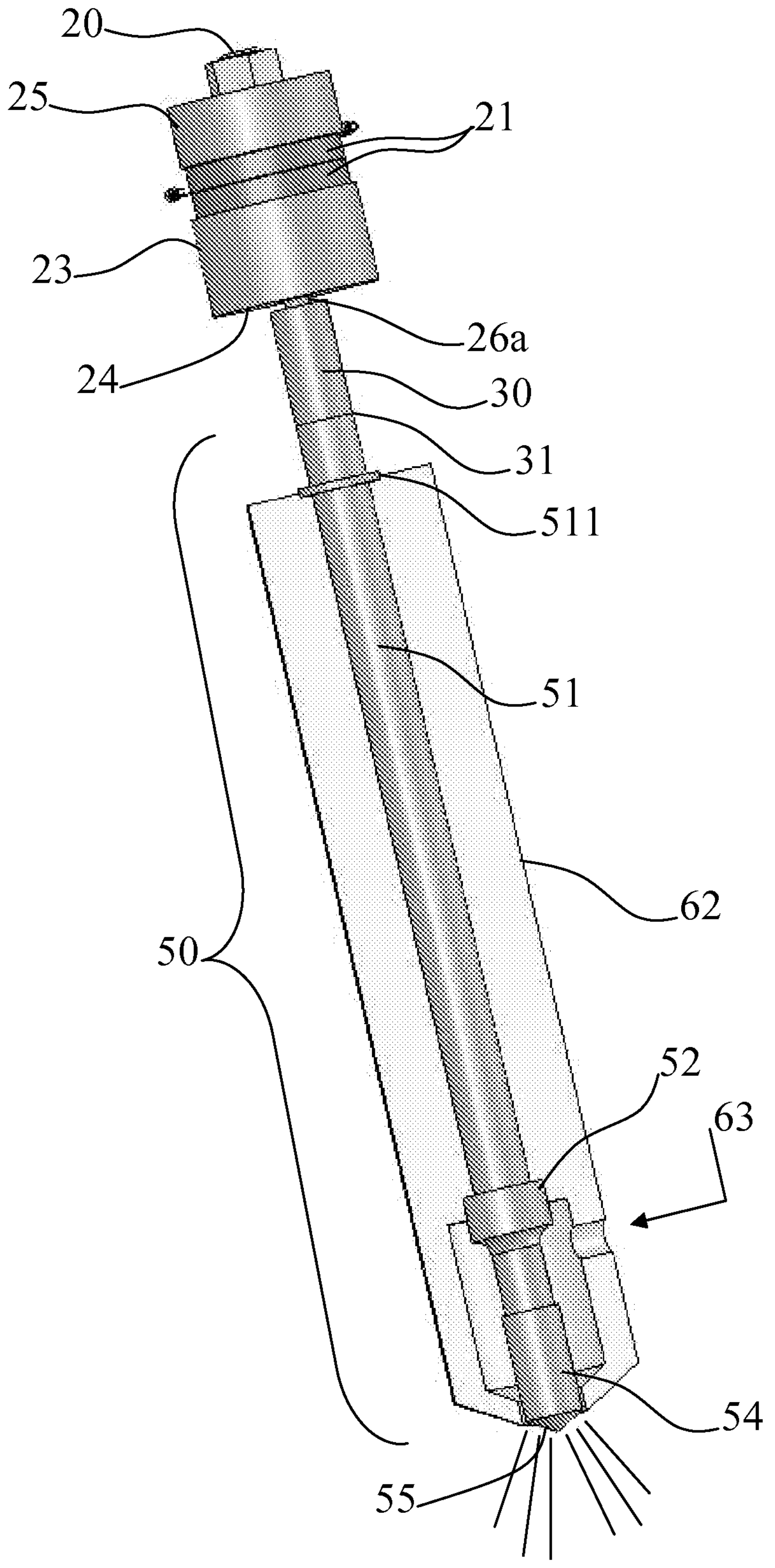

FIG. 11

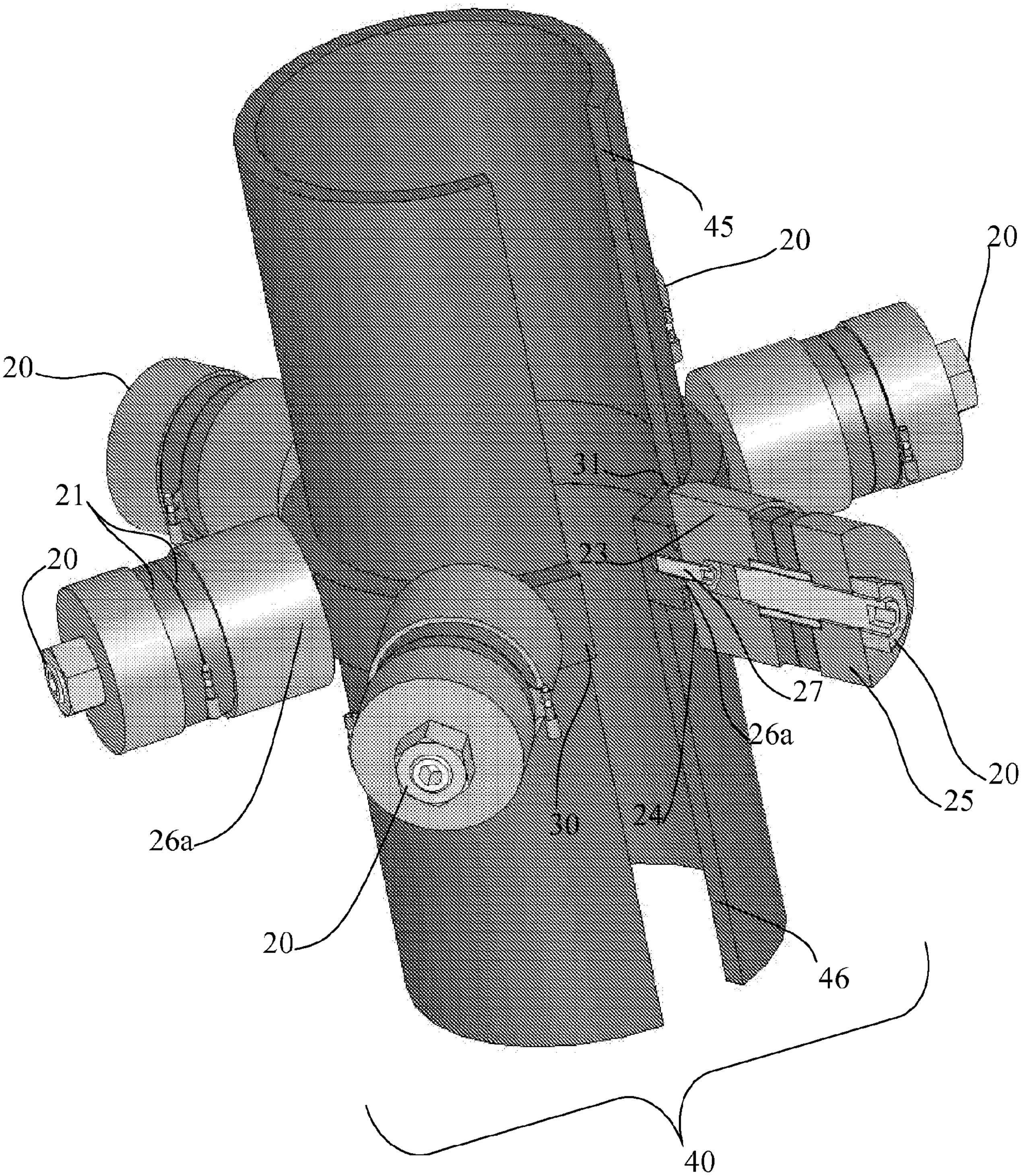

FIG. 12

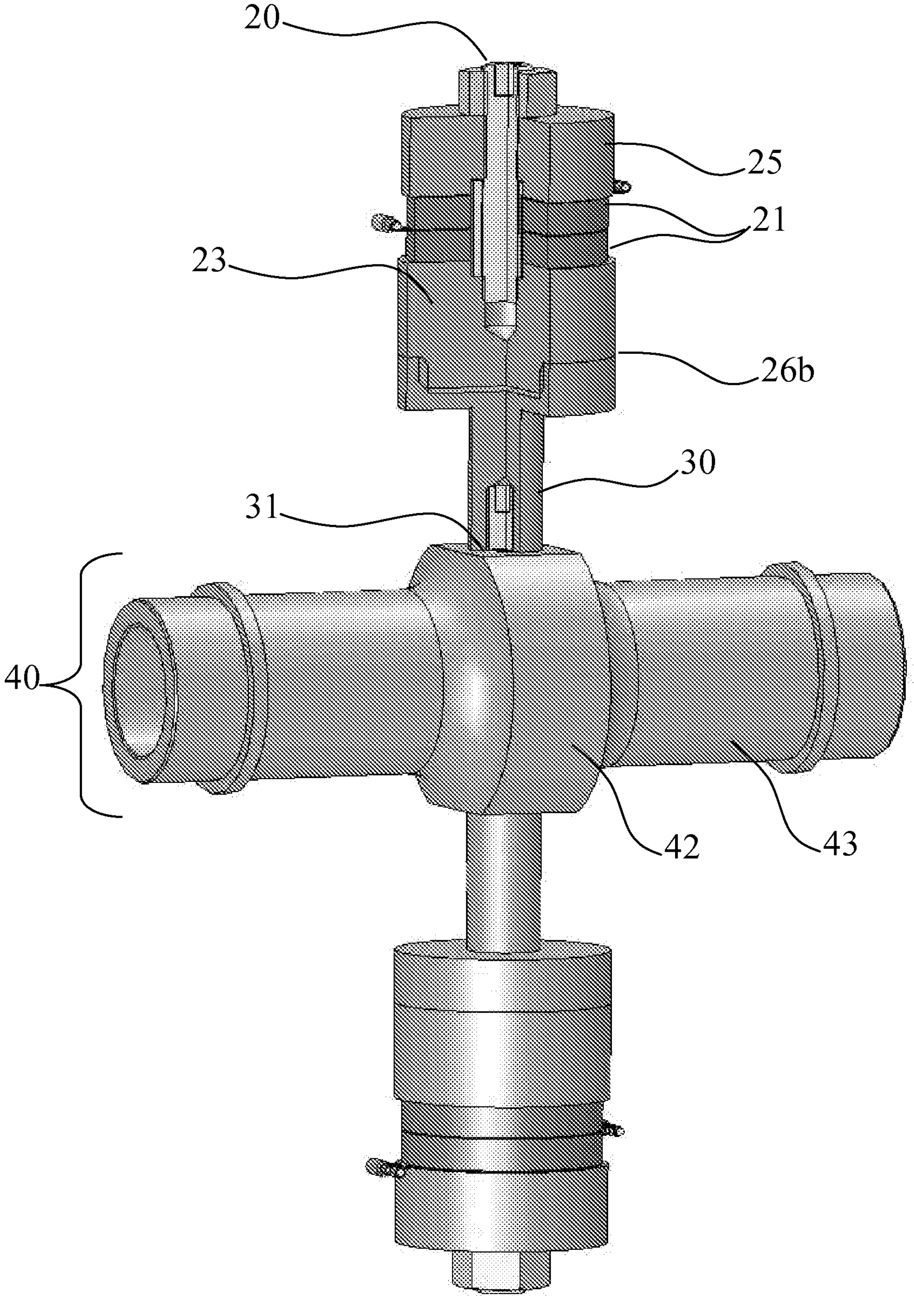

FIG. 13

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2007/064395

A. CLASSIFICATION OF SUBJECT MATTER
INV. B06B1/06 B06B3/00

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)
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 practical, 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.
A	US 5 171 387 A (WUCHINICH DAVID G [US]) 15 December 1992 (1992-12-15) column 1, line 9 - line 15 column 2, line 26 - line 33 column 6, line 51 - column 7, line 3 column 10, line 4 - line 37 column 15, line 6 - line 28; claim 1	1,20
A	FR 2 735 412 A (UNIR ULTRA PROPRE NUTRITION IN [FR]) 20 December 1996 (1996-12-20) abstract page 10, line 4 - line 20; claim 1	1,20
A	US 5 653 346 A (FREI KARL [CH] ET AL) 5 August 1997 (1997-08-05) abstract	1,20

☐ 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 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 when the document is taken alone

"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

Date of the actual completion of the international search	Date of mailing of the international search report
8 April 2008	16/04/2008
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Authorized officer Lorne, Benoît

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2007/064395

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