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(54) Drop generator for long array ink jet printer

(57) A drop generator for use in an ink jet printer is capable of stimulating long ink jet arrays at high operating frequencies. The drop generator comprises a substantially uniform cross section for a central portion and two end sections with different cross sections. The end sections have features to adjust a resonant frequency of the end sections to match that of the central portion. In particular, these features comprise cuts on a top of the drop generator. The drop generator utilizes multi-lobed radial bending modes for vibration of an array of orifices, and the vibrational modes are driven by at least two rows of transducers which extend substantially the length of the drop generator. The transducers are placed consistent with a lobe structure of an operational radial bending mode.

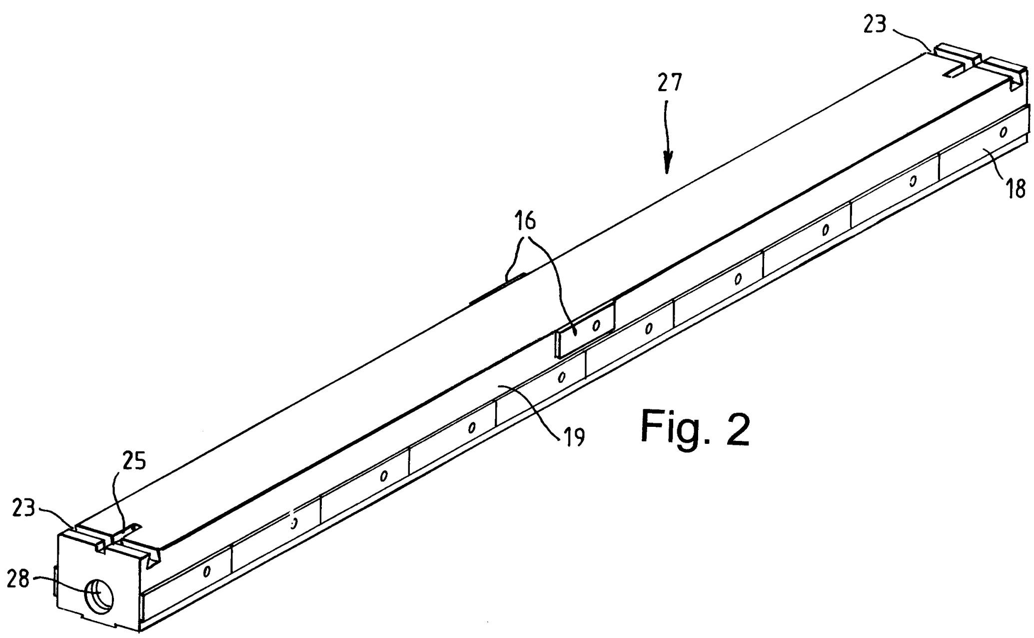

Fig. 2

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Description

Technical Field

[0001] The present invention relates to continuous ink jet printers and more particularly to the drop generator used in continuous ink jet printers.

Background Art

[0002] In continuous ink jet printing, ink is supplied under pressure to a manifold that distributes the ink to a plurality of orifices, typically arranged in linear array (s). The ink is expelled from the orifices in jets which break up due to surface tension in the ink into droplet streams. Ink jet printing is accomplished with these droplet streams by selectively charging and deflecting some droplets from their normal trajectories. The deflected or undeflected droplets are caught and re-circulated and the others are allowed to impinge on a printing surface.

[0003] U.S. Patent No. 4,999,647 describes a drop generator design for use in long array ink jet printers. The drop generator consists of a rectangular block of metal that contains a fluid cavity and to which an orifice plate is bonded. The block is designed to vibrate in the first longitudinal mode of the height direction. As the length is greater than the height, poisson ratio induced couplings can produce non-uniform vibration at the orifice plate face of such a rectangular block. To minimize the non-uniformities produced by the poison ratio induced coupling, vertical slots have been cut the block from front to back, slots perpendicular to the array direction. These slots effectively segment the drop generator reducing the effect of the poisson ratio coupling. The slots are closed at the top and bottom faces of the drop generator to maintain the stiffness of the block to inhibit flexing motion down the length.

[0004] While this design works well, it has some limitations. As the flow rate of ink through the drop generator increases, the bore of the drop generator must be increased to avoid turbulent flow which can affect jet directionality. As the bore of the part is increased, the resonant frequency of the longitudinal mode is reduced. The lowering of the resonant frequency reduces the print speed of the printer. One can increase the resonant frequency of the drop generator by reducing the height dimension of the block. The height of the drop generator can be reduced only so far before there is insufficient height for the inclusion of the slots.

[0005] U.S. Patent No. 4,188,635 describes a different type of resonant block for use in stimulating ink jet arrays. This resonant block has a small slot cut into the face to which the orifice plate is secured. The slot serves as a fluid manifold. The slot must be kept small to maintain the stiffness of the body. A piezoelectric transducer is bonded to the drop generator on the face opposite the orifice plate face. The piezoelectric must be thin compared with the thickness of the block. This design has node lines on the orifice plate face which run parallel to the array of jets. This design is not applicable to long arrays of jets since the flow requirements of a long array necessitate a large fluid cavity to maintain non turbulent flow. The introduction of a large fluid cavity into this design lowers the resonant frequency significantly, so that the design is no longer viable for use in a high speed ink jet printer.

[0006] U.S. Patent No. 4,827,285 describes another type of drop generator. This patent describes a drop generator consisting of an orifice plate which is vibrated by means of two piezoelectric crystals that are bonded directly to the orifice plate. A fluid manifold is bonded directly to the orifice plate. Driving the piezoelectric crystals causes the outer edges of the orifice plate to be displaced, inducing the orifice plate to flex. The plate flexure causes the orifices to vibrate, stimulating the jets. This drop generator concept is only useful where the array length is small, as longer arrays require larger fluid cavities to handle the fluid flow. The mass of the larger fluid cavities has a negative effect on the operating frequency range. This design is also intrinsically fragile with the orifice plate being mounted by means of the brittle piezoelectric elements. Additionally as the piezoelectric elements are electrically driving to produce the vibration in the direction normal to the plane of the orifice plate, they are also made to expand in the direction parallel to the plane of the orifice plate. This expansion of the crystals can couple into other vibrational modes of the drop generator resulting in non-uniform stimulation down the orifice array.

[0007] U.S. Patent No. 4,245,225 describes a drop generator which places a cylindrical piezoelectric concentrically inside an larger cylinder. The space between the cylinders serves as a plenum for the ink. Ink is allowed to flow through holes in the wall of the outer cylinder to the orifices from which the jets of ink are formed. The inner and outer surface of the piezoelectric cylinder are metallized to form electrodes. The piezoelectric cylinder can be electrically driven by means of these electrodes to expand and contract radially. This radial mode vibration then drives a liquid cavity resonance in the space between the inner and outer cylinders. The pressure oscillations produced by this cavity resonance in turn cause the stimulation of the jets of ink. As mentioned in the patent the radial expansion of the piezoelectric also produces a length change in the piezoelectric due to the Poisson's ratio. As the length of the cylinder is increased, standing waves can be produced down the length of the cylinder. These standing wave down the length couple back into the radial vibration so that the radial vibration is no longer uniform down the length of the cylinder or the ink jet array. The means to locate the inner piezoelectric cylinder also can couple the vibration of the inner cylinder to the outer cylinder. The resulting vibrations of the outer cylinder will tend to interfere with the desired uniform stimulation amplitude down the ink jet array. In addition to these problems, the need to place the piezoelectric in contact with the ink produces problems related to shielding the electrodes and the piezoelectric from the ink. As a result of all these problems, this design is not viable for use in high speed ink jet printers. And although U.S. Patent No. 4,245,227 describes a similar drop generator design, with the change that the outer cylinder rather than the inner one is piezoelectric, it suffers from all the same problems as the previous design.

[0008] Clearly a new means is needed for stimulating long ink jet arrays at high operating frequencies.

Summary of the Invention

[0009] It is an object of the present invention to provide a drop generation means with a long jet array and high operating frequency for use in a high speed ink jet printer

[0010] In accordance with one aspect of the present invention a drop generator is provided for use in an ink jet printer, where the drop generator is capable of stimulating long ink jet arrays at high operating frequencies. The drop generator comprises a substantially uniform cross section for a central portion and two end sections with different cross sections. The end sections have features to adjust a resonant frequency of the end sections to match that of the central portion. In particular, these features comprise cuts on a top of the drop generator. The drop generator utilizes multi-lobed radial bending modes for vibration of an array of orifices, and the vibrational modes are driven by at least two rows of transducers which extend substantially the length of the drop generator. The transducers are placed consistent with a lobe structure of an operational radial bending mode.

[0011] Other objects and advantages of the invention will be apparent from the following description and the appended claims.

Brief Description of the Drawing

[0012]

Fig. 1 shows a cross sectional view of a hollow tube, to illustrate displaced and undisplaced shapes of the hollow tube as it undergoes a radial bending mode;

Fig. 2 is a long rectangular block drop generator illustrating a preferred embodiment of the present invention;

Fig. 3 illustrates the fluid cavity geometry on the interior of the drop generator;

Fig. 4 is an end wall view of a fluid channel of the drop generator of Figs. 2 and 3, designed in accordance with the present invention; and

Fig. 5 illustrates one embodiment of a design concept according to the present invention for tuning the resonant frequency of the end sections of a drop generator to match the central sections of the drop generator.

Detailed Description of the Invention

[0013] The present invention discloses a drop generator for use in ink jet printing, which employs multiple lobed squashing resonances to stimulate an array of jets. The geometry of the ends of the drop generator is configured to make the resonant frequencies of the end sections approximately equal to that of the central portion of the drop generator. Piezoelectric drive elements are placed to effectively drive the desired resonant mode while suppressing undesirable resonant modes.

[0014] The basic concept behind the present invention is best understood by considering a cross sectional view of a hollow tube 10, as illustrated in Fig. 1. In addition to the circularly symmetric modes of the tube employed in patent nos. 4,245,225 and 4,245,227, the tube 10 also has various radial bending modes. The lowest order of such modes has two lobes 12 where the tube bulges out, and two areas 14 where it is squeezed in. Higher order modes have increasing numbers of lobes and higher resonant frequencies. For ease of explanation, the invention will be described in terms of the lowest order mode, recognizing that the same principles can be applied to the higher order radial bending modes.

[0015] The lowest order radial bending mode can be effectively driven by symmetrically placing two piezoelectric elements 18 on the walls of the tube 10. In a preferred embodiment, the length of the piezoelectric elements around the circumference should be less than one quarter of the circumference of the tube to prevent the piezoelectrics from extending across the node lines of the radial bending mode. When driven in phase at the appropriate frequency, the symmetrically placed piezoelectrics will effectively drive this two lobe radial bending mode. They will also not be very effective at driving other order radial bending modes.

[0016] This lowest order radial bending mode has associated with it a whole family of resonant modes with different profiles down the length of the tube and different resonant frequencies. The lowest order of this family of modes maintains the same phase for the bending pattern down the length of the tube. The second such mode will have the two ends of the tube bending out of phase. Higher order modes will have increasing numbers of phase shifts down the length. These modes can be thought of as compound bending modes, where the tube wall bends both radially and axially.

[0017] For the particular application in an ink jet printer, it is desirable to utilize the lowest order mode of one families of radial bending modes, preferably the one with constant phase of the radial bending down the length of the tube. That is, it is desirable for ink jet stimulation to use radial bending modes which don't have an axial bending mode component. By employing two symmetrically placed rows of piezoelectric elements extending down the length of the cylinder which are driven in phase, the radial bending mode having consistent phase down the length can be driven while the vibration of the modes with axial bending mode components can be suppressed.

[0018] While it is possible to drive the two lobe radial bending mode with a single piezoelectric, the use of symmetrically placed piezoelectric elements 18 on the sides of the cylinder 10 provides much higher drive efficiency for driving the desired resonant mode. Furthermore, the use of a single piezoelectric is less selective, that is, it is not as effective at suppressing the higher order radial bending modes as the symmetric pair of piezoelectrics. Therefore, a cylinder with a single row of piezoelectric drive elements will suffer from more interference from unwanted radial bending modes than does one with symmetrically placed piezoelectrics.

[0019] Ignoring, for the time, the problem with the ends of the tube 10, such as the need to seal the ends and means to locate the drop generator, etc., which can be at least partially addressed by using the dovetail grooves 23 for mounting, persons skilled in the art can recognize that placing orifices at the lobes of the radial bending mode will result in the desired displacement of the orifices to produce stimulation. Driving the mode which maintains a constant bending phase down the length of the tube will then produce quite uniform stimulation. Long arrays on ink jets can be stimulated at operating frequencies of over 100 kHz using such a design concept.

[0020] The need to terminate the ends of the tube-like drop generator to contain the ink, supply fluid ports, and provide means to locate the drop generator can affect the stimulation uniformity of the drop generator. The present invention overcomes this problem by designing the end of the drop generator with a cut 25 to resonate at a similar frequency to the tube-like center of the drop generator.

[0021] While the description thus far uses a cylindrical model to explain the concepts, it will be understood by those skilled in the art that, in practice, other shapes can be used. Such shapes, for example, might have a square or rectangular cross section, or even have more than four sides. Such cross sectional shapes should have a height to width ratio close to one that is between 0.5 and 2. In general, the cross sectional shape should be consistent with the symmetry of the desired operational radial bending mode shape. For example, 3 sided or 6 sided cross sections might by utilized for drop generator with the 3 lobed radial bending mode as the desired operational mode. Matching the cross sectional shape to the desired lobe shape facilitates the placement of the piezoelectric drive elements so that the desired mode can be driven. To effectively drive the higher order radial bending modes while suppressing the lower order modes, three or more rows of piezoelectrics should be used as dictated by the desired lobe shape.

[0022] In Fig. 2, there is illustrated a preferred embodiment of the present invention, comprising a long rectangular block 27. The drop generator 27 is a rectangular block made of stainless steel with approximate measurements of a length of 10 inches, a width of 0.66 inches, and a height of 0.52 inches. A fluid cavity 28 comprises a through hole 20 machined through the length of the block. A long, narrow slot 22 is machined into the bottom face of the block, connecting to the through bore. The orifice array, located at the bottom of the drop generator, in the area of 24 in Fig. 3, is secured to the block and is centered over the slot 22.

[0023] Continuing with Fig. 2, rows of piezoelectric elements 18 are secured to the front and back faces of the block. When electrically driven, these piezoelectric elements expand and contract in the z direction. This causes the side walls of the drop generator to flex. The driven mode corresponds to the two lobe squash mode described for the cylinder. As the piezoelectric elements are attached down the entire length of the drop generator, and the electrical signal is applied uniformly to all the elements, the flexing force is applied uniformly down the length of the drop generator.

[0024] The drop generator is mounted by means of thin wall stainless steel tubes (not shown) which are bonded into dovetailed grooves 23, as shown in Figs. 2, 3 and 4. Thin wall tubing has been found to supply sufficient rigidity for locating stability of the drop generator, while providing minimal vibrational coupling of the drop generator to the support frame. The dovetail grooves 23 have been found to minimize the risk of the mounting tubes breaking loose, while still facilitating easy removal of the tubing at refurbishment.

[0025] The fluid manifold comprises a through bore 20 which runs the length of the block and a long narrow fluid channel 32 connecting the through bore to the orifice plate face of the drop generator. The narrow fluid channel stops approximately 1/2" from each end. As best illustrated in Fig. 4, the end wall of the fluid channel 22 is tapered to improve the fluid flow at each end of the drop generator. Ink is supplied by fluid fittings (not shown). The fluid fittings are bonded into counter bores 30 as shown in Figs. 3 and 4. An alignment feature 34 for locating the orifice plate over the fluid cavity is also illustrated. Such alignment features were described in U.S. Patent No. 4,999,647, totally incorporated herein by reference.

[0026] In accordance with a preferred embodiment of the present invention, it is desirable to design the ends of the drop generator to have a resonant frequency approximately equal to that of the center of the drop generator. To better understand this concept, consider, for instructive purposes only, the response of a narrow cross sectional slice of the drop generator to the flexing force is considered. Initially, this response can be examined as if this section of the drop generator were independent of the other sections.

[0027] It is well known in the art, that the vibration response of such a section depends on the relationship between the resonant frequency of the cross sectional slice and the frequency of the driving force. As a result, the vibration amplitude of such a slice will reach its peak value when the driving frequency equals the resonant frequency. The phase of the vibration relative to the driving force also shifts as the driving frequency is varied across the resonance. Similarly, the vibrational amplitude and phase of any other cross sectional slice of the drop generator will depend on the relationship between the driving frequency and the resonant frequency for that slice.

[0028] Along the length of the fluid cavity slot, the uniform cross section produces the desired consistent resonant frequency. Near the ends of the drop generator, however, the fluid cavity slot must terminate, to keep ink from spraying out the ends of the drop generator. As a result, the cross section of the drop generator at each end of the body does not match the cross section in the middle of the body. The resonant frequency of the end section of the drop generator therefore, does not match the resonant frequency of the central sections of the body. The filling in of the slot tends to stiffen the cross section, raising the resonant frequency. Consequently, the vibrational amplitude and phase of the vibration at the end sections will not match the central sections.

[0029] It will be well understood by those skilled in the art, that in a typical drop generator, the different cross sectional sections are not truly independent of each other. Differences in vibration amplitude and phase are coupled from section to section. Therefore, the different vibration amplitude and phase of the end sections are coupled into the rest of the drop generator, affecting the vibration all along the drop generator.

[0030] By changing the geometry of the end section of the drop generator, in accordance with the present invention, it is possible to shift its resonant frequency to match that of the center of the drop generator. The result is a drop generator with acceptably uniform vibration amplitude down the length of the array. One preferred embodiment utilizes cuts 25 on the top surface of the drop generator. These cuts, which run parallel to the fluid cavity slot, start about even with the end of the fluid cavity slot and extend to the ends of the drop generator as shown in Fig. 4. The cut 25 gradually increases in depth, reaching full depth approximately where the taper of the fluid cavity slot ends. For the embodiment described herein, therefore, the depth of the cut is 0.052" and the width is 0.062".

[0031] While the slot shown is a preferred embodiment, it will be recognized that other cuts or features can be employed, while still within the spirit and scope of the invention to achieve the concept of the present invention, which is to tune the resonant frequency of the end section of the drop generator to match that of the center section. One such alternative embodiment, for example, is to seal the ends of the fluid cavity slot with low modulus materials, such as a low durometer rubber, that would have minimal effect on the resonant frequency of the ends.

[0032] The design concept of the present invention, of tuning the resonant frequency of the drop generator end sections to match that of the center, is applicable other drop generator designs which do not employ radial bending modes. One such design 50, for example, is shown in Fig. 5. The design of Fig. 5 has a height of 1.9", a width of 1.32", and a thickness of 0.49". The resonant mode shape is primarily that of a rectangle in the longitudinal mode, with end sections 52.

[0033] It is well known that the velocity of sound down long thin rods is lower than that of a bulk solid of the same material. This difference is caused by the Poisson's ratio. In the thin rod, if a section of the rod is compressed down in the axial direction, the radial dimension will expand as a result of the Poisson's ratio. In a rod having a large radial dimension or other large sample, if the piece is compressed in one dimension, the radial expansion is impeded by the radial bulk of the object. As a result of this radial motion being impeded, the material acts stiffer in the axial direction. The higher apparent stiffness for the larger diameter rod or the bulk sample yields a higher effective velocity of sound than for the thin rod.

[0034] Similarly, the apparent velocity of sound is lower near the walls of an object than in central portion of the object. In the central portion of the object, lateral motion due to Poisson's ratio in response to a compression or dilation in one direction is inhibited by the mass of the surrounding areas. Near the surface the lack of mass in part of the surrounding region allows lateral motion due to Poisson's ratio to occur in response to a compression or dilation in a direction parallel to the surface. The difference in the ability to move laterally in these two cases produces the apparent difference in the velocity of sound for the two regions.

[0035] By virtue of the ends of the drop generator having a different apparent velocity of sound than the central portion, the ends of the block tend to have a slightly different resonant frequency than the central portion. By contouring the side walls, which shifts the resonant frequency of the end sections of the drop generator closer to that of the center of the drop generator, the stimulation of the ink jets can be made more uniform.

[0036] As mentioned above, the preferred embodiment of the drop generator utilizes two rows of piezoelectric elements symmetrically placed extending down the length of the drop generator. These are driven to flex the sides of the drop generator to excite the radial bending mode. When driven, however, the piezoelectric elements expand also in the length direction, parallel to the axis of the fluid cavity. If the piezoelectrics are not appropriately sized and placed, they can excite undesirable axial bending modes down the length of the cavity. This problem can be avoided by identifying the wavelength for the axial bending modes which have resonant frequencies near the desired operating frequency. The length of the piezoelectric crystals should then be greater than ½ of the wavelength of such axial bending modes and less than one wavelength. This will ensure that the ends of the crystal, where most of the driving force is concentrated, will not be able to work in concert to excite such axial bending modes.

[0037] Alternatively, shear mode poled piezoelectric materials may be used to drive the drop generator. As the shearing action of such a piezoelectric element does not induce a length change in the piezoelectric, such piezoelectric transduces have less of a tendency to excite axial bending modes.

<u>Industrial Applicability and Advantages</u>

[0038] The present invention is useful in the field of ink jet printing, and has the advantage of providing an improved drop generator design, particularly for a long array ink jet printer. An additional advantage of the present invention is to provide stimulation of long ink jet arrays at high operating frequencies.

[0039] The invention has been described in detail with particular reference to certain preferred embodiments thereof, but it will be understood that modifications and variations can be effected within the spirit and scope of the invention.

Claims

1. A drop generator for use in an ink jet printer , the drop generator having first and second end sections with a length and associated center section between the end sections and a fluid cavity to which an orifice plate with an orifice plate face is bonded, the orifice plate having an array of jets, the drop generator comprising:

> substantially multi-lobed radial bending modes having an associated lobe symmetry, with at least one operational radial bending mode for vibration of an array of orifices to stimulate the jets;
> at least two rows of transducers for driving vibrational modes of the drop generator, the at least two rows of transducers extending substantially along a length of the drop generator.

2. A drop generator as claimed in claim 1 wherein the at least two rows of transducers are placed consistent with the lobe symmetry of the operational radial bending mode.

3. A drop generator as claimed in claim 1 wherein the at least two rows of transducers comprise piezoelectric transducers.

4. A drop generator as claimed in claim 3 wherein the piezoelectric transducers are driven in a thickness mode of the piezoelectric transducers.

5. A drop generator as claimed in claim 3 wherein the piezoelectric transducers are driven in a shear mode of the piezoelectric transducers.

6. A drop generator as claimed in claim 1 wherein each individual transducer of the at least two rows of transducers has a length greater than % a wavelength of axial bending modes with frequencies near an operating frequency.

7. A drop generator for use in an ink jet printer, comprising:

> a substantially uniform cross section for a central portion; and
> two end sections with different cross sections, the end sections having features to adjust a resonant frequency of the end sections to match that of the central portion.

8. A drop generator as claimed in claim 7 wherein the features comprise cuts on a top of the drop generator.

9. A drop generator as claimed in claim 7 wherein the features comprise contouring the end sections of the drop generator.

10. A drop generator as claimed in claim 7 wherein the vibrational modes are driven by at least two rows of transducers which extend substantially along a length of the drop generator.

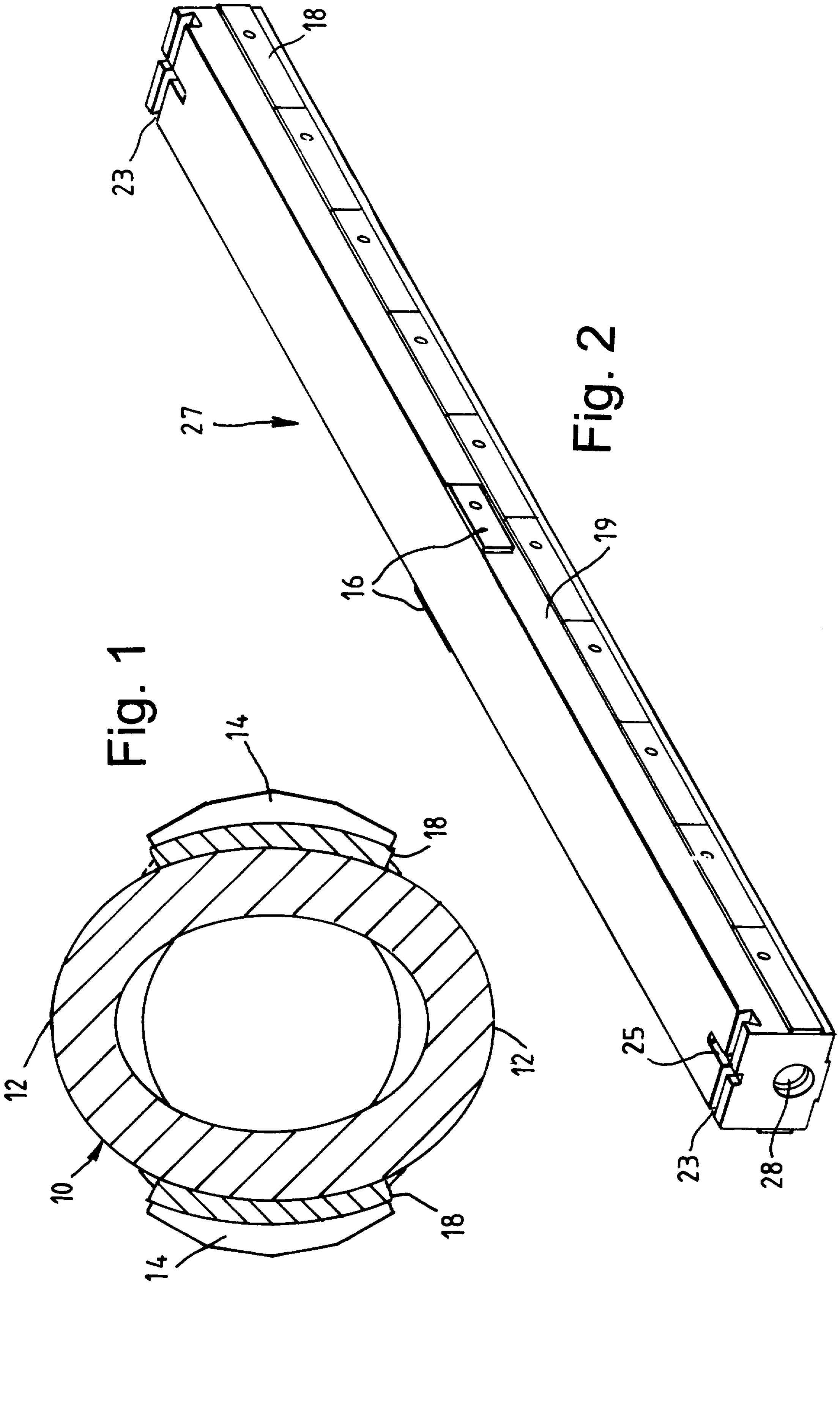

Fig. 2

Fig. 1

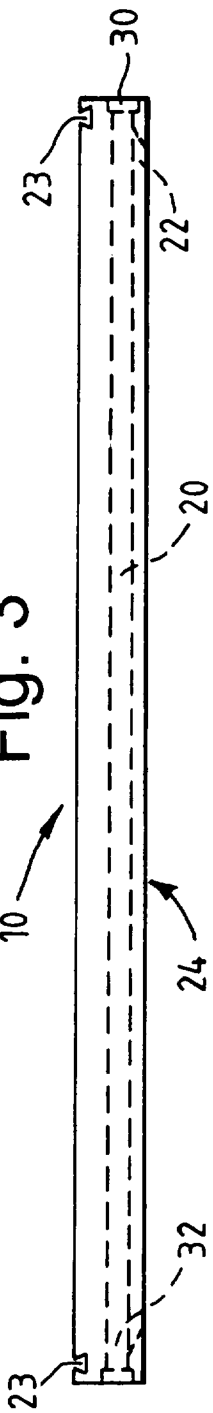

Fig. 3

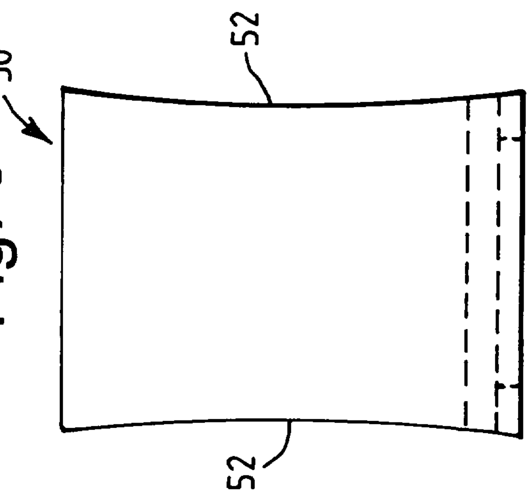

Fig. 5

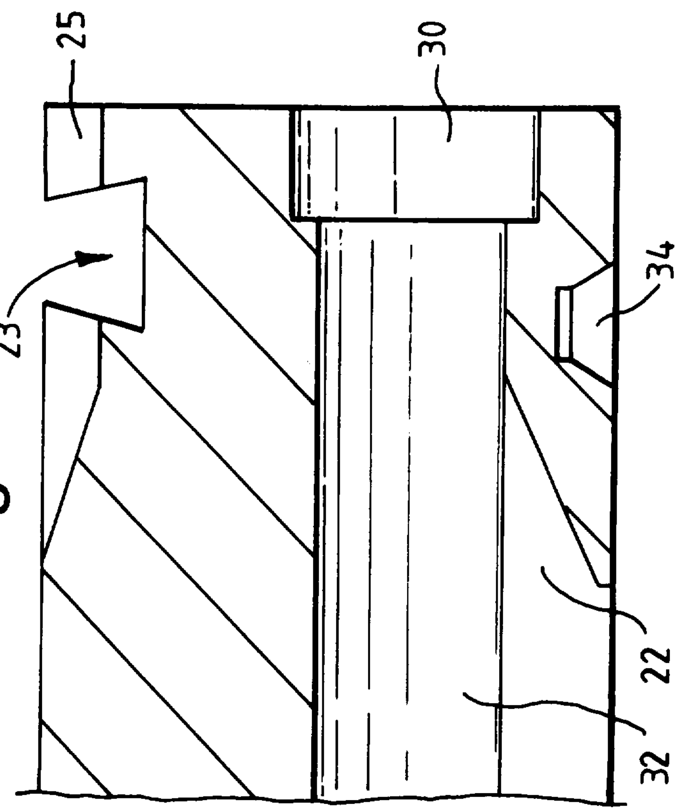

Fig. 4