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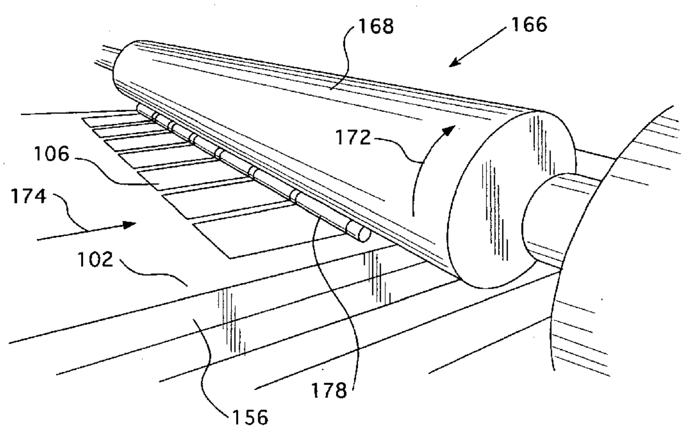
(54) Title: MACHINE AND METHODS FOR MAKING ROLLED DIELECTRIC ELASTOMER TRANSDUCERS



(57) Abstract: A method for making a rolled dielectric elastomer transducer includes rolling a dielectric film laminate into a solid dielectric elastomer transducer roll. An apparatus includes a drive mechanism for receiving a carrier plate with a dielectric film laminate located on a top surface thereof. The drive mechanism is configured to drive the carrier plate in a first direction. A scrub roller is configured to counter-rotate in a second direction relative to the first direction and frictionally engage the dielectric film to roll the dielectric film laminate into a solid dielectric elastomer transducer roll. The apparatus may also include a fixed jaw and a movable jaw movable relative to the fixed jaw to define a longitudinal aperture for receiving a solid dielectric elastomer transducer roll therein. A cutter is configured to segment the solid dielectric elastomer transducer roll into at least two or more individual solid dielectric elastomer transducer rolls.

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MACHINE AND METHODS FOR MAKING ROLLED DIELECTRIC ELASTOMER TRANSDUCERS

RELATED APPLICATIONS

This application claims the benefit, under 35 USC § 119(e), of U.S. Provisional Application Nos.: 61/683,860 filed August 16, 2012 entitled "ROLL ACTUATORS IN AXIAL TENSION, MODEL AND DATA"; 61/717,810 filed October 24, 2012 entitled "DIELECTRIC ELASTOMER TRANSDUCER WITH QUICK-CONNECT TERMINALS"; 61/719,999 filed October 30, 2012 entitled "MACHNINE AND METHODS FOR MAKING ROLLED DIELECTRIC ELASTOMER TRANSDUCERS"; 61/734,609 filed December 7, 2012 entitled "RESONANT FREQUENCIES"; 61/734,616 filed December 7, 2012 entitled "ROLL ACTUATORS"; and 61/734,622 filed December 7, 2012 entitled "SKIN CONTACT WITH DIELECTRIC ELASTOMER ACTUATORS – SYSTEMS FOR SAFETY"; the entirety of each of which is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention is directed in general to electroactive polymers and more specifically to a rolled dielectric elastomer transducer and manufacturing processes and apparatus for making rolled dielectric elastomer transducers.

BACKGROUND OF THE INVENTION

A tremendous variety of devices used today rely on actuators of one sort or another to convert electrical energy to mechanical energy. Conversely, many power generation applications operate by converting mechanical action into electrical energy. Employed to harvest mechanical energy in this fashion, the same type of device may be referred to as a generator. Likewise, when the structure is employed to convert physical stimulus such as vibration or pressure into an electrical signal for measurement purposes, it may be characterized as a sensor. Yet, the term "transducer" may be used to generically refer to any of the devices.

A number of design considerations favor the selection and use of advanced dielectric elastomer materials, also referred to as "electroactive polymers", for the fabrication of transducers. These considerations include potential force, power density, power conversion/consumption, size, weight, cost, response time, duty cycle, service requirements, environmental impact, etc. As such, in many applications, electroactive polymer technology offers an ideal replacement for piezoelectric, shape-memory alloy and electromagnetic devices such as motors and solenoids.

An electroactive polymer transducer comprises two electrodes having deformable characteristics and separated by a thin elastomeric dielectric material. When a voltage difference is applied to the electrodes, the oppositely charged electrodes attract each other thereby compressing the polymer dielectric layer therebetween. As the electrodes are pulled closer together, the dielectric polymer film becomes thinner (the Z-axis component contracts) as it expands in the planar directions (along the X- and Y-axes), i.e., the displacement of the film is in-plane. The electroactive polymer film may also be configured to produce movement in a direction orthogonal to the film structure (along the Z-axis), i.e., the displacement of the film is out-of-plane. For example, U.S. Pat. No. 7,567,681 discloses electroactive polymer film constructs which provide such out-of-plane displacement – also referred to as surface deformation or as thickness mode deflection.

The material and physical properties of the electroactive polymer film may be varied and controlled to customize the deformation undergone by the transducer. More specifically, factors such as the relative elasticity between the polymer film and the electrode material, the relative thickness between the polymer film and electrode material and/or the varying thickness of the polymer film and/or electrode material, the physical pattern of the polymer film and/or electrode material (to provide localized active and inactive areas), the tension or pre-strain placed on the electroactive polymer film as a whole, and the amount of voltage applied to or capacitance induced upon the film may be controlled and varied to customize the features of the film when in an active mode.

Numerous applications exist that benefit from the advantages provided by such electroactive polymer films whether using the film alone or using it in an electroactive polymer actuator. One of the many applications involves the use of electroactive polymer transducers as actuators to produce haptic, tactile, vibrational feedback (the communication of information to a user through forces applied to the user's body), and the like, in user interface devices. There are many known user interface devices which employ such feedback, typically in response to a force initiated by the user. Examples of user interface devices that may employ such feedback include keyboards, keypads, game controller, remote control, touch screens, computer mice, trackballs, stylus sticks, joysticks, etc. The user interface surface can comprise any surface that a user manipulates, engages, and/or observes regarding feedback or information from the device. Examples of such interface surfaces include, but are not limited to, a key (e.g., keys on a keyboard), a game pad or buttons, a display screen, etc.

The feedback provided by these types of interface devices is in the form of physical sensations, such as vibrations, pulses, spring forces, etc., which a user senses either directly (e.g., via touching of the screen), indirectly (e.g., via a vibrational effect such a when a cell phone vibrates in a purse or bag) or otherwise sensed (e.g., via an action of a moving body that creates a pressure disturbance sensed by the user). The proliferation of consumer electronic media devices such as smart phones, personal media players, portable computing devices, portable gaming systems, electronic readers, etc., can create a situation where a sub-segment of customers would benefit or desire an improved haptic effect in the electronic media device. However, increasing feedback capabilities in every model of an electronic media device may not be justified due to increased cost or increased profile of the device. Moreover, customers of certain electronic media devices may desire to temporarily improve the haptic capabilities of the electronic media device for certain activities.

Use of electroactive polymer materials in consumer electronic media devices as well as the numerous other commercial and consumer applications highlights the need to increase production volume while maintaining precision and consistency of the films.

Conventional rolled dielectric elastomer transducer based cylindrical actuators are desirable because a cylindrical shape is functional and familiar. It matches many mechanical components, such as, for example, solenoids, air cylinders, shock absorbers, etc. so mounting hardware is readily available, for example, the clevis, the ball joint, and the threaded rod. Engineers' familiarity with cylindrical actuators simplifies efforts to integrate them into new designs. Nevertheless, hollow, rolled dielectric elastomer tubes and tubes with an internal spring, called "spring rolls" have some drawbacks. Empty space inside the tube is wasted, making the transducer larger than strictly necessary. Also, accumulated tension from winding the outer layers of the tube tends to buckle and collapse the tube. In a tubular roll made with a highly prestrained acrylic dielectric, this has been found to impose a practical limit of only a few turns per transducer.

The present disclosure provides various improvements over conventional hollow rolled dielectric elastomer transducers and manufacturing processes for making transducers. The present invention overcomes these drawbacks by winding dielectric elastomer films into a solid roll. Among the advantages of a solid roll are that it does not waste space, and it does not collapse as turns are added. A rolling machine also is disclosed, along with a manufacturing process, materials, and fixtures for manufacturing dielectric elastomer actuator rolls with the machine, as described herein in the detailed description of the invention section of the present disclosure.

SUMMARY OF THE INVENTION

In one embodiment, a method comprises providing a dielectric film laminate and rolling the dielectric film laminate into a solid dielectric elastomer transducer roll.

In another embodiment, an apparatus comprises a drive mechanism for receiving a carrier plate with a dielectric film laminate located on a top surface thereof. The drive mechanism is configured to drive the carrier plate in a first direction. A scrub roller is configured to counter-rotate in a second direction relative to the first direction and frictionally engage the dielectric film to roll the dielectric film laminate into a solid dielectric elastomer transducer roll.

In yet another embodiment, the apparatus further comprises a fixed jaw and a movable jaw movable relative to the fixed jaw to define a longitudinal aperture for receiving a solid dielectric elastomer transducer roll therein. A cutter is configured to segment the solid dielectric elastomer transducer roll into at least two or more individual solid dielectric elastomer transducer rolls.

These and other features and advantages of the invention will become apparent to those persons skilled in the art upon reading the details of the invention as more fully described below. In addition, variations of the processes and devices described herein include combinations of the embodiments or of aspects of the embodiments where possible are within the scope of this disclosure even if those combinations are not explicitly shown or discussed.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is best understood from the following detailed description when read in conjunction with the accompanying drawings. To facilitate understanding, the same reference numerals have been used (where practical) to designate similar elements are common to the drawings. Included in the drawings are the following:

Fig. 1 illustrates a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 2 illustrates tension σ_p that accumulates when removing film from a liner while winding a hollow rolled dielectric elastomer transducer;

Fig. 3 illustrates radial stress ΔP developed in the hollow dielectric elastomer transducer rolls shown in Fig. 2 caused by the tension σ_p;

Fig. 4 is a graphical illustration depicting the accumulation of radial stress ΔP in the hollow dielectric elastomer transducer rolls shown in Fig. 2 as additional wraps are added to the hollow rolled dielectric elastomer transducer;

Fig. 5 illustrates inner windings of a hollow dielectric elastomer transducer rolls that have collapsed under the accumulated radial stress P imposed by tension σ_p in the outer windings;

Fig. 6 illustrates a cylindrical solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Figs. 7A-7K illustrate a manufacturing process for turning an electroded dielectric film laminate into a solid dielectric elastomer transducer roll, as shown in Figs. 7I and 7K in accordance with one embodiment of the present invention, where:

Fig. 7A illustrates lamination of dielectric films in accordance with one embodiment of the present invention;

Fig. 7B illustrates cutting a frame away from the dielectric film laminate in accordance with one embodiment of the present invention;

Fig. 7C illustrates removal of the frame from the dielectric film laminate in accordance with one embodiment of the present invention;

Fig. 7D illustrates mounting a carrier plate with the dielectric film laminate on a rolling machine in accordance with one embodiment of the present invention;

Fig. 7E illustrates the process of rolling the dielectric film laminate by moving the carrier plate under a counter rotating scrub roller into a solid roll of dielectric elastomer film in accordance with one embodiment of the present invention;

Fig. 7F illustrates the process of rolling the dielectric film laminate shown in Fig. 7E towards the end of the process in accordance with one embodiment of the present invention;

Fig. 7G illustrates the carrier plate retracting after the rolling process is complete in accordance with one embodiment of the present invention;

Fig. 7H illustrates transfer of a solid dielectric elastomer transducer roll to a cutting fixture for segmenting the roll into individual solid dielectric elastomer transducer rolls shown in Fig. 7G in accordance with one embodiment of the present invention;

Fig. 7I illustrates the solid dielectric elastomer transducer roll segmented into individual solid dielectric elastomer transducer rolls in accordance with one embodiment of the present invention;

Fig. 7J illustrates application of conductive adhesive into a terminal cup for electrically attaching to ends of the solid dielectric elastomer transducer rolls shown in Figs. 7H and 7I in accordance with one embodiment of the present invention;

Fig. 7K illustrates attaching and curing the terminal cups onto the ends of the solid dielectric elastomer transducer roll shown in Fig. 1 in accordance with one embodiment of the present invention;

Fig. 8 is a detail view of the rolling machine used in steps illustrated in Figs. 7D-F in accordance with one embodiment of the present invention;

Fig. 9 is a detail view of the cutting fixture for segmenting the solid dielectric elastomer transducer roll into individual solid dielectric elastomer transducer rolls shown in Figs. 7H and 7J in accordance with one embodiment of the present invention;

Fig. 10 is an end view of an individual segmented solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention after segmentation and prior to exposing the end to a solvent;

Fig. 11 is an end view of an individual segmented solid dielectric elastomer transducer roll after the application of a solvent to cause local swelling and separation of the layers in accordance with one embodiment of the present invention;

Fig. 12 illustrates a motion control system for controlling the rolling process of rolling up a solid dielectric elastomer transducer roll with a carrier plate under a scrub roller as illustrated in Figs. 7D-F and Fig. 8 in accordance with one embodiment of the present invention;

Fig. 13 illustrates a simplified motion control system for the rolling process illustrated in Figs. 7D-F and Fig. 8 where slip can occur between the scrub roller and a growing solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 14 illustrates a textile covering positioned over an outside surface of the scrub roller illustrated in Fig. 13 in accordance with one embodiment of the present invention;

Fig. 15 is a detailed view of the textile covering illustrated in Fig. 14 in accordance with one embodiment of the present invention;

Fig. 16 illustrates circumferential lengthening of outer layers of solid dielectric elastomer transducer roll caused by rolling a pre-strained dielectric elastomer film with excessive pre-strain during the rolling process;

Fig. 17 illustrates a wrinkle mechanism in the loosely packed space between individual solid dielectric elastomer transducer rolls in accordance with one embodiment of the present invention;

Fig. 18 illustrates an electrode pattern with overlap regions to provide support in bands between solid dielectric elastomer transducer rolls to prevent wrinkles that would otherwise start in the overlapping regions;

Fig. 19 illustrates a non-limiting example fixture for positioning electrical terminal caps on ends of a solid dielectric elastomer transducer roll during curing;

Fig. 20 illustrates a derivation model of a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 21 is a graphical illustration depicting force provided by each additional ring in a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 22 is a graphical illustration depicting capacitance change versus axial displacement of a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 23 is a graphical illustration depicting blocked force versus applied voltage response of a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 24 is a graphical illustration depicting blocked force versus axial displacement showing the difference between the solid dielectric elastomer transducer roll in compression versus tension in accordance with one embodiment of the present invention;

Fig. 25 is a graphical illustration of blocked force versus longitudinal displacement showing the difference between the solid dielectric elastomer transducer roll in compression versus tension in accordance with one embodiment of the present invention;

Fig. 26 is a graphical representation of stiffness of solid dielectric elastomer transducer rolls in accordance with one embodiment of the present invention;

Fig. 27 illustrates a solid dielectric elastomer transducer roll in flat roll mode where the roll is placed under compression in a radial direction rather than in an axial direction in accordance with one embodiment of the present invention;

Fig. 28 illustrates a geometric model of a solid dielectric elastomer transducer roll in flat roll mode where the roll is placed under compression in a radial direction in accordance with one embodiment of the present invention;

Fig. 29 is a graphical illustration depicting stretch ratio versus percent compression in a radial direction of a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 30 illustrates a static equilibrium diagram of a solid dielectric elastomer transducer roll in flat roll mode under static load in accordance with one embodiment of the present invention;

Fig. 31 is a graphical illustration depicting capacitance versus compression in a radial direction of a solid dielectric elastomer transducer roll in flat roll mode in accordance with one embodiment of the present invention;

Figs. 32A, 32B, 32C and 32D illustrate a solid dielectric elastomer transducer roll under increasing compression force in a radial direction in accordance with one embodiment of the present invention;

Fig. 33 illustrates a finite element analysis model of a solid dielectric elastomer transducer roll undergoing radial compression in accordance with one embodiment of the present invention; and

Fig. 34 illustrates the delamination of a solid dielectric elastomer transducer roll undergoing radial compression in accordance with one embodiment of the present invention.

Variation of the invention from that shown in the figures is contemplated.

DETAILED DESCRIPTION OF THE INVENTION

Examples of electroactive polymer devices and their applications are described, for example, in U.S. Pat. Nos. 6,343,129; 6,376,971; 6,543,110;

6,545,384; 6,583,533; 6,586,859; 6,628,040; 6,664,718; 6,707,236; 6,768,246; 6,781,284; 6,806,621; 6,809,462; 6,812,624; 6,876,135; 6,882,086; 6,891,317; 6,911,764; 6,940,221; 7,034,432; 7,049,732; 7,052,594; 7,062,055; 7,064,472; 7,166,953; 7,199,501; 7,199,501; 7,211,937; 7,224,106; 7,233,097; 7,259,503; 7,320,457; 7,362,032; 7,368,862; 7,378,783; 7,394,282; 7,436,099; 7,492,076; 7,521,840; 7,521,847; 7,567,681; 7,595,580; 7,608,989; 7,626,319; 7,750,532; 7,761,981; 7,911,761; 7,915,789; 7,952,261; 8,183,739; 8,222,799; 8,248,750; and in U.S. Patent Application Publication Nos.; 2007/0200457; 2007/0230222; 2011/0128239; and 2012/0126959, the entireties of which are incorporated herein by reference.

In various embodiments, the present invention provides various improvements over conventional hollow rolled dielectric elastomer transducers and manufacturing processes for making those transducers. Embodiments of the present invention overcome these drawbacks by winding dielectric elastomer films into a solid roll that does not waste space or collapse as turns are added. A rolling machine also is disclosed, along with a manufacturing process, materials, and fixtures for manufacturing dielectric elastomer actuator rolls with the machine, as described herein in the detailed description of the invention section of the present disclosure.

The various embodiments discussed hereinbelow in connection with Figs. 1-19 provide a dielectric elastomer transducer rolls formed by rolling laminated films into a compact spiral, which will be referred to herein as "solid." Multiple individual solid dielectric elastomer transducer rolls may be produced by segmented cutting of the transducer rolls, where the cutting affords electrical connections to the ends of the rolls. A conductive adhesive formulated with solvent may be used to swell the ends of the roll to improve mechanical and electrical connection of the rolls to the terminals. Also provided is a rolling machine for dielectric elastomer actuators comprised of a scrub roller that counter-rotates with respect to an advancing plate. Another rolling machine is provided in which motion control is simplified by spinning the scrub roller faster than the carrier plate advances. A non-stick textile cover for the scrub roller is provided to minimize adhesion by minimizing contact area through the use of knit threads that can locally deflect to minimize contact stress. An electrode pattern is also provided for transducer rolls in which electrodes overlap to support areas of the roll that could otherwise buckle and initiate wrinkles. Also provided are novel fixtures for cutting the roll and adhering terminals, to be used in conjunction with the rolling machine.

The solid transducer rolls overcome buckling problems that normally would limit the number of turns that can be added to a hollow type transducer roll. Solid transducer rolls also save space that is wasted by the hollow type rolls known in the art. A rolling machine forms solid rolls with geometric tolerances finer than hand-rolling, at greater speed and lower cost. A compliant, textile, non-stick cover for the scrub roller in the machine simplifies motion control and reduces machine cost. An overlapping electrode pattern prevents wrinkles.

Fig. 1 illustrates a solid dielectric elastomer transducer roll **100** in accordance with one embodiment of the present invention. The solid dielectric elastomer transducer roll **100** comprised of two layers of dielectric film **102, 104**, one of which has been patterned with one or more layers of electrodes **106, 108** on both sides. The layers of dielectric film **102, 104** are wound together into a tight solid spiral cylinder. The area **110** in which the electrodes **106, 108** overlap acts as a dielectric elastomer transducer. Electrical connection to the two plates of the capacitor can be made where the electrodes **106, 108** meet the ends of the cylinder. The electrodes **106, 108** are offset relative to each other to provide electrical connection at the ends **112, 114** of the solid dielectric elastomer transducer roll **100** such that the first electrode **106** is accessible at the top **112** and the second electrode **108** is accessible at the bottom **114** of the transducer **100**. Although in the illustrated embodiment, the solid dielectric elastomer transducer roll **100** has a right circular cylindrical form, other forms are contemplated such as triangular, square, rectangular, among other polyhedral forms.

Fig. 2 illustrates tension σ_p that accumulates when removing film **120** from a liner **122** while winding a hollow **124** rolled dielectric elastomer transducer

126. Some peeling stress σ_p is unavoidable when removing the film **120** having a thickness "t" from the liner **122**.

Fig. 3 illustrates radial stress ΔP developed in the hollow rolled dielectric elastomer transducer **126** shown in Fig. 2 caused by the tension σ_p created when the film **120** is peeled from the liner **122** (not shown). Radial stress ΔP (pressure) in the compressed layers below must support the tension of each new wrap.

Fig. 4 is a graphical illustration depicting the accumulation of radial stress ΔP in the hollow rolled dielectric elastomer transducer **126** shown in Fig. 2 as additional wraps are added to the hollow rolled dielectric elastomer transducer **126**. As more wraps are added the radial stress ΔP (pressure) in the center increases. If the force becomes large enough, the inner layers may delaminate and buckle, like an arch collapsing. As indicated by the radial stress ΔP [Pa] versus radial distance [m] curve **130** in graph **128**, the radial stress ΔP on the innermost layer **132** is much higher than the radial stress ΔP on the outermost layer **134**.

In the context of Figs. 2-4, the peel stress σ_p and strain in a single layer of dielectric film **120** are given below for values typical of a dielectric elastomer coating:

$$\sigma_p = \frac{\sigma_{PEEL}}{t} = \frac{[3.8\ \text{N/m}]}{[80\text{E}-6\ \text{m}]} = 0.048\ \text{MPa} \qquad \text{Eq. 1}$$

$$s = \frac{\sigma_p}{Y} = \frac{[0.048\ \text{MPa}]}{[0.6\ \text{MPa}]} = 0.08 = 8\%\ \text{strain} \qquad \text{Eq. 2}$$

The force balance for a half-wrap of film, as shown in Fig. 3, can be solved for the radial stress ΔP.

$$\sum F_z = -2\sigma_p t\ell + 2r\ell\Delta P = 0 \qquad \text{Eq. 3}$$

$$\Delta P = \frac{\sigma_p t}{r} = \frac{\sigma_{PEEL}}{r} \qquad \text{Eq. 4}$$

The radial stress ΔP in layer "*i*" is due to the accumulated stress of the layers above it as given in the equation below. For typical values of peel stress

σ_p on a hollow rolled dielectric elastomer transducer **126** with 1 mm internal radius, the calculated pressures have been plotted in Fig. 4.

$$P_i = \Delta P_i + \sum_{0}^{i-1} \Delta P \qquad \text{Eq. 5}$$

Fig. 5 illustrates inner windings **132** of the hollow rolled dielectric elastomer transducer **126** that have collapsed under the accumulated radial stress P imposed by tension σ_p in the outer windings **134**. This "collapsing of the inner layers" problem with the conventional hollow rolled dielectric elastomer transducer **126** provides the motivation for the present inventors' development of the solid dielectric elastomer transducer roll **100** shown in Fig. 6.

Fig. 6 illustrates a cylindrical solid dielectric elastomer transducer roll **100** in accordance with one embodiment of the present invention. The cylindrical solid dielectric elastomer transducer roll **100** does not exhibit a collapse of the inner layers **136** under the accumulated radial stress P imposed by tension σ_p in the outer windings **138**.

Figs. 7A-7K illustrate a manufacturing process for turning an electroded dielectric film laminate **101** into a solid dielectric elastomer transducer roll **178**, as shown in Figs. 7I and 7K in accordance with one embodiment of the present invention. The process rolls the dielectric film laminate **101** into a tight spiral without an opening extending axially in the center of the solid dielectric elastomer transducer roll **178**.

Fig. 7A illustrates a step of the process where two dielectric films **102, 104** are laminated **150** in accordance with one embodiment of the present invention. The first dielectric film **102** comprises a first electrode layer **106** on a top portion and a second electrode layer **108** on a bottom portion. The first dielectric film **102** with the electrodes **106, 108** patterned on both sides thereof are held in tension (pre-stressed) in a rigid frame **152**. The first film **102** with the frame **152** is then laminated to the second dielectric film **104** while it is still attached to the liner **154** used to coat it. The electroded dielectric film laminate **101** (not shown in Fig. 7A) comprising the laminated films **102, 104** is positioned on a carrier plate **156**, which will be used to hold the dielectric film laminate **101** during the rolling process.

Fig. 7B illustrates another step of the process where the frame **152** is cut **158** away from the dielectric film laminate **101** (not shown in Fig. 7B) in accordance with one embodiment of the present invention. The cut path **160** is inside the inner perimeter of the frame **152**.

Fig. 7C illustrates another step of the process where the frame **152** is removed **162** from the dielectric film laminate **101** in accordance with one embodiment of the present invention.

Fig. 7D illustrates another step of the process where the carrier plate **156** with the dielectric film laminate **101** is mounted **164** on a rolling machine **166** in accordance with one embodiment of the present invention. The rolling machine **166** comprises a scrub roller **168**, which rolls up the dielectric film laminate **101**.

Fig. 7E illustrates another step in the process where the dielectric film laminate **101** on the carrier plate **156** is rolled into a solid roll of dielectric elastomer film under a counter rotating **172** scrub roller **168** as the carrier plate **156** is moved **170** in direction **174** by a conveyor or other suitable drive mechanism in accordance with one embodiment of the present invention. As the dielectric film laminate **101** is rolled, it is released from the liner **154**. The process continues until the entire dielectric film laminate **101** is rolled. Fig. 7F illustrates the process of rolling the dielectric film laminate **101** shown in Fig. 7E towards the end of the process in accordance with one embodiment of the present invention.

Fig. 7G illustrates another step of the process where the carrier plate **156** is retracted **176** in direction **177** after the rolling process is complete in accordance with one embodiment of the present invention. As shown, a solid dielectric elastomer transducer roll **178** is provided at the end of this step.

Fig. 7H illustrates another step in the process where the solid dielectric elastomer transducer roll **178** is transferred **180** to a cutting fixture **182** for segmenting the roll **178** with a cutter **184**, such as a blade or slitter, into individual solid dielectric elastomer transducer rolls shown in Fig. 7G in accordance with one embodiment of the present invention.

Fig. 7I illustrates another step in the process where the solid dielectric elastomer transducer roll **178** is segmented **186** into individual solid dielectric elastomer transducer rolls **178a**, **178b**, and **178c** in accordance with one embodiment of the present invention.

Fig. 7J illustrates another step in the process where a conductive adhesive **192** is applied **190** into an electrical terminal **194** having a cup shape for electrically attaching to ends of the solid dielectric elastomer transducer rolls **178a**, **178b**, and **178c** shown in FIG. 7H and 7I in accordance with one embodiment of the present invention.

Fig. 7K illustrates another step in the process where terminals **$194a_1$**, **$194a_2$** are attached and cured **196** onto the ends of the solid dielectric elastomer transducer roll **178a**, terminals **$194b_1$**, **$194b_2$** are attached and cured **196** onto the ends of the solid dielectric elastomer transducer roll **178b**, and terminals **$194c_1$**, **$194c_2$** are attached and cured **196** onto the ends of the solid dielectric elastomer transducer roll **178c** in accordance with one embodiment of the present invention.

Fig. 8 is a detail view of the rolling machine **166** used in the steps illustrated in Figs. 7D-G in accordance with one embodiment of the present invention.

Fig. 9 is a detail view of the cutting fixture **182** for segmenting the solid dielectric elastomer transducer roll **178** into individual solid dielectric elastomer transducers rolls **178a**, **178b**, and **178c** shown in Figs. 7H and 7J in accordance with one embodiment of the present invention. The cutting fixture **182** comprises a movable jaw **196** and a fixed jaw **198**. The movable jaw comprises alignment slots **202** and the fixed jaw comprises alignment slots **204**, which are aligned with the alignment slots **202** of the movable jaw **202**. The cutting fixture comprises an aperture for receiving the solid dielectric elastomer transducer roll **178** therein. The movable jaw **196** moves relative to the fixed jaw **198** to define a longitudinal aperture **200** for receiving and holding the solid dielectric elastomer transducer roll **178** in place during the segmenting process. The cutter **184** is advanced through the alignment slots **202** in the movable jaw **196**, through the solid dielectric elastomer transducer roll **178**, and the alignment slots **204** in the fixed jaw **198**. The clamping action of the jaws **196, 198** also straightens the solid dielectric elastomer transducer roll **178** within the aperture **200** in preparation for segmentation.

Fig. 10 is an end view of an individual segmented solid dielectric elastomer transducer roll **100** in accordance with one embodiment of the present invention after segmentation and prior to exposing the end to a solvent.

Fig. 11 is an end view of an individual segmented solid dielectric elastomer transducer roll **100'** after the application of a solvent to the end to cause local swelling and separation of the layers **206, 208**, and **210** in accordance with one embodiment of the present invention. This improves penetration of the conductive adhesive **192**, shown in Fig. 7J. During the curing process **196** shown in Fig. 7K, the solvent evaporates, leaving inter-digitated glue that makes a robust electrical and mechanical connection between the capping end-terminal **194** shown in Figs. 7J and 7K and the electrodes **106, 108** of the solid dielectric elastomer transducer roll **100**. In one embodiment, the electrically conductive adhesive **192** may be formulated with a solvent that swells the ends of the roll **100** to improve mechanical and electrical connection of the rolls **100** to the terminals **194**.

Fig. 12 illustrates a motion control system **212** for controlling the process of rolling the dielectric film laminate **101** into a solid dielectric elastomer transducer roll **178** with the rolling machine **166**. The scrub roller **168** portion of the rolling machine **166** has a radius r_{scrub}. The motion control system **212** may be any electronic processor or digital logic based programmable motion controller configured to control the velocity and direction of rotation of the scrub roller **168** and the velocity and direction of translation of the carrier plate **156** in accordance with the present invention. As previously discussed in connection with Figs. 7D-G, the carrier plate **156** is advanced in direction **174** at velocity V_{plate} while the scrub roller **168** is rotated in a counter direction **172** at velocity V_{scrub}. As the outer surface of the scrub roller **168** contacts the dielectric film laminate **101**, the dielectric film laminate **101** begins to roll up to form the solid dielectric elastomer transducer roll **178**. The solid dielectric elastomer transducer roll **178** grows in diameter until the carrier plate **156** reaches the end of stroke. As matching the speeds of the carrier plate **156** and the scrub roller **168** can improve the rolling process and excess speed on the carrier plate **156** can jam the solid dielectric elastomer transducer roll **178** under the scrub roller **168**. On the other hand, if the solid dielectric elastomer transducer roll **178** is sticky and adheres to the scrub roller **168**, excess velocity on the scrub roller **168** can lift the solid dielectric elastomer transducer roll **178** off the liner **154** and wrap it around the scrub roller **168**. Each of these situations can result in damaging the solid dielectric elastomer transducer roll **178**. Accordingly, the motion control system **212** may be programmed in accordance with the following considerations to provide various levels of control ranging from the simple to the complex.

By way of example, the motion control system **212** may be configured in various forms from a relatively simple control system to a more complex control system. In one embodiment, the control system **212** may be configured to match the velocity of the carrier plate **156** V_{plate} in direction **174** and the velocity of the scrub roller **168** V_{scrub} in direction **172** such that $|V_{plate}| = |V_{scrub}|$. In another embodiment, the motion control system **212** may be configured to account for the velocity of the transducer roll V_{roll} in direction **214** as a new variable to compensate for the movement of the center of the solid dielectric elastomer transducer roll **178** as the diameter grows such that $|V_{plate}| - |V_{roll,\,x}| = |V_{scrub}|$. In yet another embodiment, the motion control system **212** may be configured to account for a stretch coefficient "k" to compensate for stretching of the dielectric film laminate **101** as it is peeled from the liner **154** such that $|V_{plate}| - |V_{roll,\,x}| = k|V_{scrub}|$. Finally, in another embodiment, the motion control system **212** may be configured to employ at least one sensor to sense force and provide a closed loop feedback mechanism to the motion control system **212**.

The complexity of the various configurations of the motion control system **212** outlined above can be avoided if the solid dielectric elastomer transducer roll **178** does not stick to the scrub roller **168**. In that case, the scrub roller **168** can be rotated quickly relative to the carrier plate **156** so that it always brushes the solid dielectric elastomer transducer roll **178** back, as illustrated below in Fig. 13.

Fig. 13 illustrates a simplified implementation of the motion control system **212** that is configured to account for slip **218** that can occur between the scrub roller **168** and the growing diameter of the solid dielectric elastomer transducer roll **178**. Accordingly, the motion control system **212** may be configured to control the velocity of the carrier plate **156** V_{plate} in direction **174** relative to the velocity of the scrub roller **168** V_{scrub} in direction **172** such that $|V_{plate}| << |V_{scrub}|$.

Fig. 14 illustrates a textile covering **222** positioned over an outside surface of the scrub roller **168** illustrated in Fig. 13. The textile covering **222** is made of a non-stick material to provide non-stick contact between the scrub roller **168** and the solid dielectric elastomer transducer roll **178** in accordance with one embodiment of the present invention. Fig. 15 is a detailed view of the textile covering **222** provided over the outside surface of the scrub roller **168** as illustrated in Fig. 14 in accordance with one embodiment of the present invention. With reference to Figs. 14 and 15, a suitable non-stick contact between the scrub roller **168** and the solid dielectric elastomer transducer roll **178** may be achieved by covering the scrub roller with a knit fabric **222**. The knit fabric **222** minimizes the dielectric-to-roller contact area and thus minimizes the adhesion force. The knit fabric **222** insures that the contact area is primarily empty air. Because the knit fibers can deflect, stress concentrations on the solid dielectric elastomer transducer roll **178** film are smaller than those provided by, for example, a roller made of a hard grooved plastic. This protects the solid dielectric elastomer transducer roll **178** from mechanical damage during the rolling process.

Fig. 16 illustrates circumferential lengthening of outer layers of the dielectric elastomer transducer roll **224** caused by rolling a pre-strained dielectric elastomer film with excessive pre-strain during the rolling process. An advantage of the rolling process according to one embodiment of present invention is the ability to apply a minimum of pre-strain to the dielectric elastomer transducer roll during the rolling process. In one aspect, the minimum pre-strain is only the pre-strain required for peeling the dielectric film laminate from the liner during the rolling process. This is useful because excessive pre-strain can cause relaxation of longitudinal pre-strain that can lead circumferential lengthening of the outer layers **226** of the transducer roll **224**. As shown in Fig. 16, the outer layers **224** of the transducer roll **224** have delaminated in some places and not others, causing buckling. So, even if the inner layers of the transducer roll **224** do not buckle, the outer layers **224** may slip. This problem with pre-strain may be minimized by rolling up the unstrained dielectric film laminate directly from the liner on which it was coated in accordance with one embodiment of the present invention.

Fig. 17 illustrates a wrinkling mechanism in the loosely packed space between individual electroded solid dielectric elastomer transducer rolls **178a, 178b** in accordance with one embodiment of the present invention. The bands **226** of un-electroded film in between electroded solid dielectric elastomer transducer rolls **178a, 178b** can cause rolling problems. The dielectric layers in these bands **226** are supported only loosely by underlying layers, and can therefore buckle **228** in response to non-uniform rotation along the length of the roll **168**. This is illustrated in Fig. 17, where the electroded solid dielectric elastomer transducer rolls **178a, 178b** have undergone slightly different rotation relative to the rotation rates of the band **226** therebetween. The electroded solid dielectric elastomer transducer rolls **178a, 178b** portions of the transducer roll **178** are supported by the electrodes whereas the band **226** therebetween is unsupported and can buckle. The force of peeling the laminate film from the liner can also produce V-shaped wrinkles in these bands **226**. The wrinkles propagate along the length of the roll as turns are added, which is undesirable. To minimize this problem, the regions of adjacent electroded solid dielectric elastomer transducer rolls **178a, 178b** can be overlapped as described hereinbelow in Fig. 18.

Fig. 18 illustrates an electrode pattern **230** with overlapping regions **232** to provide support in bands between adjacent (juxtaposed) layers of electrode materials to be segmented into individual solid dielectric elastomer transducer rolls **178a, 178b**. The electrode pattern **230** prevents wrinkles that would otherwise start in the overlapping regions **232** and also enables segmenting the roll into individual solid dielectric elastomer transducer rolls **178a**, **178b**. The first dielectric film **102** is shown delaminated from the second dielectric film **104** for illustration purposes. As shown, the first and second electrodes **106**, **108** are applied on opposite sides of the dielectric film **102** in a staggered (offset) manner to create overlapping regions **232**. A first side of the dielectric film **102** includes multiple layers of electrode **106_1**, **106_2**, and **106_3** material juxtaposed relative to each other and spaced apart by a gap **235** therebetween. A second side of the dielectric film **102** includes multiple layers of electrode **108_1**, **108_2**, and **108_3** material juxtaposed relative to each other and spaced apart by a gap **237** therebetween. The layers of electrodes **106_1**, **106_2**, and **106_3** on the first side of the dielectric film **102** are offset or staggered from the layers of electrodes **108_1**, **108_2**, **108_3** on the second side of the dielectric film **102** to create the overlapping regions **232_1**, **232_2** and so on. The second dielectric film **104** is still releasably attached to the liner **154** which is attached to the carrier plate **156**. As previously discussed, the first dielectric film **102** with the electrodes **106_1**, **106_2**, **106_3**, **108_1**, **108_2**, and **108_3** formed on each side thereof is laminated to the second dielectric film **104** on the liner **154**.

Fig. 19 illustrates a non-limiting example of fixture **234** for positioning the electrical terminal caps **$194a_1$**, **$194a_2$** on ends of a solid dielectric elastomer transducer roll **178a** during curing. The fixture **234** comprises a slot **236** to receive the solid dielectric elastomer transducer roll **178a** and blade terminals **238** for receiving the electrical terminal caps **$194a_1$**, **$194a_2$**. As previously discussed in Figs.7I and 7J, the electrical terminal caps **$194a_1$**, **$194a_2$** are filled with an electrically conductive adhesive **192**. The ends of the solid dielectric elastomer transducer roll **178a** are then inserted into each one of the conductive adhesive **192** filled electrical terminal caps **$194a_1$**, **$194a_2$** and then a cam **240** is used to apply a clamping force to the assembled solid dielectric elastomer transducer roll **178a** and conductive adhesive **192** filled electrical terminal caps **$194a_1$**, **$194a_2$** during the curing process.

Having described embodiments of solid dielectric elastomer transducer rolls, methods for manufacturing the solid dielectric elastomer transducer rolls, and machines for manufacturing the solid dielectric elastomer transducer rolls, the specification now turns to a description of capacitance models for a solid dielectric elastomer transducer roll in axial tension and compression modes as well as radial (flat mode) compression modes.

Fig. 20 illustrates a derivation model **300** of a solid dielectric elastomer transducer roll **302**, similar to the solid dielectric elastomer transducer roll **100, 178** described above, in accordance with one embodiment of the present invention. The diagram depicted in Fig. 20 shows the solid dielectric elastomer transducer roll **302** in a relaxed state and also shows a comparison of an outer ring **304** of the solid dielectric elastomer transducer roll **302** in a relaxed state and the outer ring **304'** when it is in tension. The solid dielectric elastomer transducer roll **302** has a length x_o when the solid dielectric elastomer transducer roll **302** is not in tension and a length $(x_o + x)$ or λx_o when tensioned. The model assumes the spiral equivalent of N rings and the volume inside each ring is conserved due to the incompressibility of the rings within and the volume of the ring itself is conserved. Each ring is an annular capacitor and the total capacitance is the sum of the all N rings.

The main equations developed in accordance with the model are:

Effective Number of Rings in Roll	$N = \left(\frac{y_0}{t_0 \pi}\right)^{1/2}$	Eq. 6
Blocked Force	$F_{total} = V^2 \pi \varepsilon \varepsilon_0 \sum_{n=1}^{N} (\ln(n+1) - \ln(n))^{-1}$	Eq. 7
Spring Rate	$k = Y(y_0 + y_p)t_0 /(x_0 + x_p)$	Eq. 8
Free Stroke	$\Delta x \cong \frac{F_{total}}{k}$	Eq. 9
Roll Diameter	$D_{composite} = 2N(t_{film} + t_{elec})$	Eq. 10

A Spiral Is Equivalent To N Rings

The outer ring **304** of the un-tensioned solid dielectric elastomer transducer roll **302** has an outer radius b_o that is equal to the N rings of thickness t_o:

$$b_0 = Nt_0 \qquad \text{Eq. 11}$$

The area of the film is same whether it is laid out flat (y_{ot}) or rolled up into a circle (πb^2_o):

$$A_{film} = y_0 t = \pi b_0^2 \qquad \text{Eq. 12}$$

$$y_o t_0 = \pi (N t_0)^2 \qquad \text{Eq. 13}$$

$$N t_0 = \left(\frac{y_0 t_0}{\pi} \right)^{1/2} \qquad \text{Eq. 14}$$

$$N = \left(\frac{y_0}{t_0 \pi} \right)^{1/2} \qquad \text{Eq. 15}$$

Volume Inside Each Ring Is Conserved

$$Volume_0 = Volume(\lambda) \qquad \text{Eq. 16}$$

$$Volume_0 = \pi a_0^2 x_0 \qquad \text{Eq. 17}$$

$$Volume(\lambda) = \pi a^2 \qquad \text{Eq. 18}$$

$$\pi a_0^2 x_0 = \pi a^2 \lambda x_0 \qquad \text{Eq. 19}$$

$$a_0^2 = a^2 \lambda \qquad \text{Eq. 20}$$

$$a^2 = \lambda^{-1} a_0^2 \qquad \text{Eq. 21}$$

$$a = \lambda^{-1/2} a_0 \qquad \text{Eq. 22}$$

Volume Of Each Ring Itself Is Conserved

$$Volume_0 = Volume(\lambda) \qquad \text{Eq. 23}$$

$$Volume_0 = \pi (b_0^2 - a_0^2) x_0 \qquad \text{Eq. 24}$$

$$Volume(\lambda) = \pi (b^2 - a^2) \lambda x_0 \qquad \text{Eq. 25}$$

$$\pi (b_0^2 - a_0^2) x_0 = \pi (b^2 - a^2) \lambda x \qquad \text{Eq. 26}$$

$$\left(b_0^2 - a_0^2\right) = \left(b^2 - a^2\right)\lambda \qquad \text{Eq. 27}$$

$$b^2 = \lambda^{-1}\left(b_0^2 - a_0^2\right) + a^2 \qquad \text{Eq. 28}$$

$$b = \left(\lambda^{-1}\left(b_0^2 - a_0^2\right) + a^2\right)^{1/2} \qquad \text{Eq. 29}$$

Using the results from Eq. 22, this can be simplified further:

$$b = \left(\lambda^{-1}\left(b_0^2 - a_0^2\right) + a^2\right)^{1/2} \qquad \text{Eq. 30}$$

$$b = \left(\lambda^{-1}\left(b_0^2 - a_0^2\right) + \left(\lambda^{-1/2}a_0\right)^2\right) \qquad \text{Eq. 31}$$

$$b = \left(\lambda^{-1}\left(b_0^2 - a_0^2\right) + \lambda^{-1}a_0^2\right)^{1/2} \qquad \text{Eq. 32}$$

$$b = \left(\lambda^{-1}\left(b_0^2 - a_0^2 + a_0^2\right)\right)^{1/2} \qquad \text{Eq. 33}$$

$$b = \left(\lambda^{-1}b_0^2\right)^{1/2} \qquad \text{Eq. 34}$$

$$b = \lambda^{-1/2}b_0 \qquad \text{Eq. 35}$$

<u>Capacitance Of The Annular Capacitor</u>

Initially the capacitance is:

$$C_0 = \frac{2\pi\varepsilon\varepsilon_0 x_0}{\ln\left(\frac{b_0}{a_0}\right)} \qquad \text{Eq. 36}$$

After it has been stretched it becomes longer, so that the length becomes (λx_0) and the radii (a and b) are no longer the initial radii (a_0 and b_0):

$$C(\lambda) = \frac{2\pi\varepsilon\varepsilon_0 x_0 \lambda}{\ln\left(\frac{b}{a}\right)} \qquad \text{Eq. 37}$$

Substituting results from Equations 22 and 35 allows the stretched capacitance to be expressed in terms of initial geometry.

$$C(\lambda) = \frac{2\pi\varepsilon\varepsilon_0 x_0 \lambda}{\ln\left(\frac{b}{a}\right)} \quad \text{Eq. 38}$$

$$C(\lambda) = \frac{2\pi\varepsilon\varepsilon_0 x_0 \lambda}{\ln\left(\frac{\lambda^{-1/2} b_0}{\lambda^{-1/2} a_0}\right)} \quad \text{Eq. 39}$$

$$C(\lambda) = \frac{2\pi\varepsilon\varepsilon_0 x_0}{\ln\left(\frac{b_0}{a_0}\right)} \lambda \quad \text{Eq. 40}$$

Capacitance is expected to vary linearly with the stretch ratio. To get the force each ring provides note that electrostatic force depends on the change in capacitance with excursion from rest.

$$F_{elec} = V^2 \frac{\partial C}{\partial x} \quad \text{Eq. 41}$$

Note that the stretch ratio can be expressed in terms of that excursion from rest.

$$\lambda = 1 + \frac{x}{x_0} \quad \text{Eq. 42}$$

$$C(x) = \frac{2\pi\varepsilon\varepsilon_0 x_0}{\ln\left(\frac{b_0}{a_0}\right)} \left(1 + \frac{x}{x_0}\right) \quad \text{Eq. 43}$$

The derivative cancels out the initial length of the actuator (x_0). This means that the electric force will not be predicted to change as the length of the actuator changes.

$$\frac{\partial C}{\partial x}=\frac{2\pi\varepsilon\varepsilon_0 x_0}{x_0\ln\left(\frac{b_0}{a_0}\right)} \qquad \text{Eq. 44}$$

$$\frac{\partial C}{\partial x}=\frac{2\pi\varepsilon\varepsilon_0}{\ln\left(\frac{b_0}{a_0}\right)} \qquad \text{Eq. 45}$$

$$F_{elec}=(1/2)V^2\frac{\partial C}{\partial x}=\frac{V^2\pi\varepsilon\varepsilon_0}{\ln\left(\frac{b_0}{a_0}\right)} \qquad \text{Eq. 46}$$

Note that the outer radius b_0 is just the inner radius (a_0) plus the thickness of the film (t_0).

$$F_{elec}=(1/2)V^2\frac{\partial C}{\partial x}=\frac{V^2\pi\varepsilon\varepsilon_0}{\ln\left(\frac{a_0+t}{a_0}\right)} \qquad \text{Eq. 47}$$

To get the total force we must sum up the contributions of all N of the rings. Note that each ring has an outer radius that is one thickness greater than the inner radius.

$$F_{total}=V^2\pi\varepsilon\varepsilon_0\sum_{n=1}^{N}\left(\ln\left(\frac{(n+1)t_0}{nt_0}\right)\right)^{-1} \qquad \text{Eq. 48}$$

Canceling like terms

$$F_{total}=V^2\pi\varepsilon\varepsilon_0\sum_{n=1}^{N}\left(\ln\left(\frac{(n+1)}{n}\right)\right)^{-1} \qquad \text{Eq. 49}$$

$$F_{total}=V^2\pi\varepsilon\varepsilon_0\sum_{n=1}^{N}(\ln(n+1)-\ln(n))^{-1} \qquad \text{Eq. 50}$$

The thickness of a layer has not, in fact, disappeared. It appears in the upper limit of the series (N). The total number of layers (N) can be expressed simply in terms of the initial geometry.

$$F_{total} = V^2 \pi \varepsilon \varepsilon_0 \sum_{n=1}^{N} (\ln(n+1) - \ln(n))^{-1} \text{, where } N = \left(\frac{y_0}{t_0 \pi} \right)^{1/2} \quad \text{Eq. 51}$$

The expected capacitance change is the force expression (Eq. 51) without the Voltage term $\frac{1}{2}V^2$:

$$\frac{\partial C}{\partial x} = 2\pi \varepsilon \varepsilon_0 \sum_{n=1}^{N} (\ln(n+1) - \ln(n))^{-1} \text{, where } N = \left(\frac{y_0}{t_0 \pi} \right)^{1/2} \quad \text{Eq. 52}$$

Both of the above are measurable. A candidate example geometry includes 48.8603 rings or approximately 49 rings. Accordingly, for approximately 49 rings, a predicted force and capacitance change rate is:

$$F_{elec} = \pi \varepsilon \varepsilon_0 V^2 \sum_{n=1}^{N} (\ln(n+1) - \ln(n))^{-1} \quad \text{Eq. 53}$$

$$F_{elec} = \pi [2.85][8.854\text{E-12 F/m}][1200\text{V}]^2 \sum_{n=1}^{49} (\ln(n+1) - \ln(n))^{-1} \quad \text{Eq. 54}$$

$$\frac{\partial C}{\partial x} = \pi [2.85][8.854\text{E-12 F/m}] \sum_{n=1}^{49} (\ln(n+1) - \ln(n))^{-1} \quad \text{Eq. 55}$$

Fig. 21 is a graphical illustration **306** depicting force **308** provided by each additional ring in a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention. Force [N] is shown along the vertical axis and ring number is shown along the horizontal axis. Accordingly, the additional force **308** provided by each ring grows linearly with the ring number. This is in conformity with expectations, as the area of each ring scales linearly with circumference. The total force of 0.1426 N approximately matches the total force for a model based on simpler assumptions: i.e., dielectric stacked, not rolled, (Eq. 56).

The calculation for parallel layers, not rolled up provides:

$$F_{elec} = (1/2)V^2 \frac{\partial C}{\partial x} = (1/2)\frac{V^2 \varepsilon \varepsilon_0 y_i}{z_i} \quad \text{Eq. 56}$$

Accordingly, the model provides a measurable prediction for capacitance change:

dC/dx=Ftot/(0.5*(1200^2)) = 1.9806e-007 [F/m]

Fig. 22 is a graphical illustration **310** depicting capacitance change versus axial displacement of a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention. Capacitance C[F] is shown along the vertical axis and axial displacement x[mm] is shown along the horizontal axis. The data substantially agrees with the model. In the graphical illustration **310** capacitance change in two solid dielectric elastomer transducer rolls with 10 mm active length are depicted by curves **312** and 14 mm total length are depicted by curves **314**. A peak *dC/dx* of 8.91E-8 F/m was observed when the transducer rolls were in tension. Although this is just (8.9E-8/1.9806E-7) = 44% of the expected *dC/dx*, the active area did not really experience all of the displacement. Some of the displacement was taken up by deformation in the passive 4 mm of the solid dielectric elastomer transducer roll. To estimate the effect that this compliance will have on measured *dC/dx*, two cases may be considered (1) negligible electrode stiffness and (2) a relatively large electrode stiffness, for example equal to the film stiffness.

Case 1 – Electrode Negligible

Assuming that the active and passive areas have equal stiffness (that is, electrode is negligible), then the observed dC/dx is scaled by (total:active = 14 mm:10 mm). The observed dC/dx is then (14/10)*([8.9E-8 F/m]/[1.9806E-7 F/m]) = 63% of expected.

Case 2 – Electrode Stiff

If the stiffness of the electrode is not negligible, then it must be taken into account. In planar devices, it may be observed that a standard electrode coating on two sides of a film increases pseudo-DC stiffness of a film by an amount equivalent to multiplying Young's modulus of the film by two. The roll is comprised of two compliances in series. The active Area is 10 mm long and has two layers of electrode, and the passive 4mm long and has one layer.

$$s1=0.010\text{m}/(2*\text{Y\_film}*\text{Area})$$

$$s2=0.004\text{m}/(1.5*\text{Y\_film}*\text{Area})$$

And the proportion of deformation occurring in the active area is

$$\Delta x_l/\Delta x_{tot}=(5/(5+2.6667)=0.6522.$$

Scaling by this factor, dC/dx is found to be ((1/0.6522)*[8.9E-8 F/m])/[1.98E-7 F/m]=69% of expected. In the absence of control data measuring electrode stiffness directly, this provides the best estimate of how the observed capacitance change relates to the nested ring model.

Fig. 23 is a graphical illustration **316** depicting blocked force versus applied voltage response **318** of a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention. The response **318** was obtained by measuring a sample on an INSTRON instrument for measuring tension / compression, made by INSTRON of Norwood, MA, at 1200V and a blocked force at 1200V of 0.102N was observed, as shown in Fig. 23. The blocked force measurement is ([0.102 N]/[0.1363 N])=74% of the model prediction.

Fig. 24 is a graphical illustration **320** depicting blocked force versus axial displacement demonstrating the difference between the solid dielectric elastomer transducer roll in compression versus tension in accordance with one embodiment of the present invention. Measuring blocked force on the INSTRON instrument, shows a clear difference between using the solid dielectric elastomer transducer roll in compression **322** versus tension **324**, consistent with the slope differences observed in *dC/dx*. In compression, layers of the solid dielectric elastomer transducer roll undergo localized buckling rather than uniform compression. This occurs at forces (0.1 N) lower than the Euler buckling limit for the entire column (1.5N calculated, 1.4 N observed).

Fig. 25 is a graphical illustration **326** of blocked force versus longitudinal displacement showing the difference between the solid dielectric elastomer transducer roll in compression **328** versus tension **330** in accordance with one embodiment of the present invention.

Fig. 26 is a graphical representation **332** of stiffness of solid dielectric elastomer transducer rolls in accordance with one embodiment of the present invention. The simplest prediction of stiffness for the solid rolls is to neglect electrode stiffness and the rigid boundary conditions:

$k_{simple}=YA/l$ = [0.6E6 Pa]*([2*160E-3 m]*[40E-6 m])/[14E-3 m]=548.6 N/m.

This estimate of the stiffness is relatively good. Observed stiffness is higher than theoretical by only 6-13% in these two samples.

[582 N/m , 621 N/m]./[548.6 N/m] = [1.06 1.13]

This suggests that the effect of the electrode on the stiffness of the solid dielectric elastomer transducer rolls is relatively small and not the 2x factor in the active area that was considered in the dC/dx calculation above. It appears a better assumption may be to treat the electrode stiffness as negligible and to estimate that the observed dC/dx is about 63% of that expected by the model.

Fig. 27 illustrates a solid dielectric elastomer transducer roll **400** in flat roll mode where the roll **400** is placed under compression **402** in a radial direction rather than in an axial direction in accordance with one embodiment of the present invention. As shown, a portion of the solid dielectric elastomer transducer roll **400** is clamped between jaws **404a**, **404b** such that is compresses the transducer roll **400** radially rather axially. Experimental results indicate that the peak capacitance change dC/dx in radial ("flat roll") mode is approximately 5-times the capacitance change dC/dx in axial mode.

Fig. 28 illustrates a geometric model **410** of a solid dielectric elastomer transducer roll **412** in radial ("flat roll") mode where the roll **412** is placed under compression in a radial direction in accordance with one embodiment of the present invention. The cross-sectional area of the uncompressed roll **412** is depicted as a circle in phantom, whereas the cross-sectional area $A(x)$ of the roll **412'** under radial compression is depicted in solid line as a flattened elongated structure with flat regions in the center over a length l and rounded ends. The model assumes the following:

Long out of plane → Plane strain;

Incompressible → $A(x) = A_0$; and

Flat regions slip → Equal strain around perimeter P.

The geometric model for the solid dielectric elastomer transducer roll **412** in radial mode ("flat roll') is described by the following equations:

$$P_0 = \pi x_0 \quad \text{Eq. 57}$$

$$P(x) = 2\ell + \pi(x_0 - x) \quad \text{Eq. 58}$$

$$A_0 = \frac{\pi}{4} x_0^2 \quad \text{Eq. 59}$$

$$A(x) = \ell(x_0 - x) + \frac{\pi}{4}(x_0 - x)^2 \quad \text{Eq. 60}$$

$$A_0 = A(x) \quad \text{Eq. 61}$$

$$\frac{\pi}{4} x_0^2 = \ell(x_0 - x) + \frac{\pi}{4}(x_0 - x)^2 \quad \text{Eq. 62}$$

$$\ell = \frac{\pi\left(x_0^2 - (x_0 - x)^2\right)}{4(x_0 - x)} \quad \text{Eq. 63}$$

$$P(x) = 2\ell + \pi(x_0 - x) \quad \text{Eq. 64}$$

$$\lambda_P(x) = \frac{P(x)}{P_0} = \frac{P(x)}{\pi x_0} \quad \text{Eq. 65}$$

$$C = C_0 \lambda_P^2 \quad \text{Eq. 66}$$

Fig. 29 is a graphical illustration **414** depicting stretch ratio versus percent compression in a radial direction of a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention. Stretch ration [L/L_0] is shown along the vertical axis and percent compression [x/x_0] is shown along the horizontal axis. The curve **416** shows non-linear behavior of stretch ration versus percent compression.

Fig. 30 illustrates a static equilibrium diagram **418** of a solid dielectric elastomer transducer roll **420** in radial compression ("flat roll") mode under static load in accordance with one embodiment of the present invention. Static equilibrium is defined as follows:

$$F_{elec} + F_S + F_L = 0 \qquad \text{Eq. 67}$$

where F_{elec} is electric force, F_S is spring force and F_L is an external load. The electric force is proportional to the capacitance change dC/dx which is in turn proportional to the stretch ratio of the dielectric layers $\lambda=P/P_0$. Because this stretch is approximately quadratic with respect to compression of the roll, (Figs. 29 and 31), the electric force, which is the slope of the capacitance curve, can be approximated with a single constant such that $dC/dx=k_1x$. The spring force is also approximated well with a single term such that $F_s=k_3x^2$

$$\tfrac{1}{2} V^2 (k_1x) + k_3x^2 + F_L = 0 \qquad \text{Eq. 68}$$

$$k_1V^2/2\, x + k_3x^2 + F_L = 0 \qquad \text{Eq. 69}$$

$$k_3x^2 + (\tfrac{1}{2} k_1V^2)x + F_L = 0 \qquad \text{Eq. 70}$$

The equilibrium displacement of the roll subjected to the static load is found from the roots of the quadratic equation, where $a = k_3$, $b = \tfrac{1}{2} k_1V^2$ and $c = F_L$.

$$x = [-b \pm \sqrt{(b^2 - 4ac)}] / 2a \qquad \text{Eq. 71}$$

<u>The Pseudo-DC Roll Model</u>

$$F_{elec} = \tfrac{1}{2} V^2\, dC/dx \qquad \text{Eq. 72}$$

$$F_{elec} = \tfrac{1}{2} V^2 (k_1x) \qquad \text{Eq. 73}$$

$$F_S = k_3x^2 \qquad \text{Eq. 74}$$

$F_L = -4$, [N], for example.

Fig. 31 is a graphical illustration **422** depicting capacitance versus compression in a radial direction of a solid dielectric elastomer transducer roll in flat roll mode in accordance with one embodiment of the present invention. Capacitance C[F] is shown along the vertical axis and compression x[m] is shown along the horizontal axis. The flat roll model curve **424** provides a reasonable first approximation of the capacitance change versus compression as compared to the measurements results **426**. Potential contributors to the difference between actual measurements **426** and the model **424** may be that just 7.5 mm of 10 mm active length was compressed in an INSTRON test instrument and the rigid boundary may limit extension of the outer layers.

Figs. 32A, 32B, 32C and 32D illustrate a solid dielectric elastomer transducer roll **430** under increasing compression force in a radial direction in accordance with one embodiment of the present invention. From left to right, the solid dielectric elastomer transducer roll **430** undergoes increasing compression force such that the roll **430** in under no compression force, roll **430′** is under greater compression force than the roll **430**, roll **430″** is under greater compression force than the roll **430′**, and the roll **430‴** is under greater compression force than the roll **430″**. As shown in Figs. 32B, 32C and 32D, the roll begins to delaminate as it is subjected to increasing greater compression forces. This delamination causes deviation from the model, and presents a practical limit on compression of the roll.

Fig. 33 illustrates a finite element analysis model **432** of a solid dielectric elastomer transducer roll **434** undergoing radial compression in accordance with one embodiment of the present invention and indicates where stretch orientation is and is not well-aligned with the orientation of the layers.

Fig. 34 illustrates the delamination of inner layers **434** of a solid dielectric elastomer transducer roll **436** undergoing radial compression in accordance with one embodiment of the present invention. As the finite element analysis predicts, delamination occurs in regions where the principal stretch is oriented through the thickness of dielectric films.

As for other details of the present invention, materials and alternate related configurations may be employed as within the level of those with skill in the relevant art. The same may hold true with respect to process-based aspects of the invention in terms of additional acts as commonly or logically employed. In addition, though the invention has been described in reference to several examples, optionally incorporating various features, the invention is not to be limited to that which is described or indicated as contemplated with respect to each variation of the invention. Various changes may be made to the invention described and equivalents (whether recited herein or not included for the sake of some brevity) may be substituted without departing from the true spirit and scope of the invention. Any number of the individual parts or subassemblies shown may be integrated in their design. Such changes or others may be undertaken or guided by the principles of design for assembly.

Various aspects of the subject matter described herein are set out in the following numbered clauses in any combination thereof:

1. A method for making a rolled dielectric elastomer transducer, comprising: applying an electrode material on a first side and a second side of a first dielectric film; laminating the first dielectric film onto a side of a second dielectric film to produce a dielectric film laminate; and rolling the dielectric film laminate into a solid dielectric elastomer transducer roll.

2. The method according to Claim 1, wherein applying the electrode material comprises applying at least a first layer of electrode material on the first side of the first dielectric film; and applying at least a second layer of the electrode material on the second side of the first dielectric film; and wherein the at least first layer and the at least second layer of the electrode material are offset relative to each other.

3. The method according to Claim 2, further comprising applying at least one additional first layer of electrode material juxtaposed and spaced apart from the at least one first layer of the electrode material on the first side of the first dielectric film, wherein the at least one additional first layer of electrode material on the first side of the first dielectric film partially overlaps the at least one second layer of the electrode material on the second side of the first dielectric film.

4. The method according to Claim 3, further comprising segmenting the solid dielectric elastomer transducer roll into two or more individual solid dielectric elastomer transducer rolls at the region where the at least one additional first layer on the first side of the first pre-strained dielectric film overlaps with the at least one second layer of the electrode material on the second side of the first pre-strained dielectric film.

5. The method according to any one of Claims 1 to 4, further comprising pre-straining the first and second dielectric films.

6. The method according to any one of Claims 1 to 5, further comprising applying an electrically conductive adhesive on a first end and a second end of the solid dielectric elastomer transducer roll; and applying an electrical terminal on the first and second ends of the solid dielectric elastomer transducer roll.

7. The method according to Claim 6, further comprising applying a solvent on the first and second ends of the solid dielectric elastomer transducer roll prior to applying the electrically conductive adhesive.

8. An apparatus, comprising a drive mechanism for receiving a carrier plate having a dielectric film laminate located on a first surface thereof, the drive mechanism configured to drive the carrier plate in a first direction; and a scrub roller configured to counter-rotate in a second direction relative to the first direction, the scrub roller configured to frictionally engage the dielectric film to wind the dielectric film laminate into a solid dielectric elastomer transducer roll.

9. The apparatus according to Claim 8, further comprising a motion control system for controlling the velocity of the drive mechanism and the scrub roller.

10. The apparatus according to Claim 9, wherein the motion control system is configured to control the velocity of the carrier plate V_{plate} in the first direction and the velocity of the scrub roller V_{scrub} in the second opposite direction such that $|V_{plate}| = |V_{scrub}|$.

11. The apparatus according to Claim 9, wherein the motion control system is configured to control the velocity of the carrier plate V_{plate} in the first direction and the velocity of the scrub roller V_{scrub} in the second opposite direction and to compensate for the velocity of the solid dielectric elastomer transducer roll such that $|V_{plate}| - |V_{roll,x}| = |V_{scrub}|$.

12.. The apparatus according to Claim 9, wherein the motion control system is configured to control the velocity of the carrier plate V_{plate} in the first direction and the velocity of the scrub roller V_{scrub} in the second opposite direction and to compensate for the velocity of the solid dielectric elastomer transducer roll and to compensate for dielectric film stretch defined by a stretch coefficient "k" caused by peel stress such that $|V_{plate}| - |V_{roll,x}| = k|V_{scrub}|$.

13. The apparatus according to Claim 9, further comprising at least one sensor to sense force and provide a closed loop feedback mechanism to the motion control system.

14. The apparatus according to any one of Claims 9 to 13, further comprising a covering positioned over an outside surface of the scrub roller.

15. The apparatus according to Claim 14, wherein the covering is made of a non-stick material.

Also, it is contemplated that any optional feature of the inventive variations described may be set forth and claimed independently, or in combination with any one or more of the features described herein. Reference to a singular item, includes the possibility that there are plural of the same items present. More specifically, as used herein and in the appended claims, the singular forms "a," "an," "said," and "the" include plural referents unless the specifically stated otherwise. In other words, use of the articles allow for "at least one" of the subject item in the description above as well as the claims below. It is further noted that the claims may be drafted to exclude any optional element. As such, this statement is intended to serve as antecedent basis for use of such exclusive terminology as "solely," "only" and the like in connection with the recitation of claim elements, or use of a "negative" limitation. Without the use of such exclusive terminology, the term "comprising" in the claims shall allow for the inclusion of any additional element – irrespective of whether a given number of elements are enumerated in the claim, or the addition of a feature could be regarded as transforming the nature of an element set forth in the claims. Stated otherwise, unless specifically defined herein, all technical and scientific terms used herein are to be given as broad a commonly understood meaning as possible while maintaining claim validity.

WHAT IS CLAIMED IS:

1. A method for making a rolled dielectric elastomer transducer, comprising:

applying an electrode material on a first side and a second side of a first dielectric film;

laminating the first dielectric film onto a side of a second dielectric film to produce a dielectric film laminate; and

rolling the dielectric film laminate into a solid dielectric elastomer transducer roll.

2. The method according to Claim 1, wherein applying the electrode material comprises,

applying at least a first layer of electrode material on the first side of the first dielectric film; and

applying at least a second layer of the electrode material on the second side of the first dielectric film; and

wherein the at least first layer and the at least second layer of the electrode material are offset relative to each other.

3. The method according to Claim 2, further comprising applying at least one additional first layer of electrode material juxtaposed and spaced apart from the at least one first layer of the electrode material on the first side of the first dielectric film, wherein the at least one additional first layer of electrode material on the first side of the first dielectric film partially overlaps the at least one second layer of the electrode material on the second side of the first dielectric film.

4. The method according to Claim 3, further comprising segmenting the solid dielectric elastomer transducer roll into two or more individual solid dielectric elastomer transducer rolls at the region where the at least one additional first layer on the first side of the first pre-strained dielectric film overlaps with the at least

one second layer of the electrode material on the second side of the first pre-strained dielectric film.

5. The method according to any one of Claims 1 to 4, further comprising pre-straining the first and second dielectric films.

6. The method according to any one of Claims 1 to 5, further comprising:

applying an electrically conductive adhesive on a first end and a second end of the solid dielectric elastomer transducer roll; and

applying an electrical terminal on the first and second ends of the solid dielectric elastomer transducer roll.

7. The method according to Claim 6, further comprising applying a solvent on the first and second ends of the solid dielectric elastomer transducer roll prior to applying the electrically conductive adhesive.

8. An apparatus, comprising:

a drive mechanism for receiving a carrier plate having a dielectric film laminate located on a first surface thereof, the drive mechanism configured to drive the carrier plate in a first direction; and

a scrub roller configured to counter-rotate in a second direction relative to the first direction, the scrub roller configured to frictionally engage the dielectric film to wind the dielectric film laminate into a solid dielectric elastomer transducer roll.

9. The apparatus according to Claim 8, further comprising a motion control system for controlling the velocity of the drive mechanism and the scrub roller.

10. The apparatus according to Claim 9, wherein the motion control system is configured to control the velocity of the carrier plate V_{plate} in the first direction and

the velocity of the scrub roller V_{scrub} in the second opposite direction such that $|V_{plate}| = |V_{scrub}|$.

11. The apparatus according to Claim 9, wherein the motion control system is configured to control the velocity of the carrier plate V_{plate} in the first direction and the velocity of the scrub roller V_{scrub} in the second opposite direction and to compensate for the velocity of the solid dielectric elastomer transducer roll such that $|V_{plate}| - |V_{roll,x}| = |V_{scrub}|$.

12. The apparatus according to Claim 9, wherein the motion control system is configured to control the velocity of the carrier plate V_{plate} in the first direction and the velocity of the scrub roller V_{scrub} in the second opposite direction and to compensate for the velocity of the solid dielectric elastomer transducer roll and to compensate for dielectric film stretch defined by a stretch coefficient "k" caused by peel stress such that $|V_{plate}| - |V_{roll,x}| = k|V_{scrub}|$.

13. The apparatus according to Claim 9, further comprising at least one sensor to sense force and provide a closed loop feedback mechanism to the motion control system.

14. The apparatus according to any one of Claims 9 to 13, further comprising a covering positioned over an outside surface of the scrub roller.

15. The apparatus according to Claim 14, wherein the covering is made of a non-stick material.

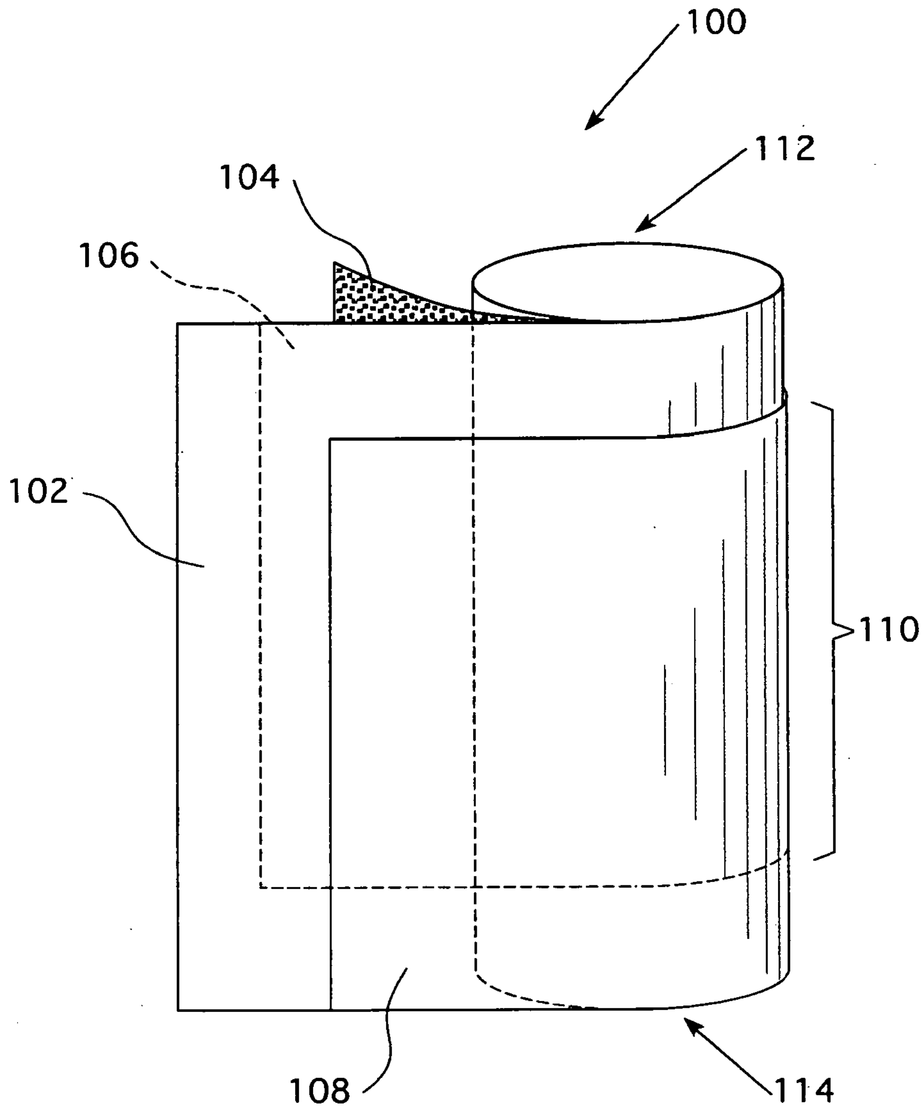


FIG. 1

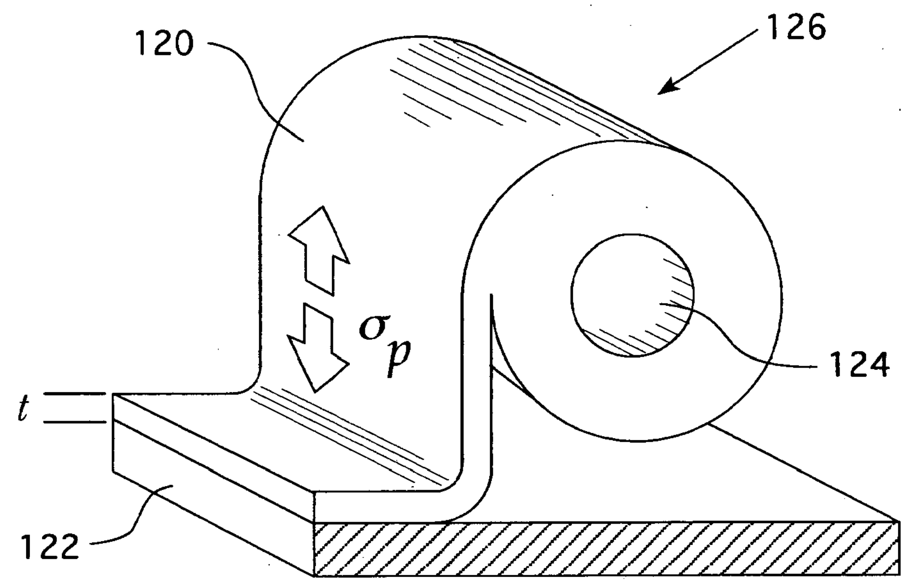


FIG. 2

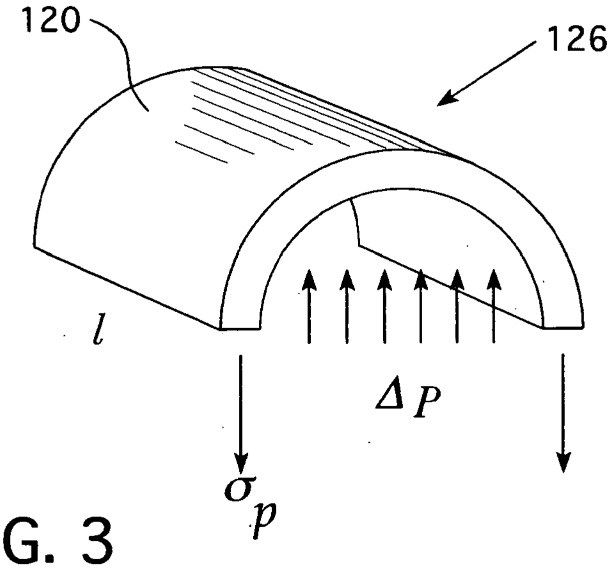
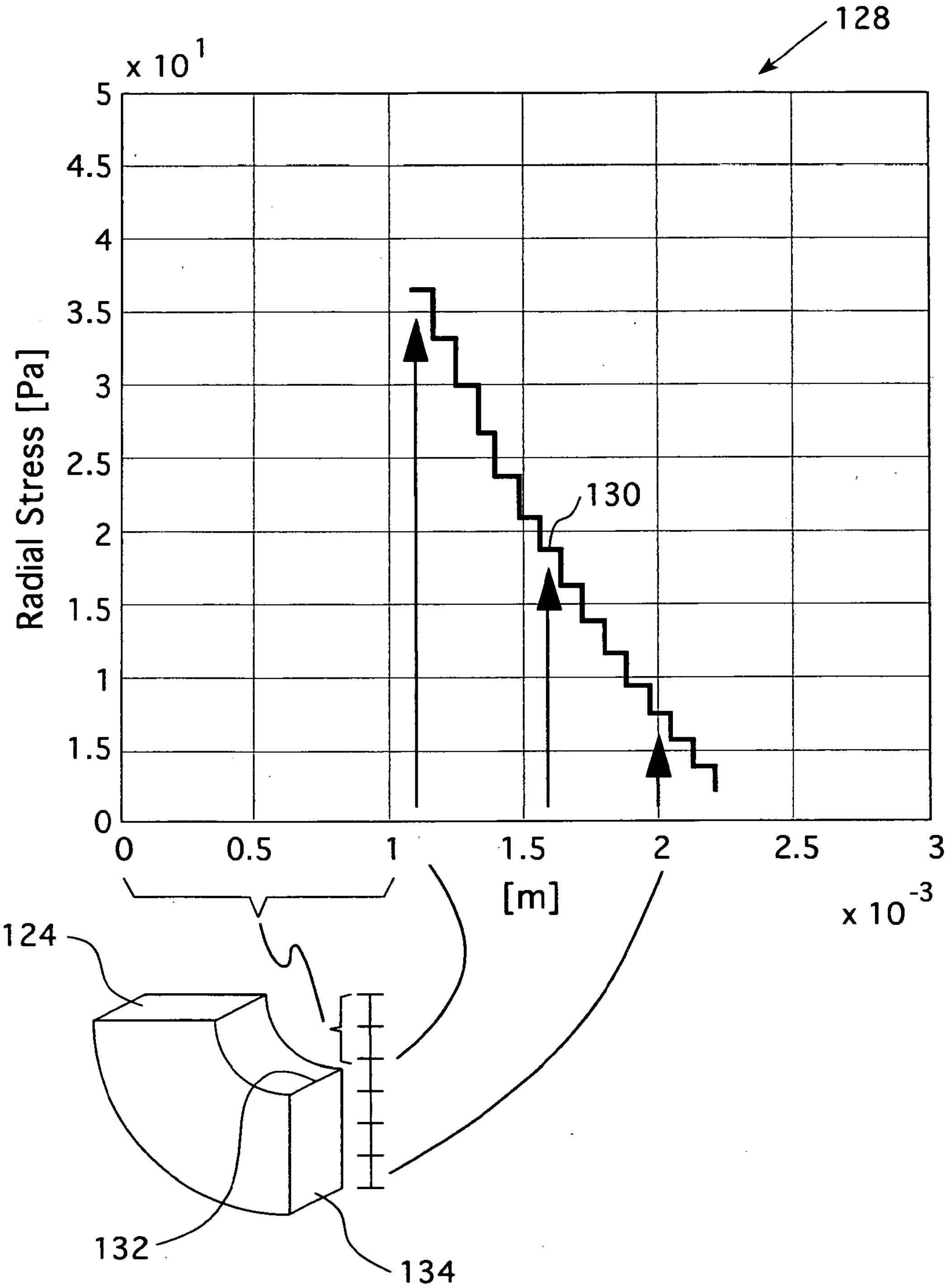


FIG. 3



128
x 10^1
5
4.5
4
3.5
3
2.5
2
1.5
1
1.5
0
Radial Stress [Pa]
130
0
0.5
1
1.5
2
2.5
3
[m]
x 10^-3
124
132
134

FIG. 4

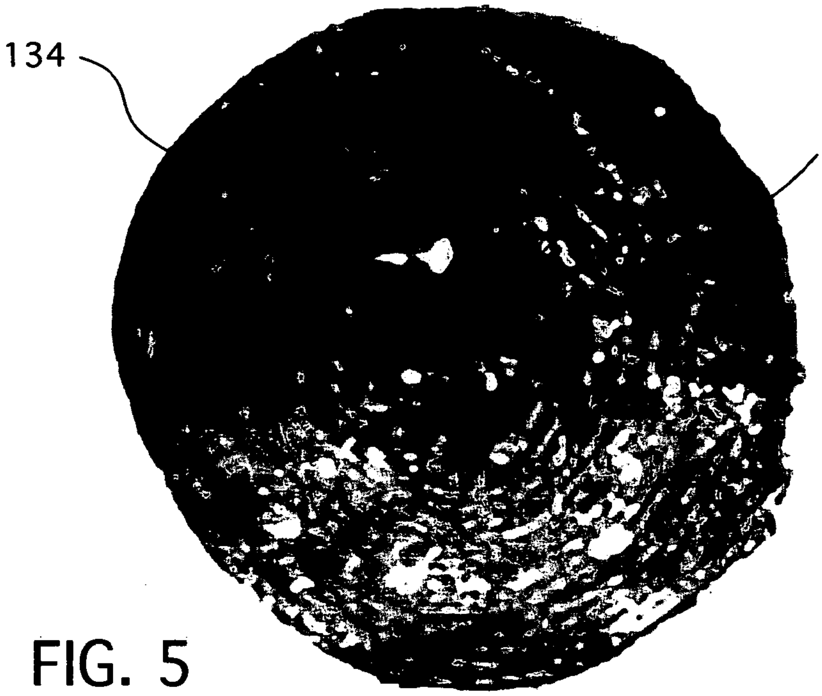


FIG. 5

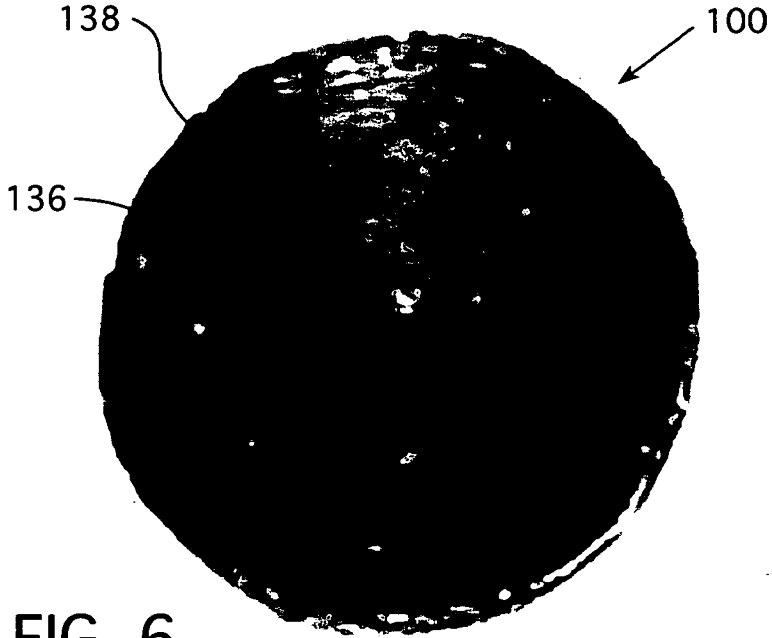


FIG. 6

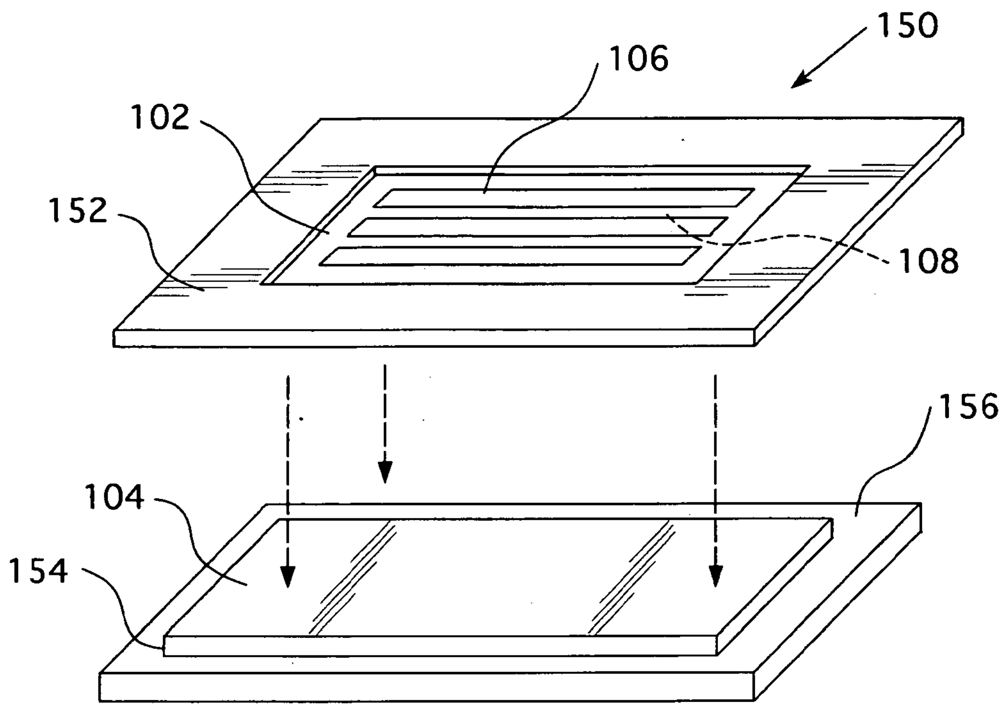


FIG. 7A

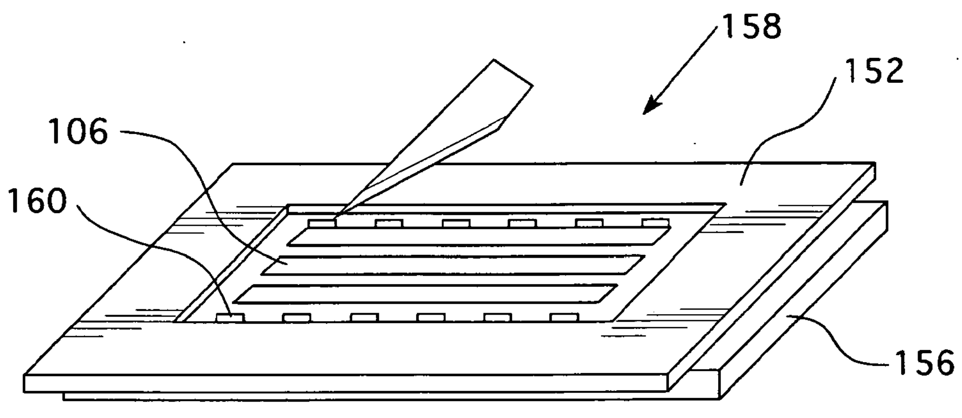


FIG. 7B

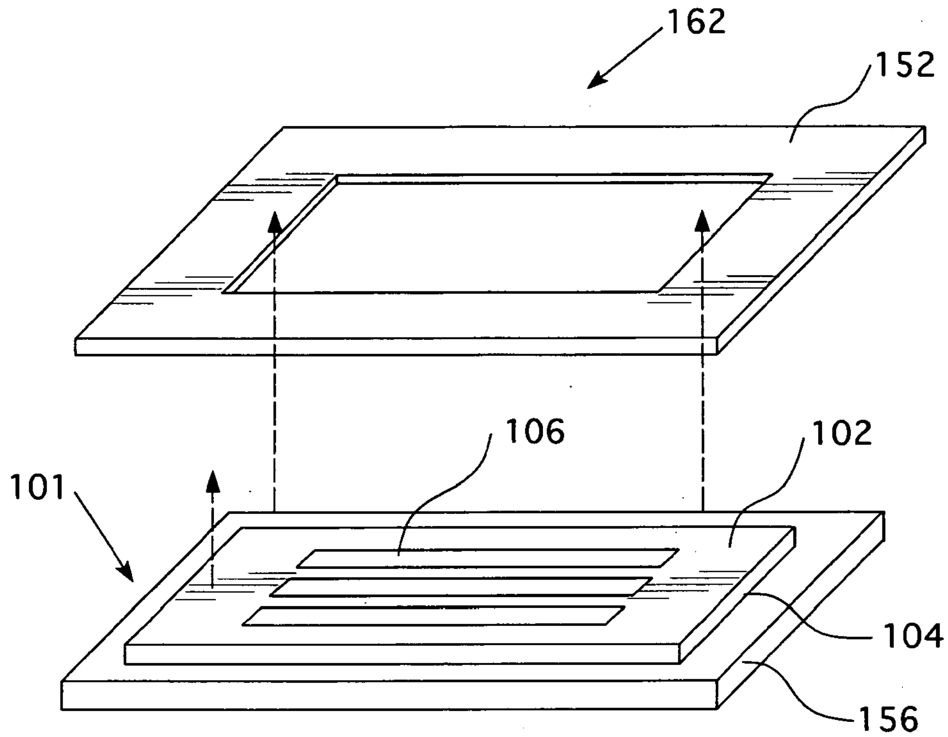


FIG. 7C

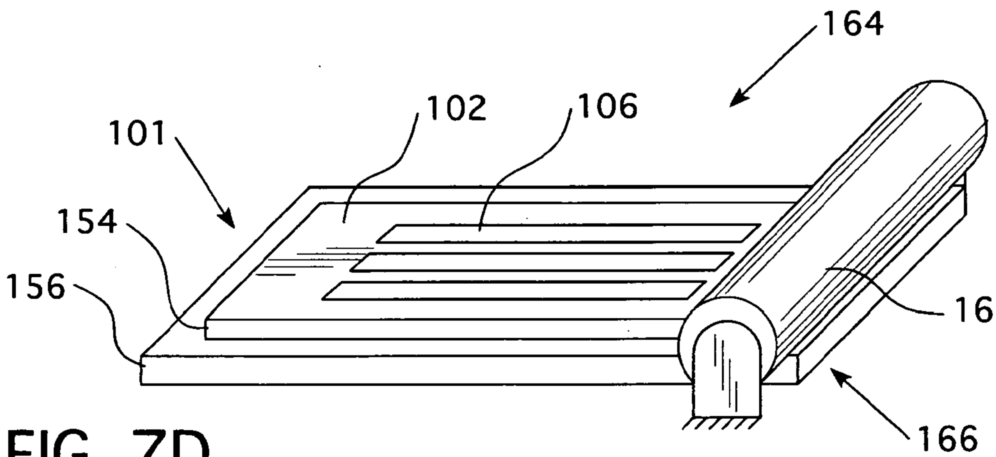


FIG. 7D

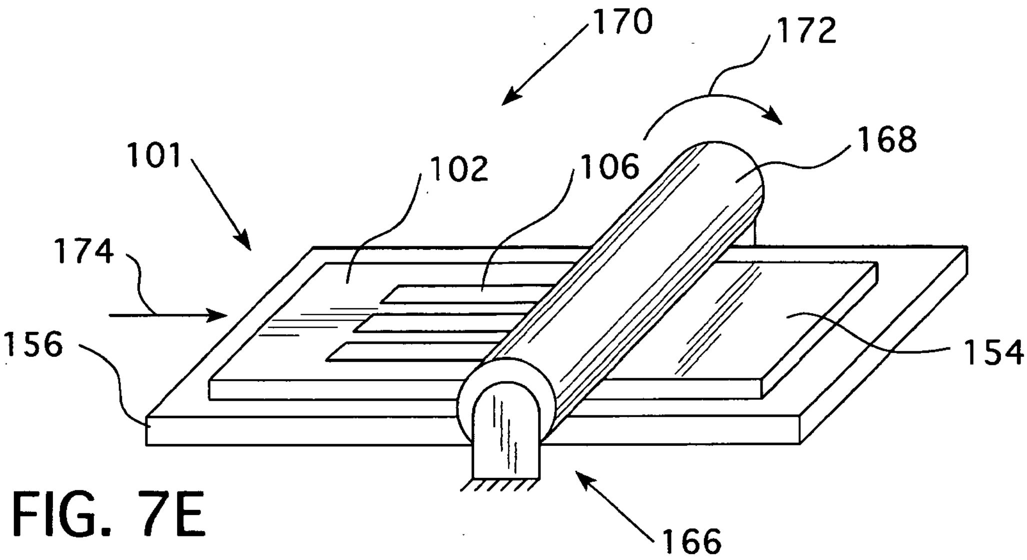

170
172
168
101
102
106
174
156
154
166

FIG. 7E

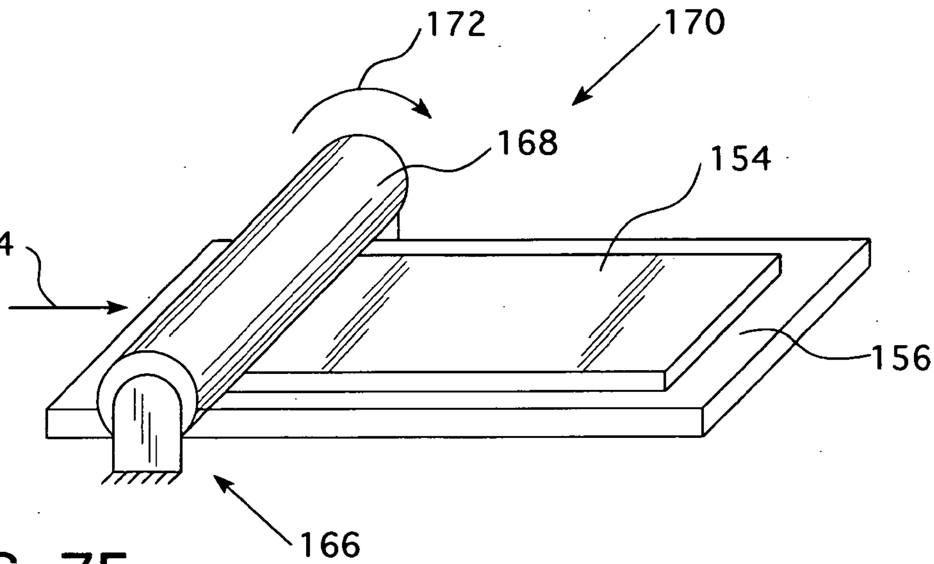

172
170
168
154
174
156
166

FIG. 7F

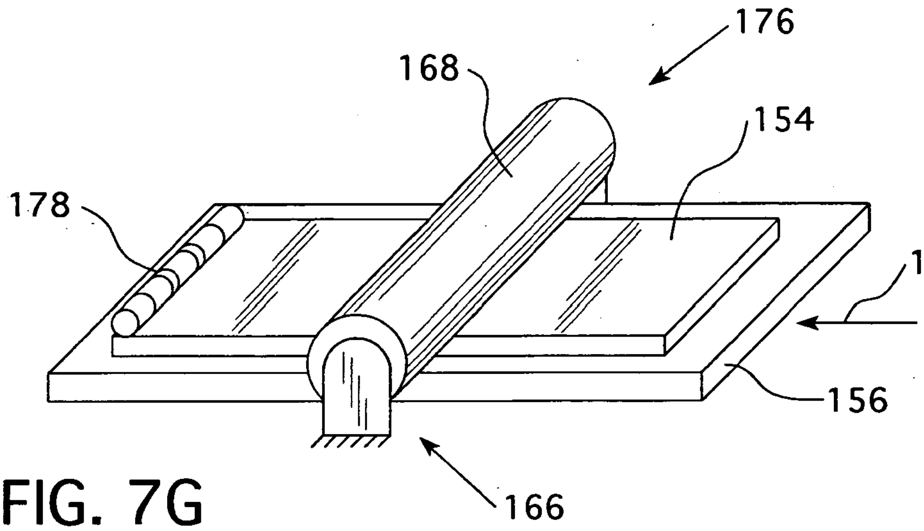


FIG. 7G

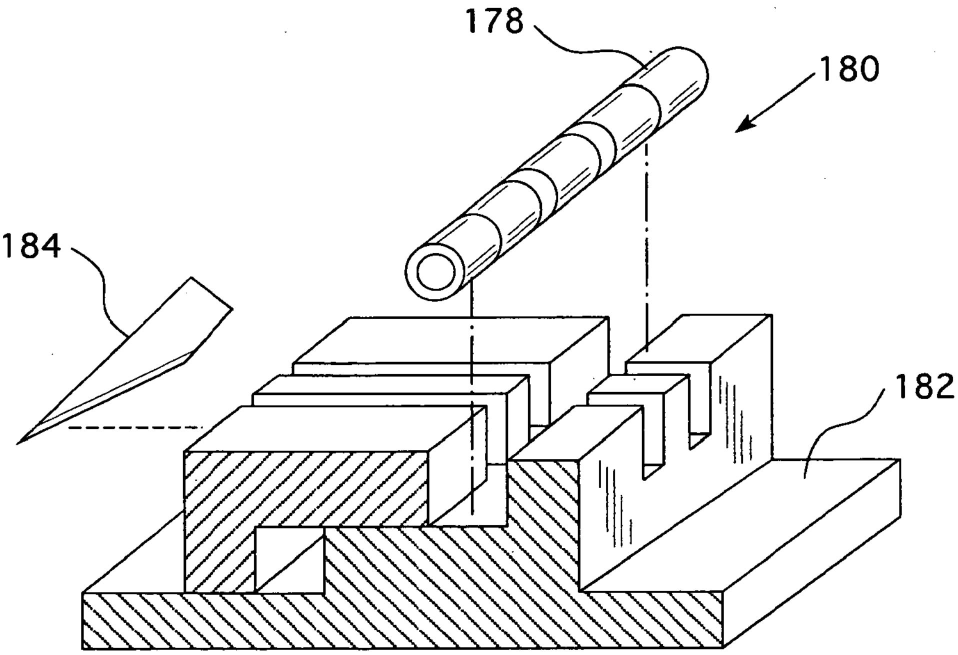


FIG. 7H

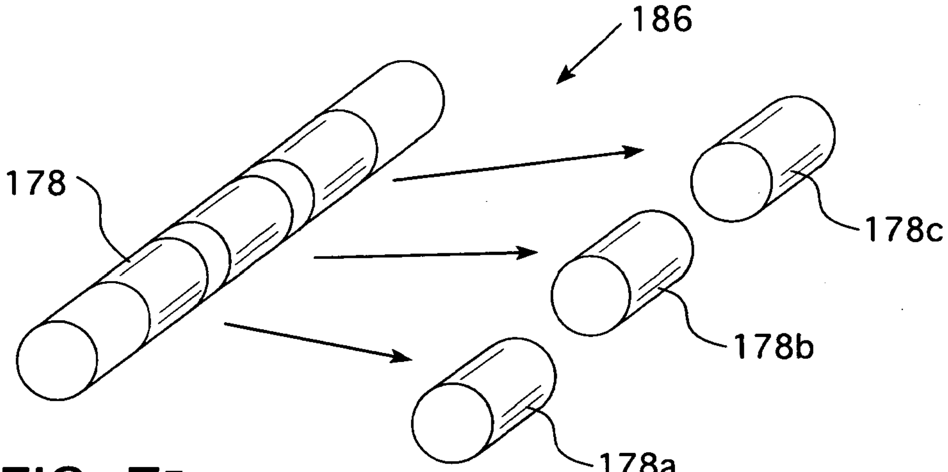


FIG. 7I

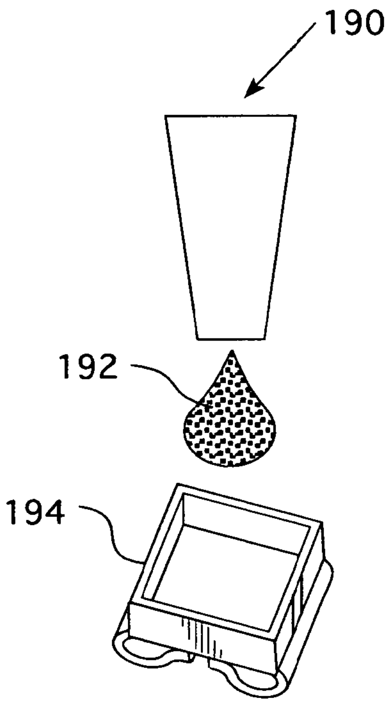


FIG. 7J

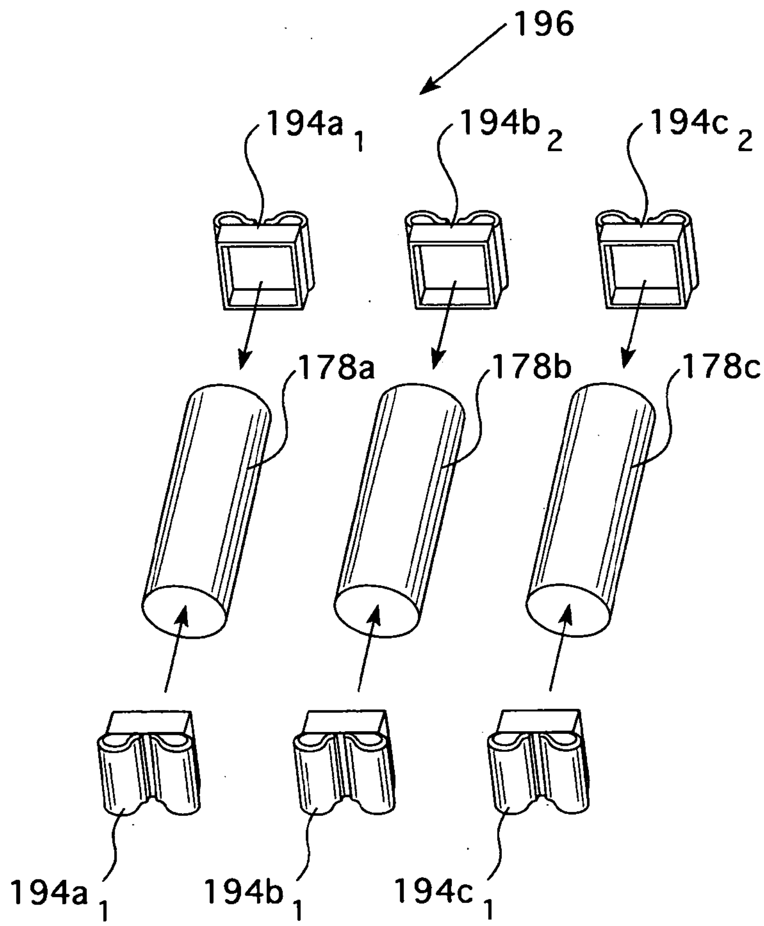


FIG. 7K

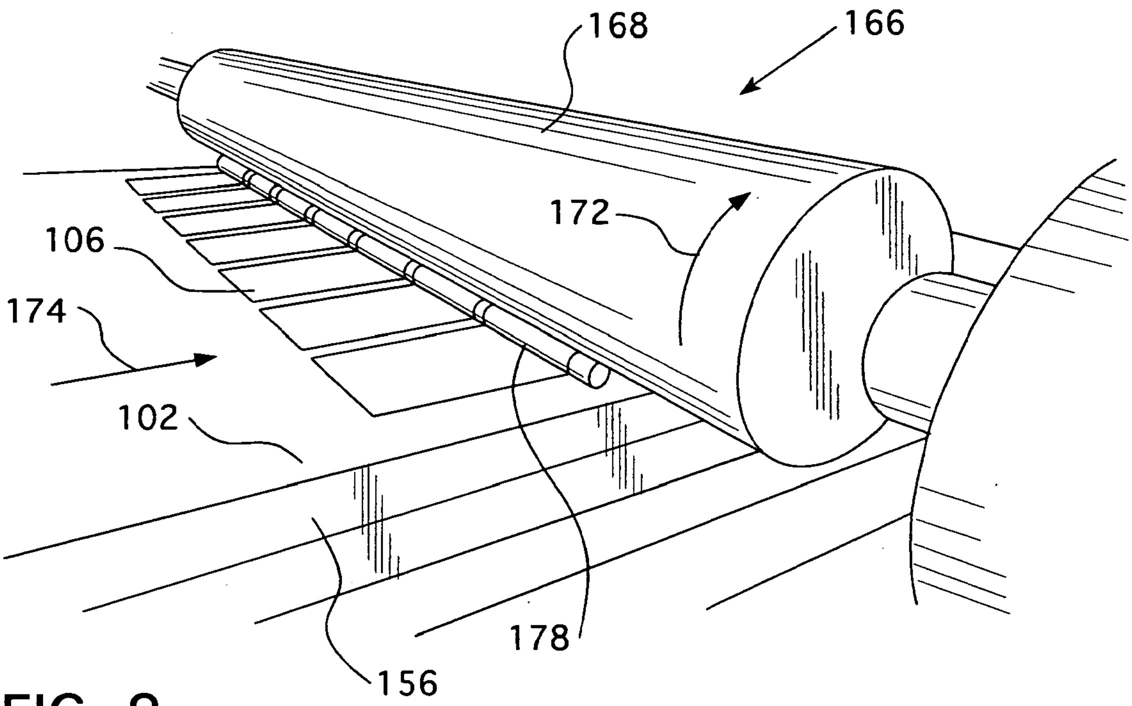

168
166
172
106
174
102
178
156

FIG. 8

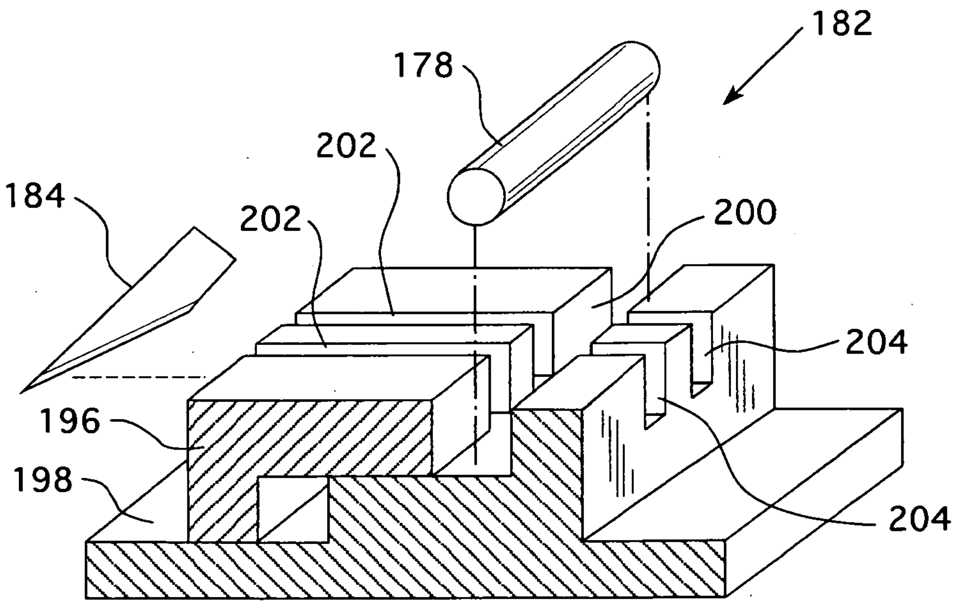

182
178
202
184
202
200
204
196
198
204

FIG. 9

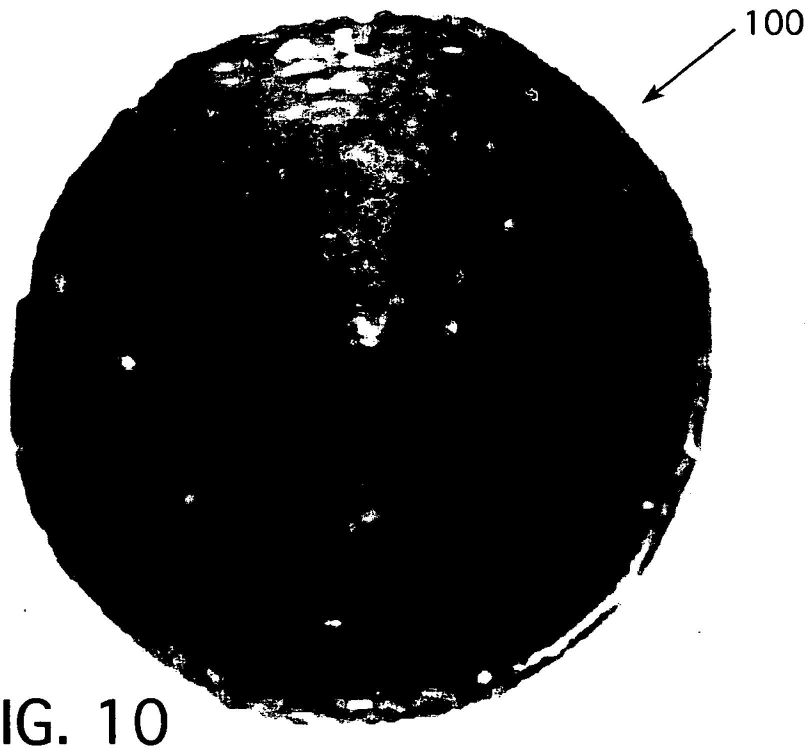


FIG. 10

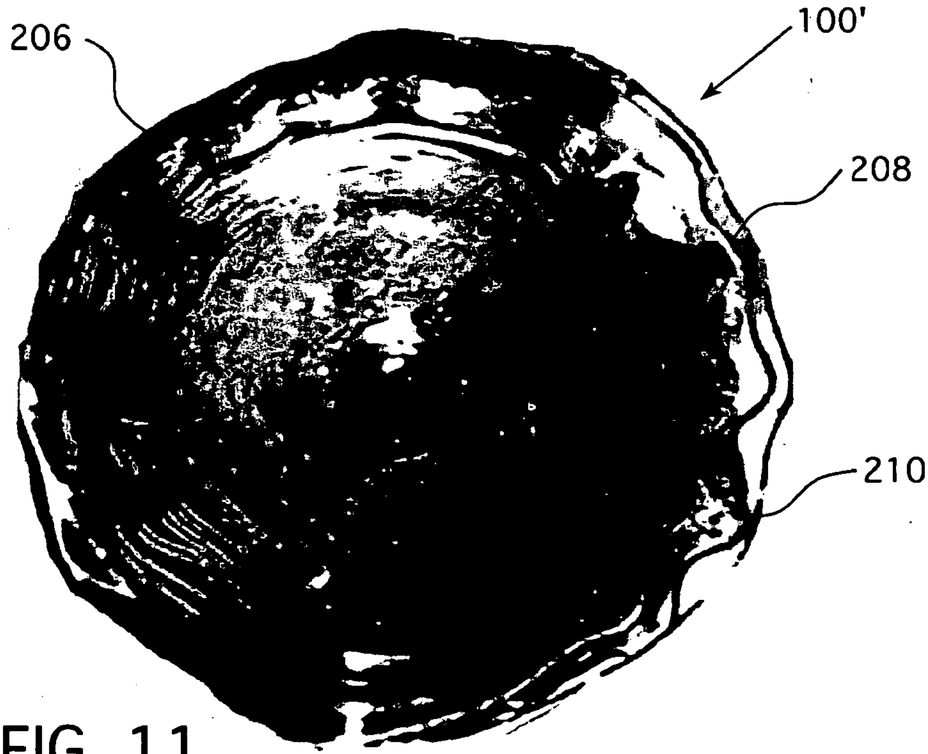


FIG. 11

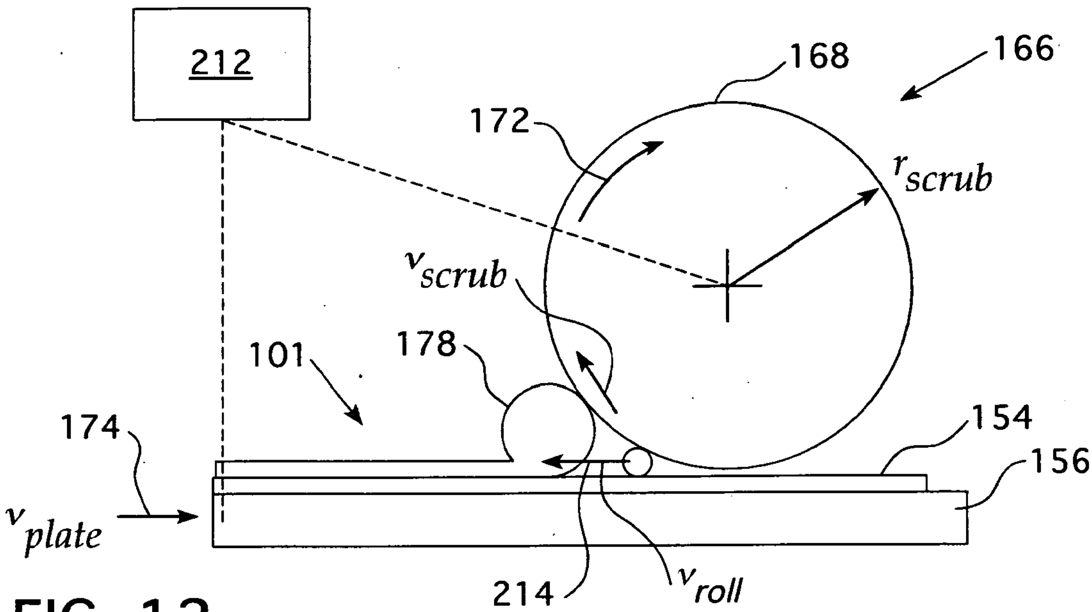

212
168
166
172
r_{scrub}
v_{scrub}
101
178
174
154
156
v_{plate}
214
v_{roll}

FIG. 12

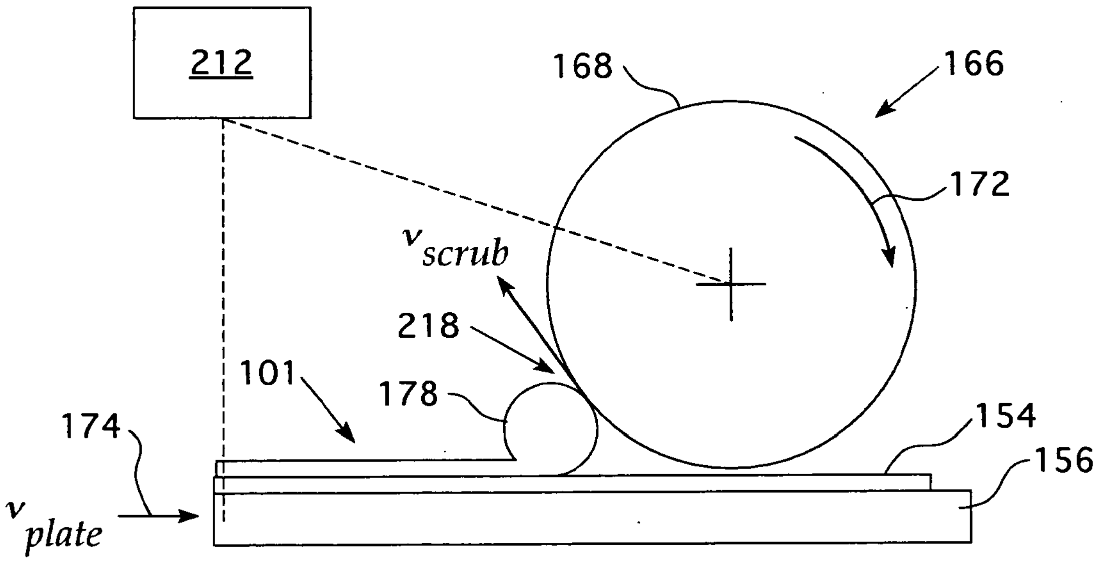

212
168
166
172
v_{scrub}
218
101
178
174
154
156
v_{plate}

FIG. 13

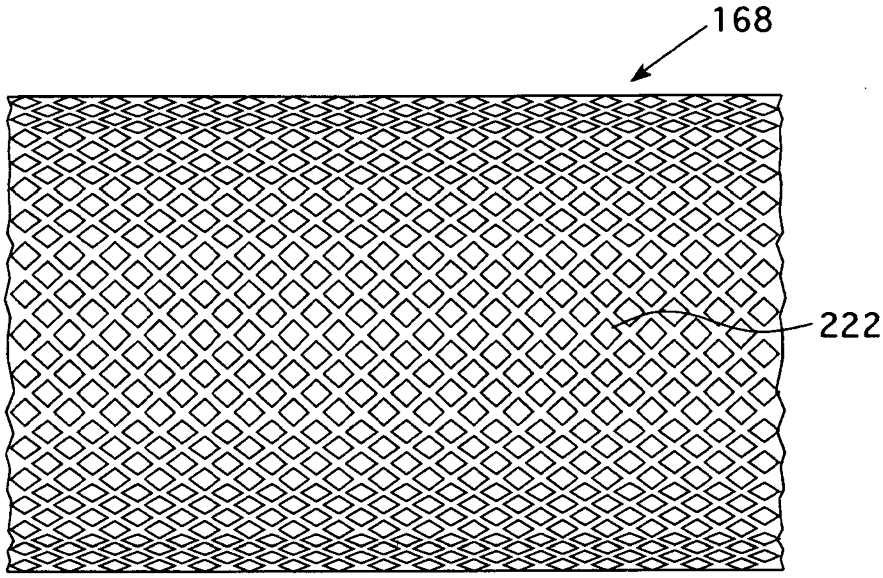


FIG. 14

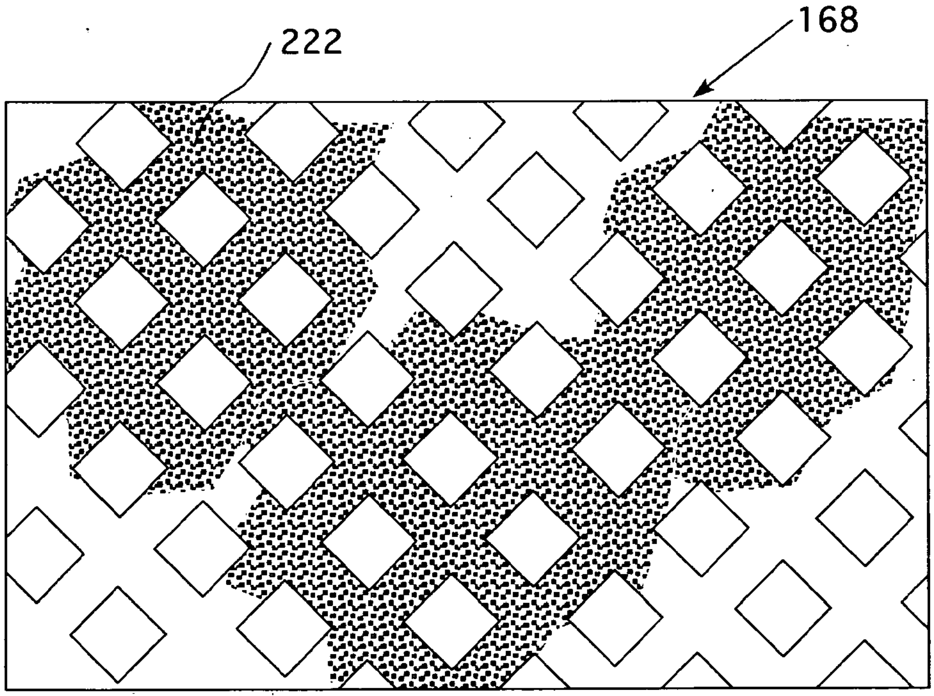


FIG. 15

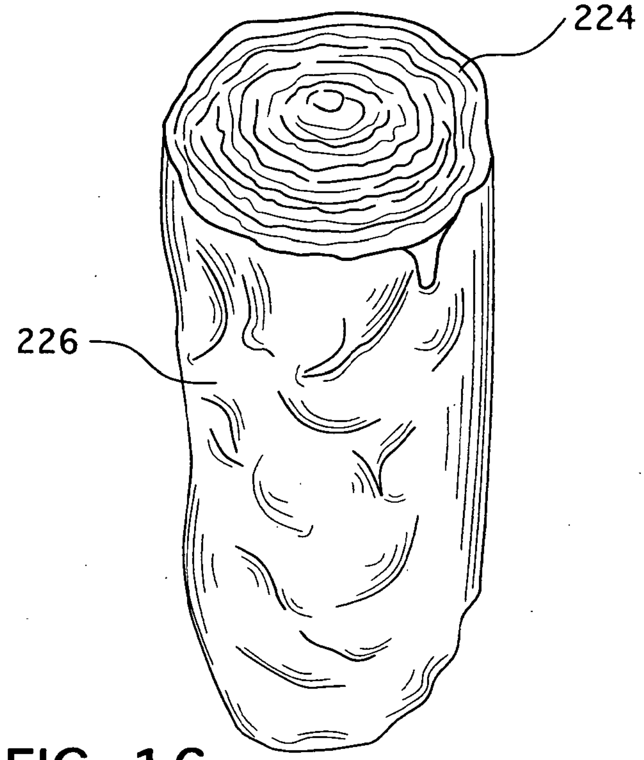

224
226

FIG. 16

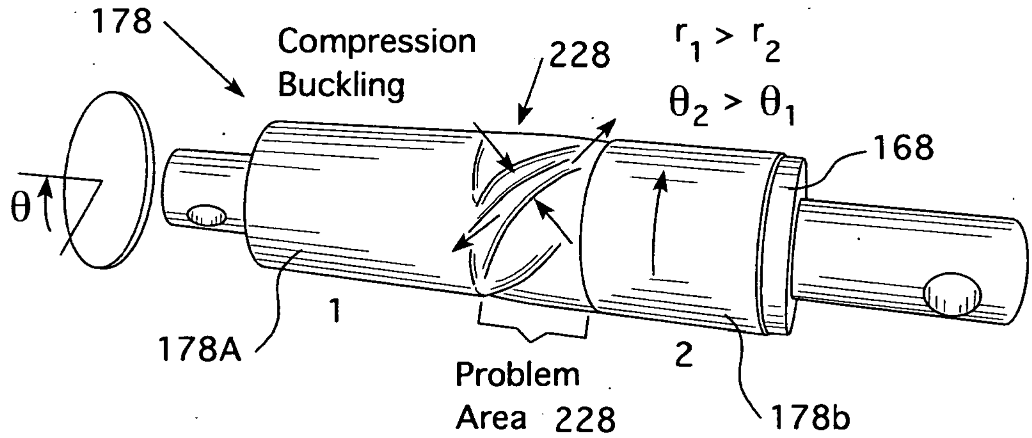

178
Compression
Buckling
228
r1 > r2
θ2 > θ1
168
θ
178A
1
Problem
Area 228
2
178b

FIG. 17

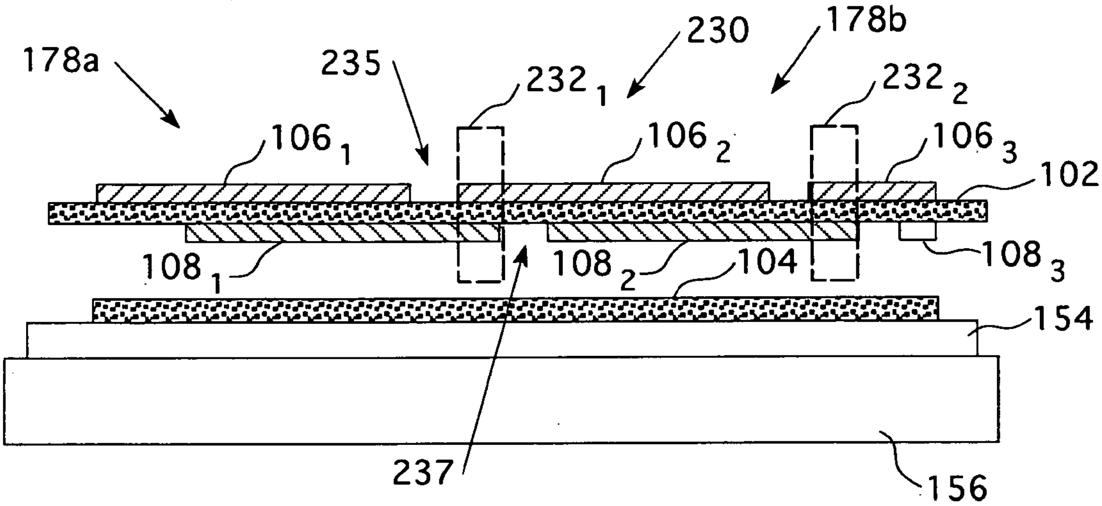

178a
235
232 1
230
178b
232 2
106 1
106 2
106 3
102
108 1
108 2
104
108 3
154
237
156

FIG. 18

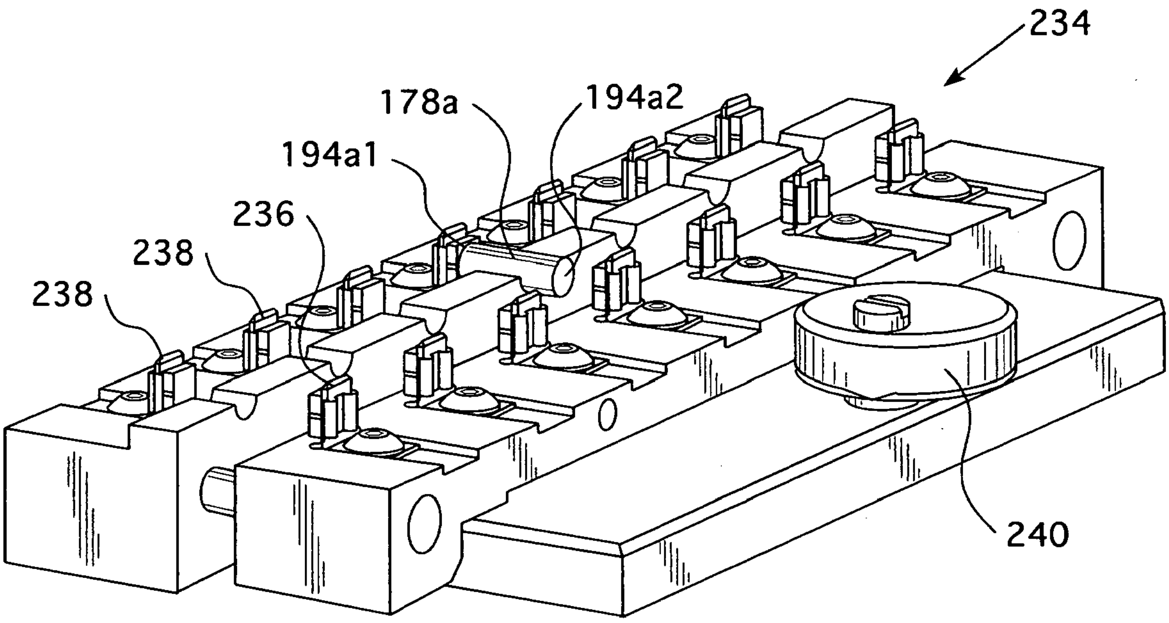

234
178a
194a2
194a1
236
238
238
240

FIG. 19

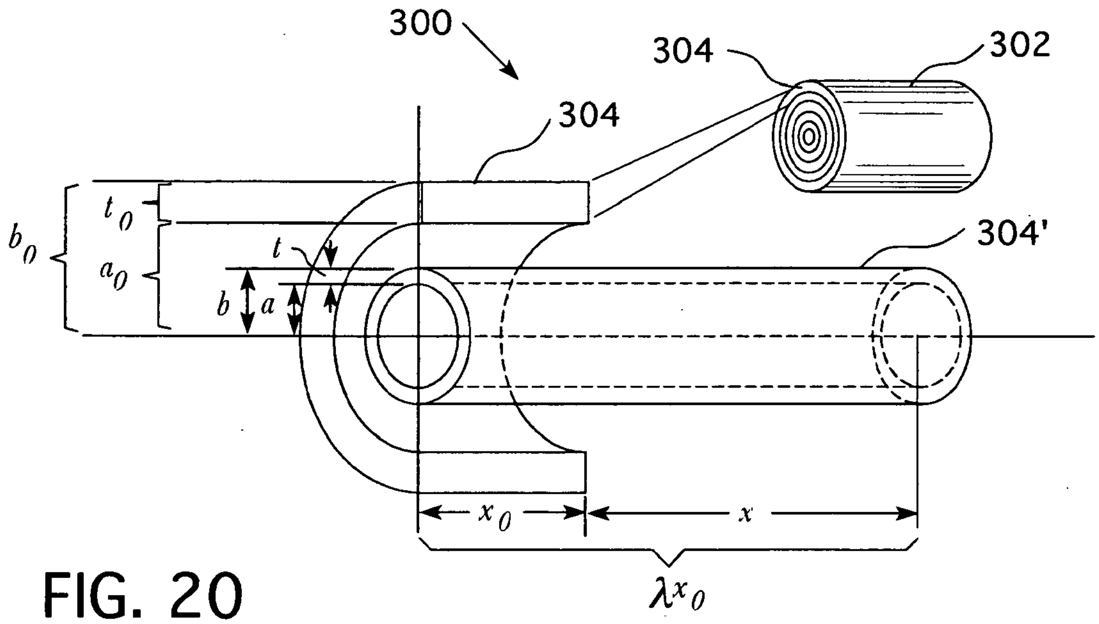

300
304
302
304
304'
t_0
b_0
a_0
t
b
a
x_0
x
λx_0

FIG. 20

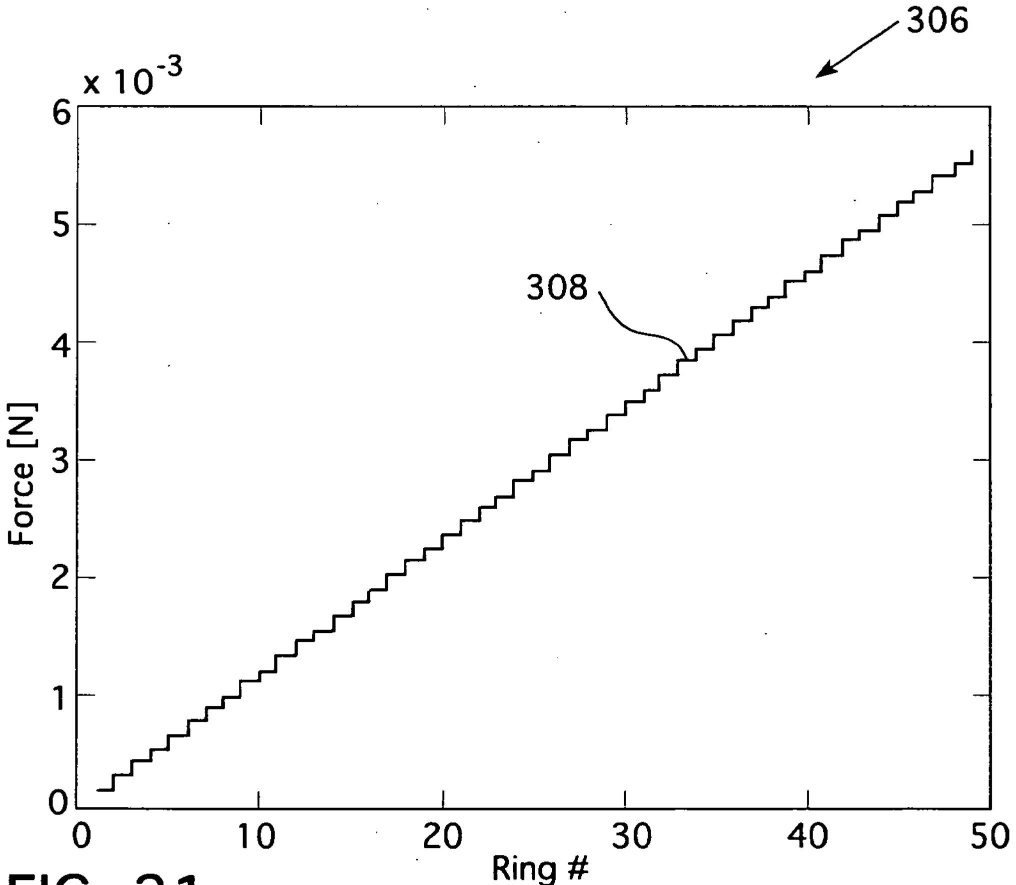

306
x 10^-3
308
Force [N]
Ring #
0
1
2
3
4
5
6
0
10
20
30
40
50

FIG. 21

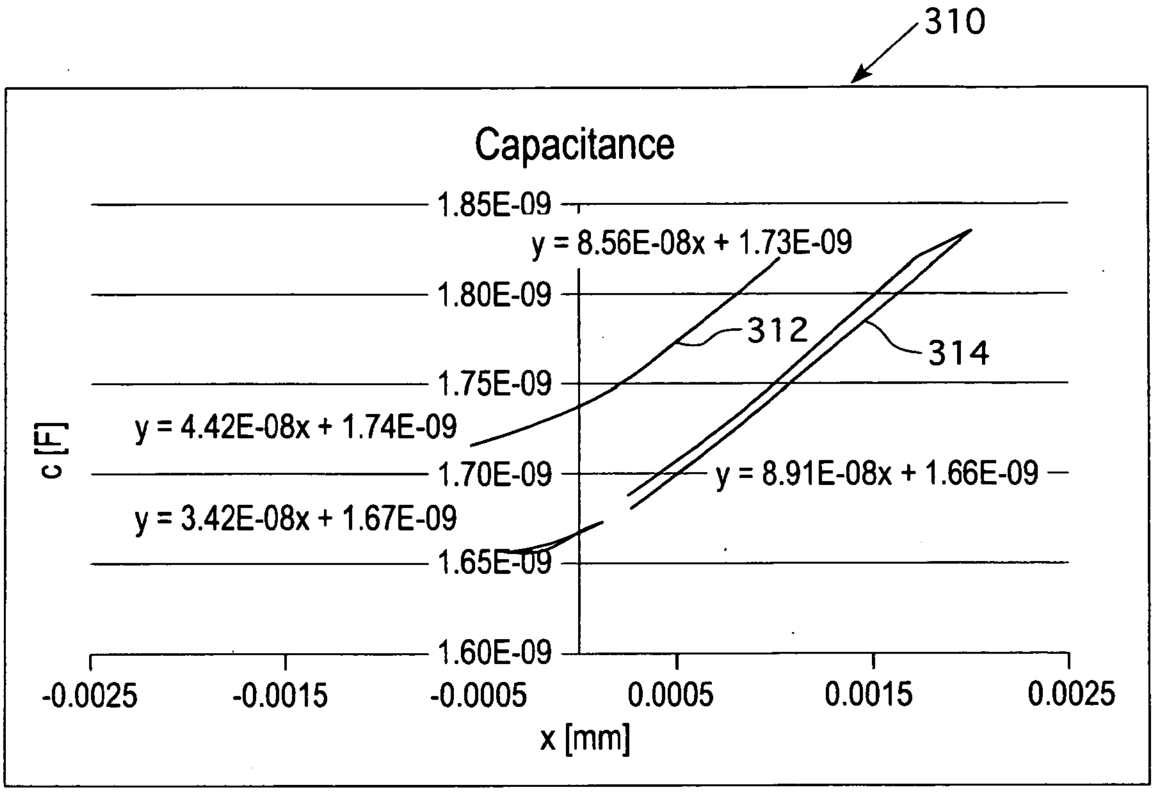

310
Capacitance
1.85E-09
y = 8.56E-08x + 1.73E-09
1.80E-09
312
314
1.75E-09
y = 4.42E-08x + 1.74E-09
c [F]
1.70E-09
y = 8.91E-08x + 1.66E-09
y = 3.42E-08x + 1.67E-09
1.65E-09
1.60E-09
-0.0025
-0.0015
-0.0005
0.0005
0.0015
0.0025
x [mm]

FIG. 22

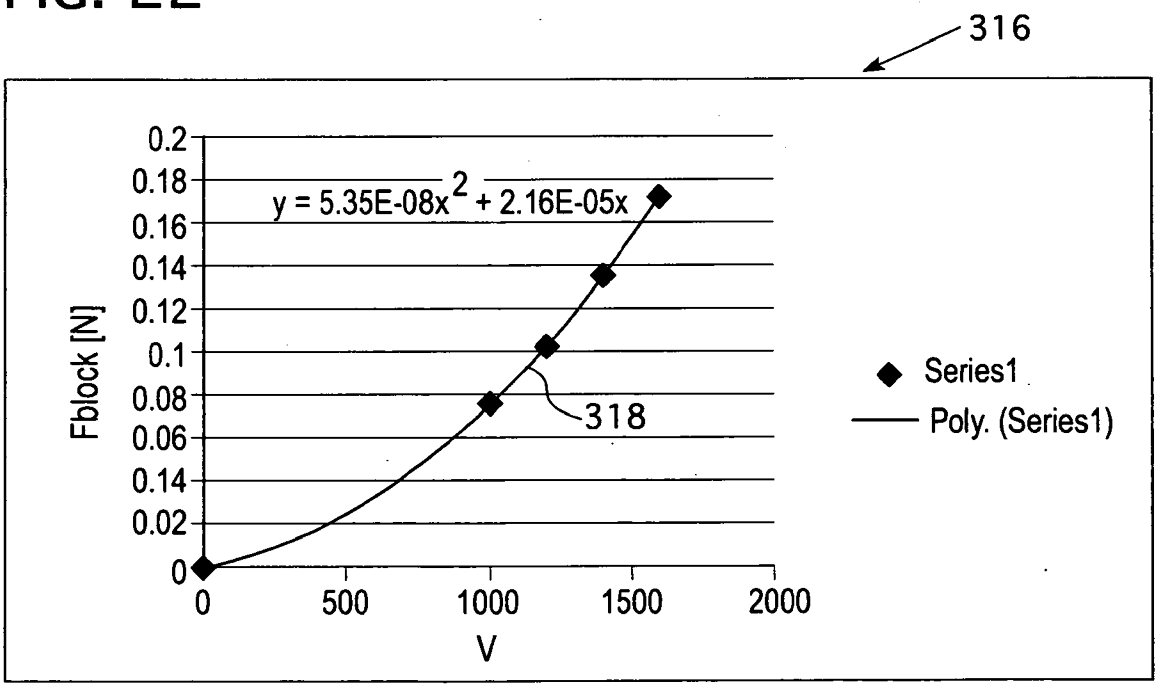

316
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.14
0.02
0
y = 5.35E-08x2 + 2.16E-05x
Fblock [N]
318
Series1
Poly. (Series1)
0
500
1000
1500
2000
V

FIG. 23

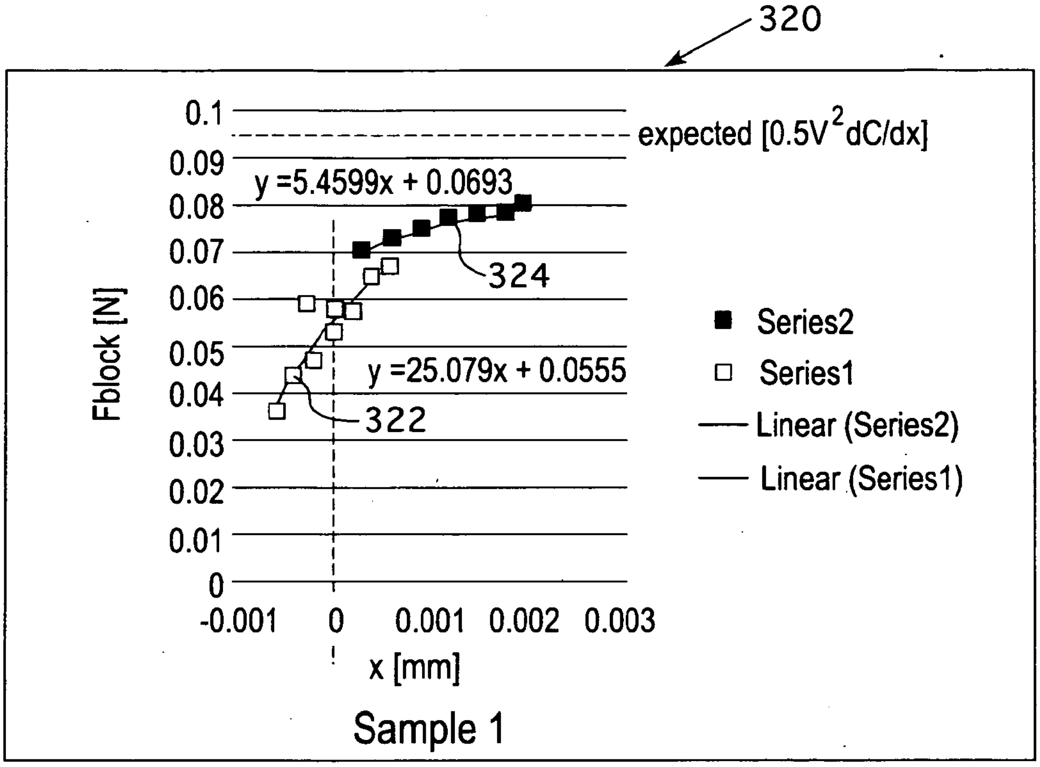

320
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
expected [0.5V²dC/dx]
y =5.4599x + 0.0693
324
y =25.079x + 0.0555
322
Fblock [N]
-0.001
0
0.001
0.002
0.003
x [mm]
Series2
Series1
Linear (Series2)
Linear (Series1)
Sample 1

FIG. 24

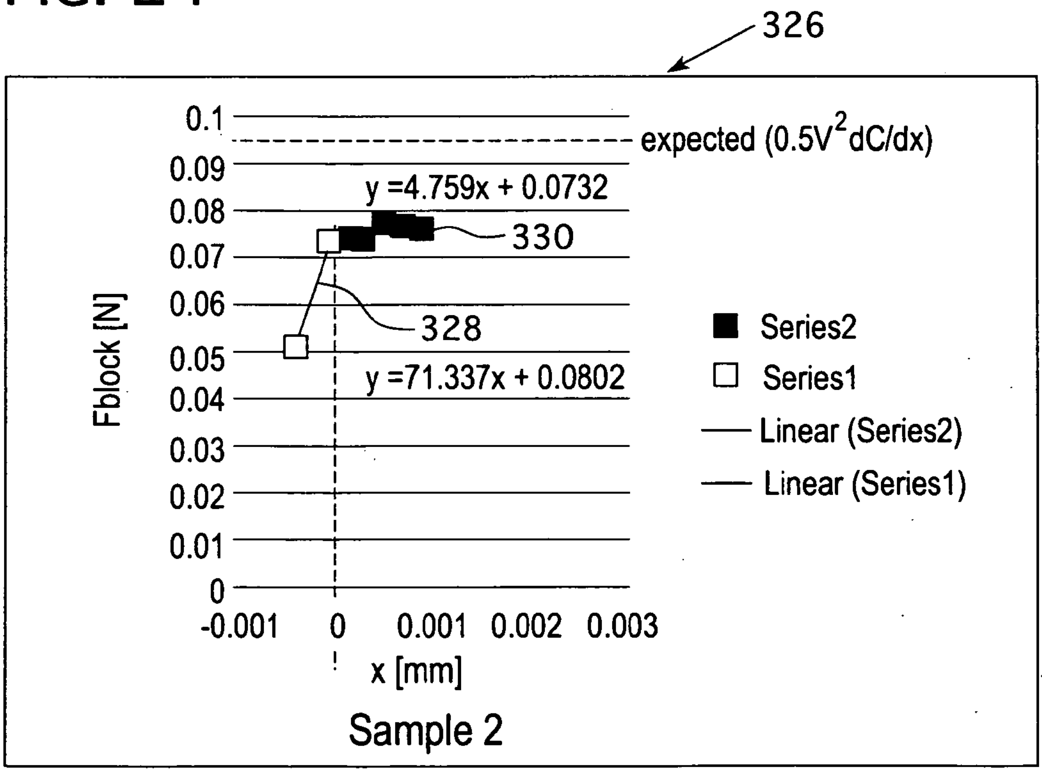

326
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
expected (0.5V²dC/dx)
y =4.759x + 0.0732
330
328
y =71.337x + 0.0802
Fblock [N]
-0.001
0
0.001
0.002
0.003
x [mm]
Series2
Series1
Linear (Series2)
Linear (Series1)
Sample 2

FIG. 25

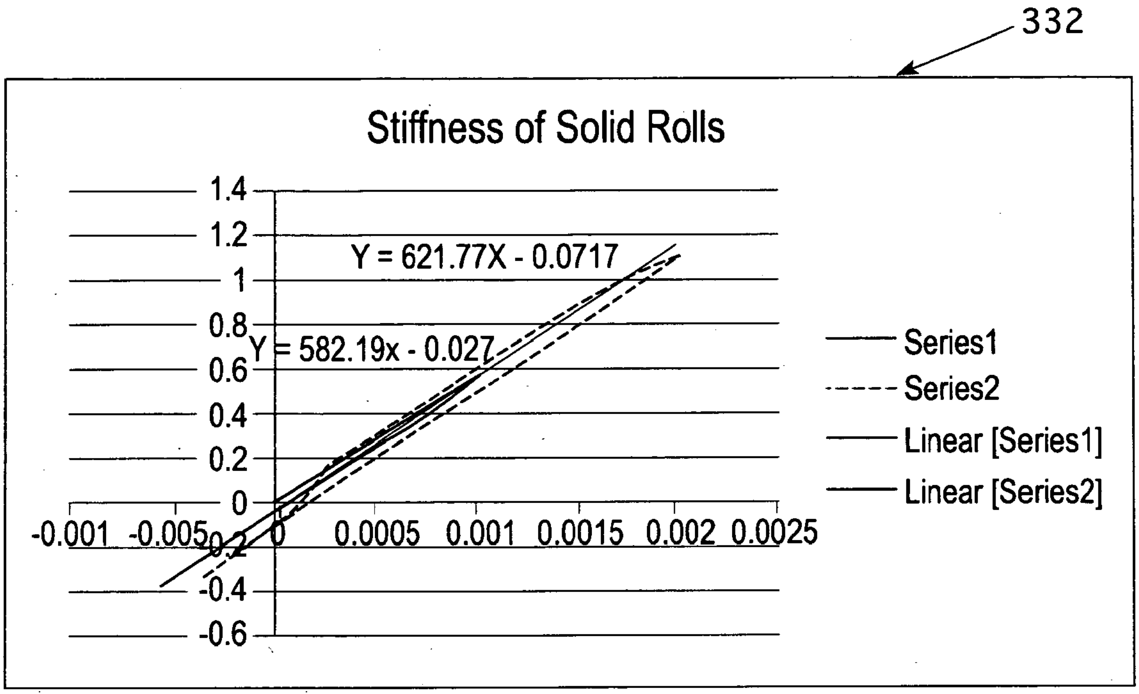

332
Stiffness of Solid Rolls
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.001
-0.005
0
0.0005
0.001
0.0015
0.002
0.0025
Y = 621.77X - 0.0717
Y = 582.19x - 0.027
Series1
Series2
Linear [Series1]
Linear [Series2]

FIG. 26

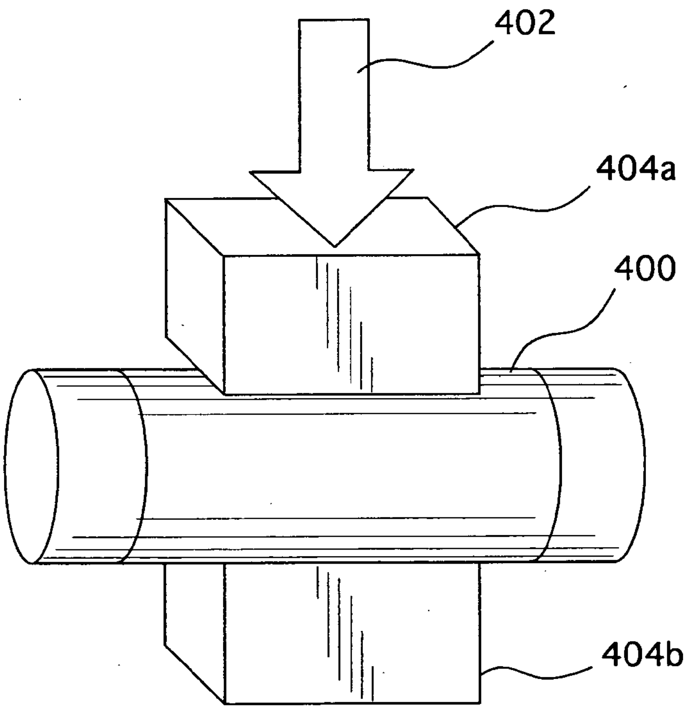

402
404a
400
404b

FIG. 27

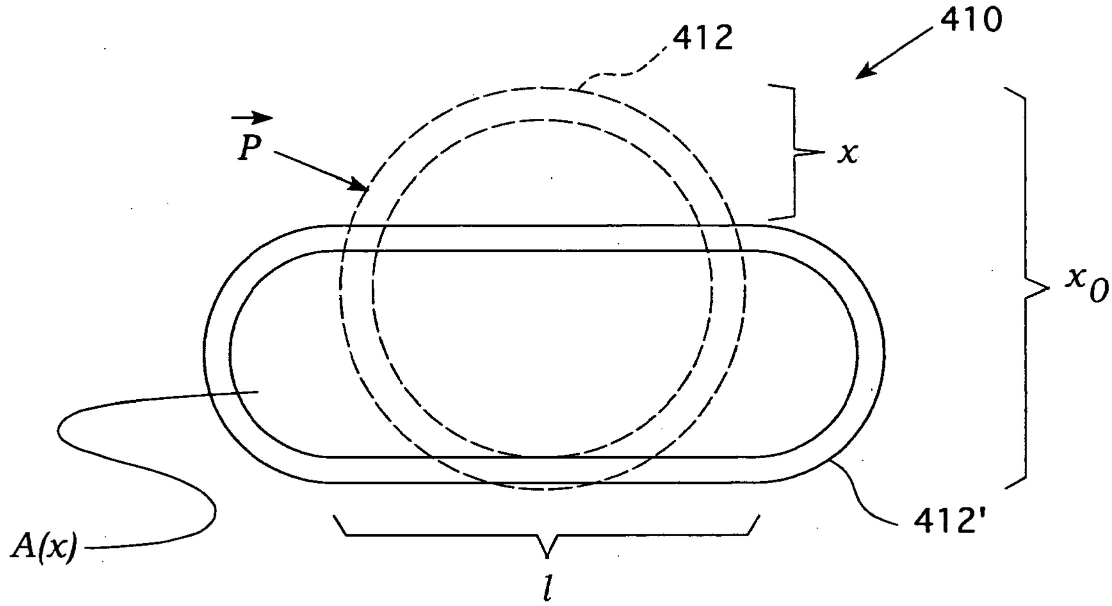

412
410
P
x
x0
A(x)
412'
l

FIG. 28

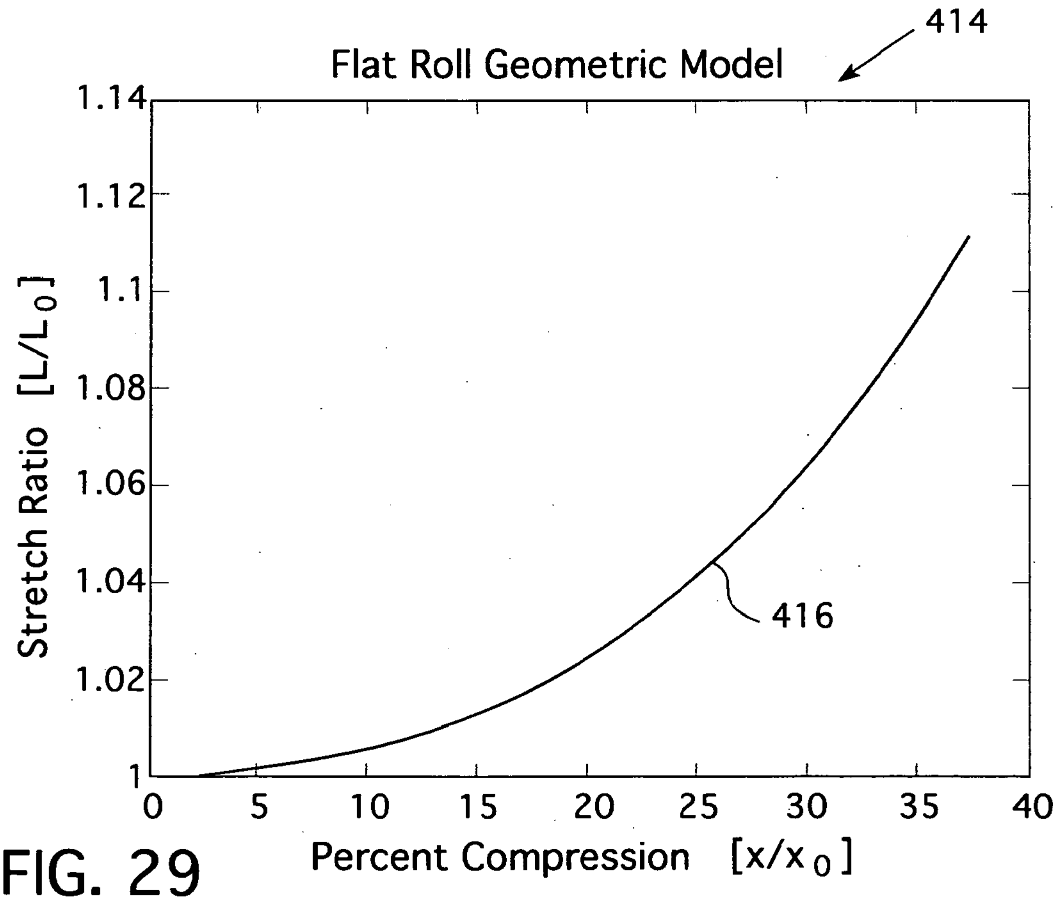

414
Flat Roll Geometric Model
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1
Stretch Ratio [L/L0]
0
5
10
15
20
25
30
35
40
Percent Compression [x/x0]
416

FIG. 29

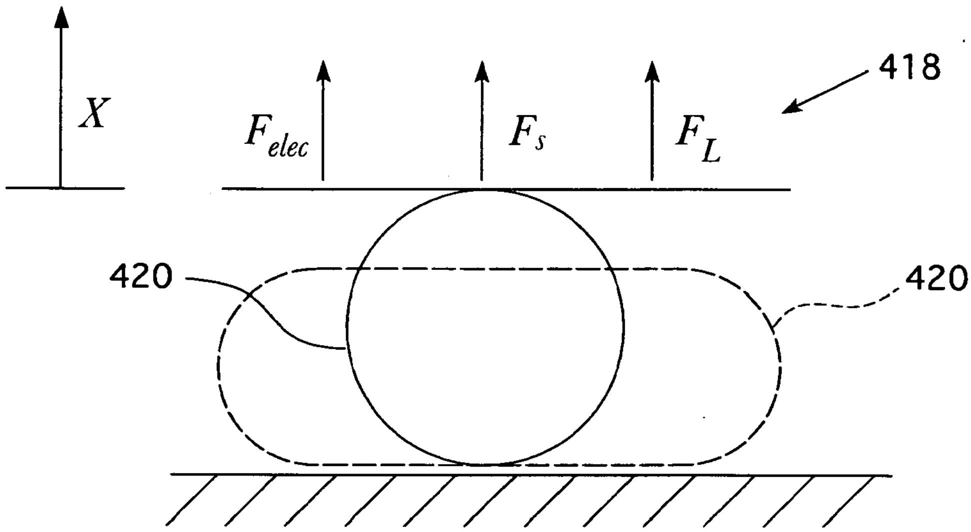

X
F_{elec}
F_s
F_L
418
420
420'

FIG. 30

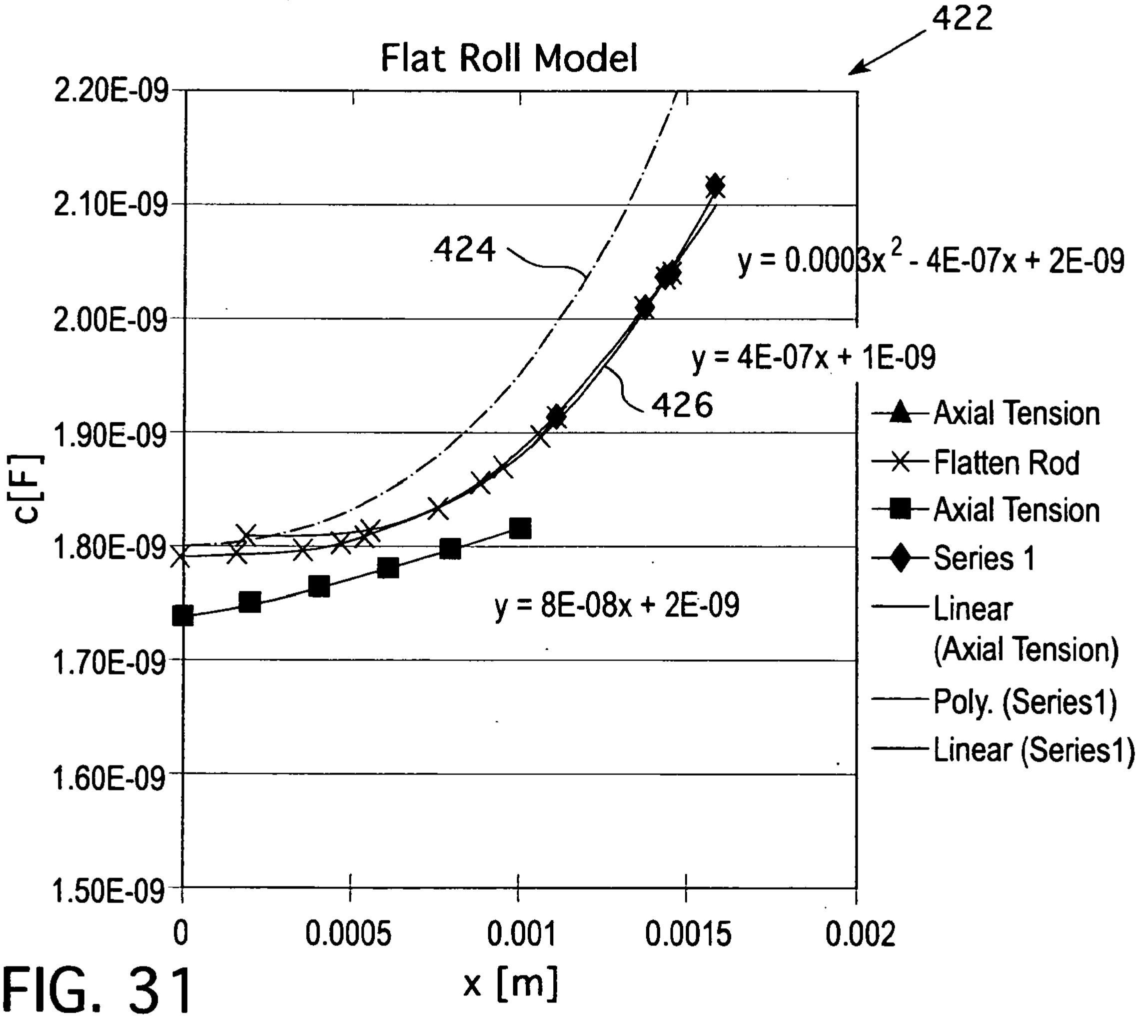

422
Flat Roll Model
2.20E-09
2.10E-09
2.00E-09
1.90E-09
1.80E-09
1.70E-09
1.60E-09
1.50E-09
c[F]
424
y = 0.0003x² - 4E-07x + 2E-09
y = 4E-07x + 1E-09
426
y = 8E-08x + 2E-09
Axial Tension
Flatten Rod
Axial Tension
Series 1
Linear (Axial Tension)
Poly. (Series1)
Linear (Series1)
0
0.0005
0.001
0.0015
0.002
x [m]

FIG. 31

REPLACEMENT FIGURES

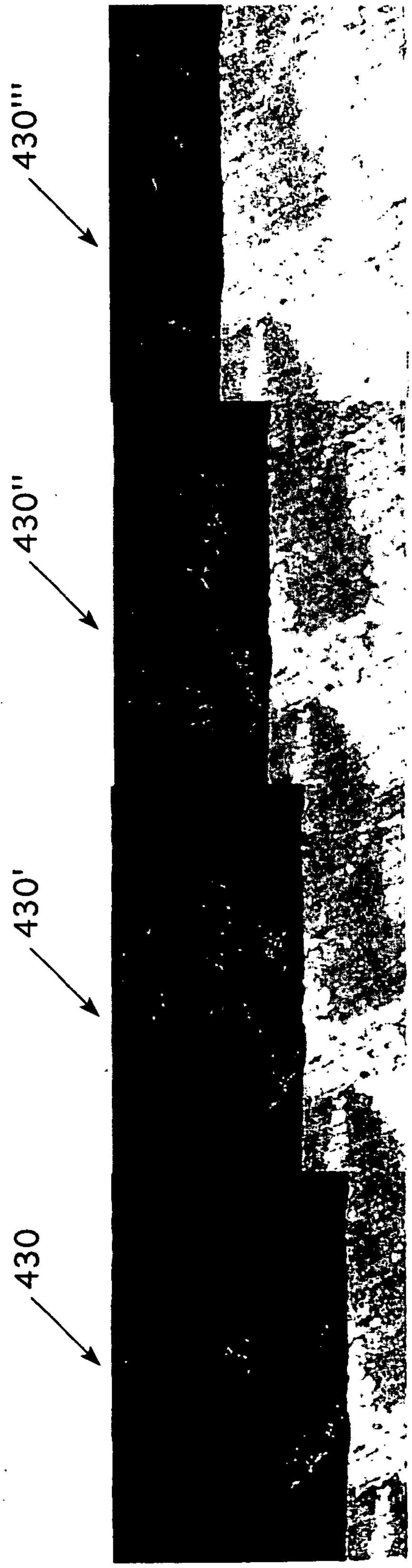


FIG. 32A FIG. 32B FIG. 32C FIG. 32D

REPLACEMENT FIGURES

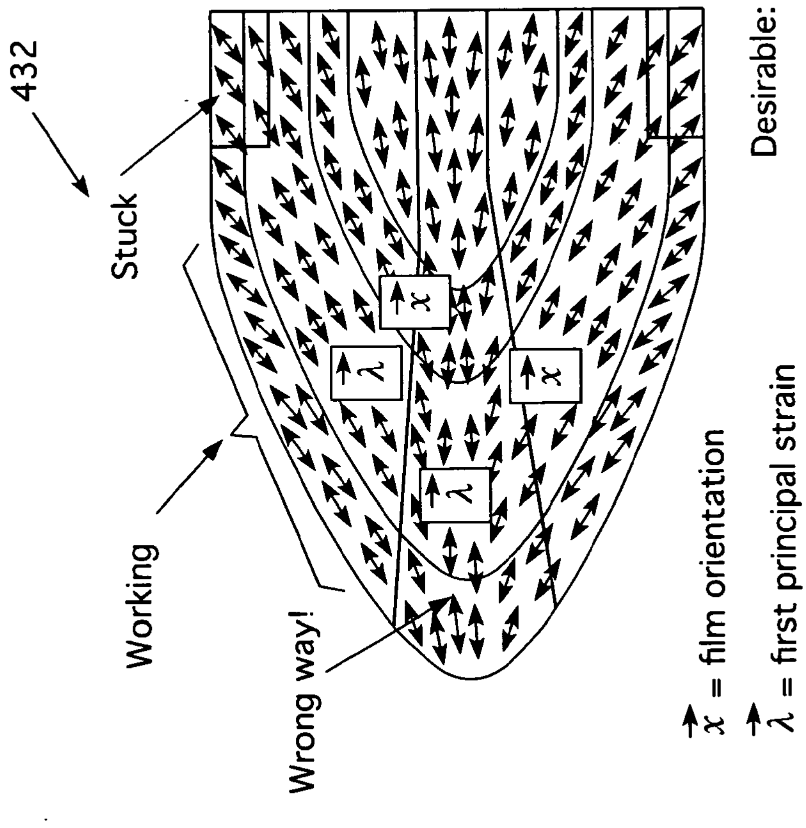


FIG. 33

Desirable: $\text{abs}\left(\left(\frac{\vec{\lambda}}{\|\vec{\lambda}\|}\right)\cdot\vec{x}\right) = 1$, everywhere

FIG. 34

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/055299

A. CLASSIFICATION OF SUBJECT MATTER

H02N 2/04(2006.01)i, H02N 2/02(2006.01)i, H02N 2/00(2006.01)i

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)
H02N 2/04; H01L 41/04; H01L 41/047; H01L 29/82; G10H 3/14; B29C 51/02; H01L 41/053; H01L 41/00; H01L 21/00; H02N 2/02; H02N 2/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: roll, dielectric elastomer transducer, film, laminate, carrier plate

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2007-0114885 A1 (MOPHAMED YAHIA BENSLIMANE et al.) 24 May 2007 See abstract, paragraphs [0060]-[0071],[0120],[0133],[0151], claims 1,44, and figures 2a-3b,5a-12b.	1-3
A		4-5,8-15
Y	US 2011-0198971 A1 (MICHAEL TRYSON et al.) 18 August 2011 See abstract, paragraphs [0042],[0046]-[0048], claims 1,6,16,19, and figures 1-7.	1-3
A		4-5,8-15
A	US 2011-0025170 A1 (MARCUS A. ROSENTHAL et al.) 03 February 2011 See paragraphs [0041]-[0043], claims 1,7, and figures 1A-3D.	1-5,8-15
A	US 2006-0186493 A1 (TAKASHI NAKAMURA) 24 August 2006 See abstract, paragraphs [0026]-[0031], claims 1,5, and figure 1.	1-5,8-15
A	US 2004-0159224 A1 (HEIKKI EERO RAISANEN) 19 August 2004 See paragraphs [0030]-[0033] and claims 1-3.	1-5,8-15

☐ 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
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of 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
27 November 2013 (27.11.2013)	**27 November 2013 (27.11.2013)**

Name and mailing address of the ISA/KR
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon Metropolitan City, 302-701, Republic of Korea
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/055299

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

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

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 7
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
Claim 7 is too broad to make a meaningful search because it is a dependent claim of multiple dependent claim which also refers to other multiple dependent claim.

3. ☒ Claims Nos.: 6
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

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

1. ☐ As all required addtional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2013/055299

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Information on patent family members

International application No.

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