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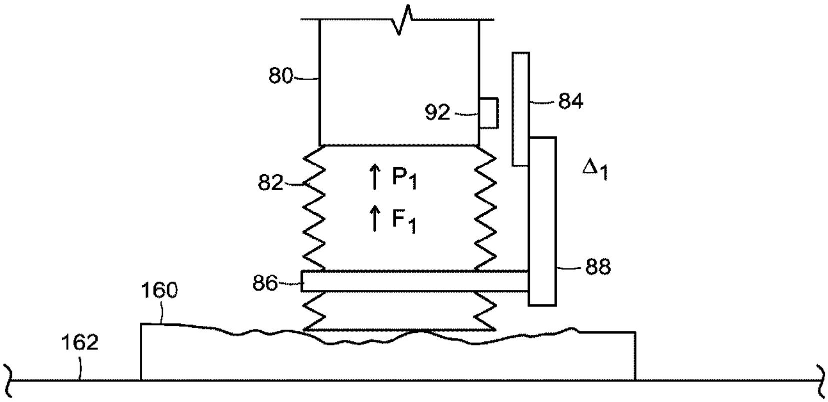

(57) Abrégé/Abstract:
A system is disclosed for providing high flow vacuum control to an end effector of an articulated arm. The system includes a high flow vacuum source that provides an opening with an area of high flow vacuum at the end effector such that objects may be

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engaged while permitting substantial flow of air through the opening, and a load detection system for characterizing the load presented by the object.

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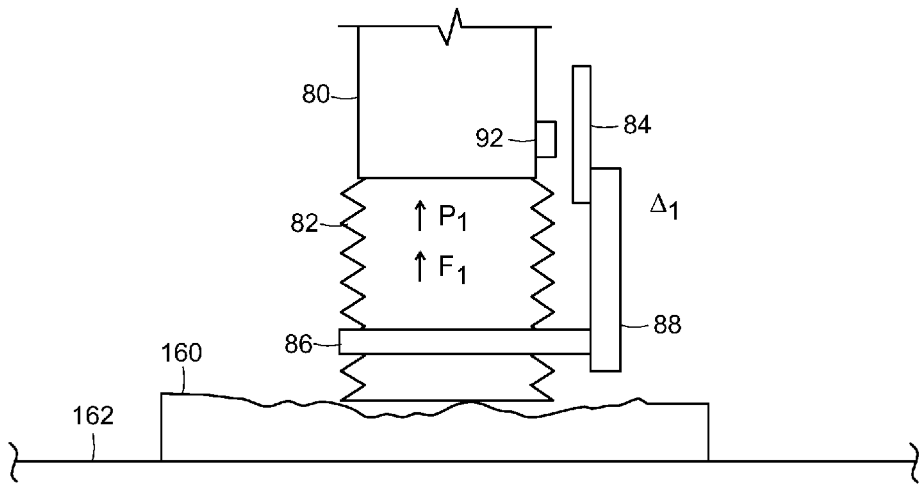

FIG. 8A

(57) Abstract: A system is disclosed for providing high flow vacuum control to an end effector of an articulated arm. The system includes a high flow vacuum source that provides an opening with an area of high flow vacuum at the end effector such that objects may be engaged while permitting substantial flow of air through the opening, and a load detection system for characterizing the load presented by the object.

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SYSTEMS AND METHODS FOR PROVIDING HIGH FLOW VACUUM ACQUISITION IN AUTOMATED SYSTEMS

BACKGROUND

The invention generally relates to robotic and other sortation systems, and relates in particular to robotic systems having an articulated arm with an end effector that employs vacuum pressure to engage objects in the environment.

Most vacuum grippers employ vacuum pressures well below 50% of atmospheric pressure, and are referred to herein as *high vacuum*. A typical source for a high vacuum gripper is a Venturi ejector, which produces high vacuum but low maximum air flow. Because of the low flow, it is essential to get a good seal between a vacuum gripper and an object, and it is also important to minimize the volume to be evacuated.

Suppliers of ejectors and related system components include Vaccon Company, Inc. of Medway, MA, Festo US Corporation of Hauppauge, NY, Schmalz, Inc. of Raleigh, NC and others. In some instances where a good seal is not possible, some systems use high flow devices. Typical high flow devices are air amplifiers and blowers, which produce the desired flows, but cannot produce the high vacuum of a high vacuum source. High flow sources include the side-channel blowers supplied by Elmo Rietschle of Gardner, Denver, Inc. of Quincy, IL, Fuji Electric Corporation of America of Edison, NJ, and Schmalz, Inc. of Raleigh, NC. It is also possible to use air amplifiers as supplied by EDCO USA of Fenton, MO and EXAIR Corporation of Cincinnati, OH. Multistage ejectors are also known to be used to evacuate a large volume more quickly, wherein each stage provides higher levels of flow but lower levels of vacuum.

Despite the variety of vacuum systems, however, there remains a need for an end effector in a robotic or other sortation system that is able to accommodate a wide variety of applications, involving engaging a variety of types of items. There is further a need for an end

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effector that is able to provide high flow and that is able to handle a wide variety of objects weights.

SUMMARY

In an aspect, there is provided a system for providing high flow vacuum control to an end effector of an articulated arm, the system comprising: a cover at a distal end of the end effector, the cover allowing air to flow through one or more openings defined therein; and a high flow vacuum source that provides a vacuum at the end effector such that an object is engaged and lifted while permitting substantial flow of air through the one or more openings; wherein the cover includes a larger amount of opening area near the center of the cover and a smaller amount of opening area near a periphery of the cover, such that the one or more openings allow more air to flow near the center of the cover than near the periphery of the cover.

In another aspect, there is provided an object acquisition system comprising a high flow vacuum source that provides an opening at a distal end of an end effector of a programmable motion device with an area of high flow vacuum such that objects are engaged at the opening while permitting substantial flow of air through the opening; and a load assessment system that assesses the load responsive to the flow and any of a load weight or load balance, wherein the distal end of the end effector includes a larger amount of opening area near the center of the distal end of the end effector and a smaller amount of opening area near a periphery of the distal end of the end effector, such that the opening provides more air to flow near the center of the opening than near the periphery of the opening.

In another aspect, there is provided a method of engaging a load presented by an object at an end effector in a high flow vacuum system, the method comprising the steps of: providing a high flow vacuum at an opening at a distal end of the end effector; engaging an object at the

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opening while permitting an air flow through the opening; restricting the air flow at a periphery of the opening, while permitting relatively more air flow at a center of the opening by providing a larger amount of opening area near the center of the distal end of the end effector and a smaller amount of opening area near the periphery of the distal end of the end effector; assessing grasp characteristics of the load presented by the object using a load detection device; and increasing the air flow through the opening at the distal end of the end effector based on the grasp characteristics of the load provided by the load detection device.

In another aspect, there is provided a system for providing high flow vacuum control to an end effector of an articulated arm, the system comprising a blower for providing a high flow vacuum source at an opening having a center at a distal side of the end effector, with an area of high flow vacuum at the end effector such that an object is engageable at the opening for movement by the articulated arm while permitting substantial flow of air through the opening, wherein the opening is provided by a single contiguous opening that includes elongated open areas extending radially from the center of the opening, and wherein the end effector includes no other openings at the distal side thereof, wherein the single contiguous opening has a larger amount of opening area near the center of the distal side of the end effector and a smaller amount of opening area near a periphery of the distal end of the end effector, such that the single contiguous opening provides more air to flow near the center of the distal side of the end effector than near the periphery of the distal side of the end effector.

In another aspect, there is provided an object acquisition system comprising a high flow vacuum source including a blower that provides a high flow vacuum through an opening having a center at a distal end of an end effector of a programmable motion device, wherein the end effector includes a cover having a compliant distally facing foam material, the opening passing through the

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foam material such that an object is engageable at the opening without passing through the opening while permitting substantial flow of air through the opening that assists in maintaining the object against the opening for movement by the end effector, wherein the opening is provided as a single contiguous opening of the end effector that includes radially extending open areas that extend radially from the center of the opening toward a periphery of the opening, wherein the single contiguous opening has a larger amount of opening area near the center of the cover and a smaller amount of opening area near a periphery of the cover, such that the single contiguous opening allows more air to flow near the center of the cover than near the periphery of the cover.

In another aspect, there is provided a method of engaging and moving a load presented by an object at an end effector in a high flow vacuum system, the method comprising the steps of: providing a high flow vacuum using a blower, the high flow vacuum being provided at an opening at a distal end of the end effector; engaging the object at the opening while permitting substantial flow of air through the opening, wherein the opening is provided by a single contiguous opening of the end effector of an articulated arm that includes elongated areas extending radially from the center of the opening, wherein the single contiguous opening has a larger amount of opening area near the center of the distal side of the end effector and a smaller amount of opening area near a periphery of the distal end of the end effector, such that the single contiguous opening provides more air to flow near the center of the distal side of the end effector than near the periphery of the distal side of the end effector; and moving the engaged object using the end effector.

In another aspect, there is provided a method of engaging and moving a load presented by an object at an end effector of an articulated arm in a high flow vacuum system, the method comprising the steps of: providing a high flow vacuum using a blower, the high flow vacuum being provided at all of plural openings at a contact surface of the end effector, the end effector including

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a flexible bellows and including a central region of the contact surface; engaging the object at the contact surface while permitting substantial flow of air through all of the openings, the substantial flow of air being greater at the central region of the contact surface than at regions more radially peripheral to the central region of the contact surface; lifting the engaged object using the end effector while permitting substantial flow of air through all of the openings and while permitting flexing of the bellows in any of three mutually orthogonal directions; and moving the engaged object using the end effector and the articulated arm.

In another aspect, there is provided a system for providing high flow vacuum control to an end effector of an articulated arm, the system comprising a high flow vacuum source that provides a high flow vacuum at a contact surface at a distal side of the end effector such that an object is engageable at the contact surface for movement by the articulated arm while permitting substantial flow of air through the contact surface, wherein the contact surface includes a central region, and wherein the contact surface includes a plurality of openings, the plurality of openings providing more air flow at the central region of the contact surface than at a peripheral region of the contact surface.

In another aspect, there is provided a system for providing high flow vacuum control to an end effector of an articulated arm, the system comprising a high flow vacuum source that provides a high flow vacuum at a contact surface at a distal side of the end effector such that an object is engageable at the contact surface for movement by the articulated arm while permitting substantial flow of air through the contact surface, wherein the contact surface includes a cover with a central region, and wherein the cover includes a plurality of openings, the plurality of openings providing restricted air flow at a peripheral region of the cover as compared to air flow at the central region of the cover by the plurality of openings providing a larger amount of

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opening area at the center region of the cover and a smaller amount of opening area at the peripheral region of the cover.

In another aspect, there is provided a method of engaging and moving a load presented by an object at an end effector in a high flow vacuum system, the method comprising: providing a high flow vacuum at a contact surface of the end effector; engaging the object at the contact surface while permitting substantial flow or air through the contact surface, wherein the contact surface includes a central region, and wherein the contact surface includes a plurality of openings, the plurality of openings providing more air flow at the central region of the contact surface than at a peripheral region of the contact surface; and moving the engaged object using the end effector.

In another aspect, there is provided a method of engaging and moving a load presented by an object at an end effector in a high flow vacuum system, the method comprising: providing a high flow vacuum at a contact surface of the end effector; engaging the object at the contact surface while permitting substantial flow of air through the contact surface, wherein the contact surface includes a cover with a central region, and wherein the cover includes a plurality of openings, the plurality of openings providing restricted flow at a peripheral region of the cover as compared to air flow at the central region of the cover by the plurality of openings providing a larger amount of opening area at the center region of the contact surface and a smaller amount of opening area at the peripheral region of the contact surface; and moving the engaged object using the end effector.

In another aspect, there is provided a system for providing high flow vacuum control to an end effector of an articulated arm, the system comprising: a cover at a distal end of the end effector, the cover allowing air to flow through one or more openings defined therein; a vacuum source that provides a high flow vacuum at the end effector such that an object is engaged and lifted with a high flow grasp at the one or more openings defined in the cover of the end effector, wherein the

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one or more openings allow more air to flow near the center of the cover than near the periphery of the cover; a load detection device attached to the end effector, the load detection device including a magnetic field sensor that senses a magnet mounted on the articulated arm to determine a position of the load detection device responsive to movements of the end effector; and a flow monitor that monitors changes in air flow within the end effector, a controller that communicates with the load detection device and the flow monitor to determine whether the high flow grasp of the end effector on the object is sufficient for transport based on the position of the load detection device and the changes in air flow within the end effector.

In another aspect, there is provided a method of controlling a high flow vacuum acquisition of an object, the method comprising: attaching a load detection device to an end effector of an articulated arm, wherein the load detection device includes a magnetic field sensor that senses a magnet mounted on the articulated arm; providing a high flow vacuum from a vacuum source through an opening of the end effector, wherein the opening is configured to allow more air to flow at the center of the opening than at the periphery of the opening; engaging and lifting an object at the opening of the end effector with a high flow grasp; determining a position of the load detection device responsive to movements of the end effector engaging and lifting the object by sensing the magnet on the articulated arm with the magnetic field sensor; monitoring changes in air flow within the end effector; and determining whether the high flow grasp of the end effector on the object is sufficient for transport based on the position of the load detection device and the changes in air flow within the end effector.

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BRIEF DESCRIPTION OF THE DRAWINGS

The following description may be further understood with reference to the accompanying drawings in which:

Figure 1 shows an illustrative block diagrammatic view of a system in accordance with an embodiment of the present invention;

Figure 2 shows an illustrative diagrammatic view of an example of a system of Figure 1;

Figures 3A and 3B show illustrative diagrammatic views of an end effector of a system of an embodiment of the invention engaging different types of objects;

Figure 4 shows an illustrative diagrammatic view of a detection system together with an end effector of a system of an embodiment of the present invention;

Figures 5A and 5B show illustrative photographic views of an end effector cover for use in a system of an embodiment of the present invention;

Figure 6 shows an illustrative diagrammatic view of an end effector of an embodiment of the invention engaging an object;

Figures 7A – 7D show illustrative diagrammatic views of other covers for use with end effectors of systems of further embodiments of the present invention;

Figure 8A and 8B show illustrative diagrammatic views of an end effector in a system of an embodiment of the present invention engaging a relatively light object;

Figure 9A and 9B show illustrative diagrammatic views of an end effector in a system of an embodiment of the present invention engaging a relatively heavy object;

Figure 10A and 10B show illustrative diagrammatic views of an end effector in a system of an embodiment of the present invention engaging an object that presents an unbalanced load;

Figure 11 shows an illustrative graphical representation of air flow verses pressure differential for different vacuum sources;

Figure 12 shows an illustrative graphical representation of air flow verses pressure differential for different parameterizations of performance;

Figure 13 shows an illustrative diagrammatic model of an end effector aperture and object in a system in accordance with an embodiment of the present invention;

Figure 14 shows an illustrative diagrammatic end view of the system of Figure 13 showing the relative areas of the opening;

Figure 15 shows an illustrative diagrammatic side view of the system of Figure 13 showing flow direction and pressure;

Figure 16 shows an illustrative graphical representation of grip offset from a base versus angle in a system in accordance with an embodiment of the present invention; and

Figure 17 shows illustrative diagrammatic representations of objects being held at the offset points in Figure 16.

The drawings are shown for illustrative purposes only and are not to scale.

DETAILED DESCRIPTION

There are numerous applications for a novel gripping system that could handle a broad variety of objects, varying in size, weight, and surface properties. In accordance with certain embodiments, the invention provides a system for providing high flow vacuum control to an end effector of an articulated arm. In accordance with various embodiments, the invention provides a dynamic high flow gripping system, and may optionally include a mechanism to select between the high flow source and a high vacuum source, depending on the application. High flow vacuum systems of the invention may therefore optionally be used with high vacuum sources.

The system, for example, may include a first vacuum source for providing a first vacuum pressure with a first maximum air flow rate; and a second vacuum source for providing a second vacuum pressure with a second maximum air flow rate, wherein the second vacuum pressure is higher than the first vacuum pressure and wherein the second maximum air flow rate is greater than the first maximum air flow rate. The flow rates are characterized as maximum air flow rates because, when an object is engaged at an end effector, the flow rate may drop significantly. The high flow source may be used together with a high vacuum source, or as a single source.

Figure 1, for example, shows a system 10 in accordance with an embodiment of the present invention in which an optional high vacuum source 12 is provided as well as a high flow source 14 and a release source 16 that are each coupled to a selection unit 18, that is coupled to an end effector 20. The selection unit 18 selects between the high vacuum source 12, high flow source 14 and the release source 16 for providing any of high vacuum, vacuum with high flow, or a release flow to the end effector. Figure 1 therefore shows a general form of the invention, comprising mechanisms for producing high vacuum and high flow, a release source providing either atmospheric pressure via a vent or high pressure (blow off) via a compressor or reservoir, and a mechanism for selecting the source best suited to the present situation.

In particular, Figure 2 shows a system in accordance with an embodiment of the invention that includes a compressor 30 that is coupled to an ejector 32 to provide a high vacuum source that is coupled to a solenoid valve 34. A blower 36 is also coupled to the solenoid valve 34 via a non-return valve 38, and the blower 36 provides a vacuum source with a high maximum flow rate. A vent or blow-off source is also provided to the solenoid valve 34, the output of which is provided to an end effector 40. The system therefore, provides the ejector 32 as the high vacuum source, the regenerative blower 36 as the high flow source, the non-return valve 38 as a passive selection mechanism, and the solenoid valve 34 connecting the effector to the release source, either vent or blow-off.

The vacuum pressure provided by the ejector 32 may be, for example, at least about 90,000 Pascals below atmospheric and the vacuum pressure provided by the blower 36 may be only no more than about 25,000 Pascals below atmospheric in some examples, and no more than about 50,000 Pascals below atmospheric in other examples. The vacuum pressure provided by the blower 36 is therefore higher than the vacuum pressure provided by the ejector 32. The maximum air flow rate of the ejector may be, for example, no more than about 5 cubic feet per minute (e.g., 1 – 2 cubic feet per minute), and the maximum air flow rate of the blower may be, for example at least about 100 cubic feet per minute (e.g., 130 – 140 cubic feet per minute).

For example, with reference to Figure 3A, if a good seal is formed between an end effector 60 (which may for example, be a tubular or conical shaped bellows) and an object 62 on an articulated arm 64, then the vacuum pressure may remain high vacuum and low flow. This will provide that the grasp of object 62 will be maintained by the high vacuum with a lower maximum air flow rate. With reference to Figure 3B, if a good seal is not formed between an end effector 70 and an irregularly shaped object 72 on an articulated arm 74, then the high flow source will dominate maintaining a high flow, and maintaining a grasp of object 72 with a higher maximum air flow rate.

With reference to Figure 4, in accordance with a further embodiment, the system may include an articulated arm 80 to which is attached an end effector 82, again, which may be a tubular or conical shaped bellows. The end effector 82 also includes a sensor 84 that includes an attachment band 86 on the bellows, as well as a bracket 88 attached to magnetic field sensor 84, and a magnet 92 is mounted on the articulated arm 80. The bellows may move in any of three directions, e.g., toward and away from the articulated arm as shown diagrammatically at A, in directions transverse to the direction A as shown at B, and directions partially transverse to the direction A as shown at C. The magnetic field sensor 84 may communicate (e.g., wirelessly) with a controller 90, which may also communicate with a flow monitor 94 to determine whether a high flow grasp of an object is sufficient for continued grasp and transport as discussed further below. In an embodiment, for example, the system may return the object if the air flow is insufficient to carry the load, or may increase the air flow to safely maintain the load.

During low vacuum / high flow use, a specialized end effector may be used that provides improved grasping of long narrow objects. Certain grippers that are designed for high flow use to acquire and hold an object generally require large apertures in order to obtain an air flow rate that is high enough to be useful for object acquisition. One drawback of some such grippers in certain applications, is that the object to be acquired may be small, not so small that each of its dimensions is smaller than the high flow opening, but small enough that certain of an object's dimensions is smaller than the opening. For example, long narrow objects such as pens, pencils etc., do not occlude enough of the high flow opening to generate sufficient negative forces to hold the object securely.

In accordance with an embodiment therefore, the invention provides a specialized cover for use with a high flow vacuum gripper. In particular and as shown in Figures 5A (articulated arm facing side) and 5B (object facing side), such a cover 100 may include a proximal back side 102 that does not permit air to flow through the material, and distal front side 104 for engaging objects that is formed of a foam material. Slit openings 106 in form of a star or asterisk shape are provided through the material in this example. During use, elongated objects may be received along opposing slit openings and held by the foam material.

Figure 6, for example, shows an elongated object 96 being held against the foam material 104 of a cover 100 that is coupled to the end effector 82. While the elongated object 96 covers some of the opening provided by the slits 106, other portions 108 of the opening provided by the slits 106 remain open. The pattern cut into the material allows for enough area to still obtain a relatively high flow, while providing a number or positions (or orientations) for a long, thin object to block (and thus be held by) a sufficiently high percentage of the air flow.

The compliant foam on the surface 104 contacts the object to be acquired, giving the gripper some compliance while also acting to seal the aperture around the object as the foam is compressed and the high flow vacuum is applied. The aperture cover therefore allows a high flow gripper to effectively pick up long narrow objects with an easy to attach cover that may be held in a tool changer and added or removed from the gripper autonomously during real-time operation

In accordance with various embodiments, the cover 100 may be applied to the end effector by a human worker into a friction fitting on the end of the end effector, or in certain embodiments, the cover may be provided in a bank of available end effector attachments that the articulated arm may be programmed to engage as needed, and disengage when finished, e.g., using forced positive air pressure and /or a grasping device that secures the end effector attachment for release from the articulated arm.

The invention therefore provides a system for providing vacuum control to an end effector of an articulated arm, where the system includes a vacuum source for providing a vacuum pressure at a flow rate to the end effector, and the end effector includes a cover including an air flow resistant material on a proximal side of the cover and a compliant material on a distal side of the cover for contacting objects to be grasped. The cover may include an opening that varies significantly in radius from a center of the cover, and the opening may include finger openings that extend radially from the center of the opening. The opening may be generally star shaped or asterisk shaped. The cover may be formed of a compliant material and include compliant foam on a distal side of the cover that engages an object to be grasped, and the cover may include an air flow resistant material on a proximal side of the cover. The vacuum pressure may be no more than about 25,000 Pascals or 50,000 Pascals below atmospheric, and the air flow rate may be at least about 100 cubic feet per minute.

Covers with other types of openings are shown in Figure 7A – 7D. Figure 7A, for example, shows a cover 120 that includes slit openings 122. Figure 7B shows a cover 130 that includes different sized square openings 132, 134. Cover 140 shown in Figure 7C includes small circular openings 142, and cover 150 shown in Figure 7D includes differently shaped openings 152 and 154. In each of the covers 100, 120, 130, 140 and 150, a compliant foam surface may face the object to be acquired, and more area of the cover is provided to be open closer to the center of the cover with respect to the outer periphery of each cover. For example, in the cover 100, the center of the asterisk shape is most open. In the cover 120, the larger slits are provided in the center. In the cover 130, the larger square openings are provided in the center. In the cover 140, the greater concentration of the circular openings is provided in the center, and in the cover 150, the larger shape 154 is provided in the center.

Systems in accordance with certain embodiments of the invention are able to monitor flow within the end effector as well as the weight and balance of an object being grasped. Figures 8A and 8B show an object 160 being lifted from a surface 162 by the end effector 82 that includes the load detection device of Figure 4. Upon engaging the object 160, the system notes the position of the detection device and the level of flow (F_1) within the end effector as well as the vacuum pressure (P_1) and load (W_1) as shown in Figure 8A. Once the object 160 is lifted (Figure 8B), the system notes the change in the amount of flow (ΔF_1). In this example, the load provided by the object 160 is relatively light (ΔW_1), and a small variation (ΔF_1) in flow (when considering the load and aperture size) may be accepted. Figures 9A and 9B, however, show the end effector lifting a heavy object.

Figures 9A and 9B show an object 170 being lifted from a surface 172 by the end effector 82 that includes the load detection device of Figure 4. Upon engaging the object 170, the system notes the position of the detection device and the level of flow (F_2) within the end effector as well as the vacuum pressure (P_2) and load (W_2) as shown in Figure 9A. Once the object 170 is lifted (Figure 9B), the system notes the change in the amount of flow (ΔF_2). As noted above, in this example, the object 170 is heavy, presenting a higher load (ΔW_2). The system will evaluate the load in combination with the flow (F_2) and pressure (P_2) as well as the change in flow (ΔF_2) and change in pressure (ΔP_2) to assess the grasp of the object. The system may use look-up tables of flow and load values for the sized aperture opening, and / or may use machine learning to develop and maintain information regarding loads that are suitable for different apertures sizes and flow rates. In further embodiments, the system may employ linear performance curves for the vacuum sources for maximum flow and maximum pressure, as adjusted by aperture opening size.

The system may also detect whether a load is not sufficiently balanced. Figures 10A and 10B show an object 180 being lifted from a surface 182 by the end effector 82 that includes the load detection device of Figure 4. Upon engaging the object 180, the system notes the position of the detection device and the level of flow (F_3) within the end effector as well as the vacuum pressure (P_3) and load (W_3) as shown in Figure 10A. Once the object 180 is lifted (Figure 10B), the system notes the change in the amount of flow (ΔF_3). In this example, the object 180 presents a non-balanced load. The system will evaluate the load in combination with the flow (F_3) and pressure (P_3) as well as the change in flow (ΔF_3) and change in pressure (ΔP_3) to assess the grasp of the object. Again, the system may use look-up tables of flow and load values for the sized aperture opening, and / or may use machine learning to develop and maintain information regarding loads that are suitable for different apertures sizes and flow rates. In further embodiments, the system may employ linear performance curves for the vacuum sources for maximum flow and maximum pressure, as adjusted by aperture opening size.

The lifting force may be characterized as a function using any of machine learning, large data analytics, fuzzy logic or linear approximation. Lifting force depends on the vacuum generator performance model and the area of the object within the opening. Hose length and friction are also important. At high flow, pressure loss is related to flow velocity. Pressure loss is related to hose length and hose friction. Absent a performance curve, a linear approximation of the vacuum generator performance may be used.

Figure 11 shows linear performance curves for a blower (at 200) and a shop vacuum (at 202). Performance curves may also be concave or convex, depending on the parameter ds. The term ds parameterizes whether the relationship curve is concave or convex. The degree of concavity or convexity affects high flow gripper performance. Figure 12 shows vacuum performance curves for $ds = 0.25$ (as shown at 220), $ds = 1$ (as shown at 222) and $ds = 1.5$ (as shown at 224).

Figures 13 – 15 show a two-pipe model of an example of a high flow gripper for illustrative purposes. As shown in Figure 13, an end effector 250 is engaging an object 252. Figure 14 shows that the area of the opening, a_1 is partially blocked by the object, leaving openings on either side of the object having a total area of a_2. The area that is blocked is shown as $(a_1\text{-}a_2)$. Figure 16 shows at 260 deflection angles versus lateral offset for an object using a bellows suction cup. An optimal aperture for a given maximum flow and maximum pressure, as well as $(a_1 - a_2)/a_1$ may be provided. Also, knowing the center of mass of the held object with respect to the gripper, as well as any rotation of the object, the torque may be determined.

As shown in Figure 16, the deflection angles range correlate with grip offset from the base showing offset in one direction (as shown at 262 in Figure 16 and 282 in Figure 17), a balanced load (as shown at 270 in Figure 16 and 290 in Figure 17), and offset in an opposite direction (as shown at 276 in Figure 16 and 296 in Figure 17). The remaining points 264, 266, 268, 272 and 274 correspond with the images 284, 286, 288, 292 and 294 in Figure 17.

The invention therefore provides, in various embodiments, that load weight, load balance, and flow may be used in a high flow system to provide accurate acquisition and transport of objects in a sortation system.

Those skilled in the art will appreciate that numerous modifications and variations may be made to the above disclosed embodiments without departing from the spirit and scope of the present invention.

What is claimed is:

CLAIMS

1. A system for providing high flow vacuum control to an end effector of an articulated arm, said system comprising:

a cover at a distal end of the end effector, said cover allowing air to flow through one or more openings defined therein; and

a high flow vacuum source that provides a vacuum at the end effector such that an object is engaged and lifted while permitting substantial flow of air through the one or more openings;

wherein the cover includes a larger amount of opening area near the center of the cover and a smaller amount of opening area near a periphery of the cover, such that the one or more openings allow more air to flow near the center of the cover than near the periphery of the cover.

2. The system as claimed in claim 1, wherein vacuum pressure is no more than about 50,000 Pascals below atmospheric.

3. The system as claimed in claim 1, wherein a maximum air flow rate is at least about 100 cubic feet per minute.

4. The system as claimed in claim 1, wherein said cover includes a compliant outwardly facing material.

5. The system as claimed in claim 1, wherein the system further includes a load detection assembly, wherein the load detection assembly determines whether to maintain a grasp on an object responsive to the load detection assembly.

6. The system as claimed in claim 5, wherein the load detection assembly monitors load weight.

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7. The system as claimed in claim 5, wherein the load detection assembly monitors load balance.

8. The system as claimed in claim 5, wherein the load detection assembly monitors the flow of air through the end effector.

9. An object acquisition system comprising a high flow vacuum source that provides an opening at a distal end of an end effector of a programmable motion device with an area of high flow vacuum such that objects are engaged at the opening while permitting substantial flow of air through the opening; and a load assessment system that assesses the load responsive to the flow and any of a load weight or load balance, wherein the distal end of the end effector includes a larger amount of opening area near the center of the distal end of the end effector and a smaller amount of opening area near a periphery of the distal end of the end effector, such that said opening provides more air to flow near the center of the opening than near the periphery of the opening.

10. The object acquisition system as claimed in claim 9, wherein vacuum pressure is no more than about 50,000 Pascals below atmospheric.

11. The object acquisition system as claimed in claim 9, wherein a maximum air flow rate is at least about 100 cubic feet per minute.

12. The object acquisition system as claimed in claim 9, wherein the system further includes a cover at the opening, said cover including a complaint outwardly facing material.

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13. The object acquisition system as claimed in claim 12, wherein the cover includes a larger amount of opening area near the center of the cover, and a smaller amount of opening area near the periphery of the cover.

14. A method of engaging a load presented by an object at an end effector in a high flow vacuum system, said method comprising the steps of:

providing a high flow vacuum at an opening at a distal end of the end effector;

engaging an object at the opening while permitting an air flow through the opening;

restricting the air flow at a periphery of the opening, while permitting relatively more air flow at a center of the opening by providing a larger amount of opening area near the center of the distal end of the end effector and a smaller amount of opening area near the periphery of the distal end of the end effector;

assessing grasp characteristics of the load presented by the object using a load detection device; and

increasing the air flow through the opening at the distal end of the end effector based on the grasp characteristics of the load provided by the load detection device.

15. The method as claimed in claim 14, wherein the high flow vacuum provided at the opening at the distal end of the end effector has a vacuum pressure equal to no more than 50,000 Pascals below atmospheric.

16. The method as claimed in claim 14, wherein the air flow provided through the opening has a maximum air flow rate equal to at least 100 cubic feet per minute.

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17. The method as claimed in claim 14, further comprising determining whether to maintain a grasp on the object responsive to the grasping characteristics of the load provided by the load detection device.

18. The method as claimed in claim 14, wherein the step of assessing the grasping characteristics of the load presented by the object comprises determining a weight of the object using the load detection device.

19. The method as claimed in claim 14, wherein the step of assessing the grasping characteristics of the load presented by the object comprises determining a balance of the load provided by the object using the load detection device.

20. The method as claimed in claim 17, further comprising moving the object using the end effector in response to determining that the grasp on the object should be maintained, and repositioning the distal end of the end effector on the object in response to determining that the grasp on the object should not be maintained.

21. A system for providing high flow vacuum control to an end effector of an articulated arm, said system comprising a blower for providing a high flow vacuum source at an opening having a center at a distal side of the end effector, with an area of high flow vacuum at the end effector such that an object is engageable at the opening for movement by the articulated arm while permitting substantial flow of air through the opening, wherein the opening is provided by a single contiguous opening that includes elongated open areas extending radially from the center of the opening, and wherein the end effector includes no other openings at the distal side thereof, wherein the single contiguous opening has a larger amount of opening area near the center of the distal side of the end effector and a smaller amount of opening area near a periphery of the distal

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end of the end effector, such that the single contiguous opening provides more air to flow near the center of the distal side of the end effector than near the periphery of the distal side of the end effector.

22. The system as claimed in claim 21, wherein vacuum pressure is no more than about 50,000 Pascals below atmospheric.

23. The system as claimed in claim 21, wherein a maximum air flow rate is at least about 100 cubic feet per minute.

24. The system as claimed in claim 21, wherein the system determines whether to maintain a grasp on an object responsive to a load detection system that characterizes a load presented by the object.

25. The system as claimed in claim 24, wherein the load detection system monitors load weight.

26. The system as claimed in claim 24, wherein the load detection system monitors load balance.

27. An object acquisition system comprising a high flow vacuum source including a blower that provides a high flow vacuum through an opening having a center at a distal end of an end effector of a programmable motion device, wherein the end effector includes a cover having a compliant distally facing foam material, the opening passing through the foam material such that an object is engageable at the opening without passing through the opening while permitting substantial flow of air through the opening that assists in maintaining the object against the opening for movement by the end effector, wherein the opening is provided as a single

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contiguous opening of the end effector that includes radially extending open areas that extend radially from the center of the opening toward a periphery of the opening, wherein the single contiguous opening has a larger amount of opening area near the center of the cover and a smaller amount of opening area near a periphery of the cover, such that the single contiguous opening allows more air to flow near the center of the cover than near the periphery of the cover.

28. The object acquisition system as claimed in claim 27, wherein vacuum pressure is no more than about 50,000 Pascals below atmospheric.

29. The object acquisition system as claimed in claim 27, wherein a maximum air flow rate is at least about 100 cubic feet per minute.

30. The object acquisition system as claimed in claim 27, wherein the system determines whether to maintain a grasp on an object responsive to a load detection system that characterizes a load presented by the object.

31. A method of engaging and moving a load presented by an object at an end effector in a high flow vacuum system, said method comprising the steps of:

providing a high flow vacuum using a blower, said high flow vacuum being provided at an opening at a distal end of the end effector;

engaging the object at the opening while permitting substantial flow of air through the opening, wherein the opening is provided by a single contiguous opening of the end effector of an articulated arm that includes elongated areas extending radially from the center of the opening, wherein the single contiguous opening has a larger amount of opening area near the center of the distal side of the end effector and a smaller amount of opening area near a periphery of the distal end of the end effector, such that the single contiguous opening provides more air to

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flow near the center of the distal side of the end effector than near the periphery of the distal side of the end effector; and

moving the engaged object using the end effector.

32. The method as claimed in claim 31, wherein vacuum pressure is no more than about 50,000 Pascals below atmospheric.

33. The method as claimed in claim 31, wherein a maximum air flow rate is at least about 100 cubic feet per minute.

34. The method as claimed in claim 31, wherein the method further includes the step of determining whether to maintain a grasp on an object responsive to a characterization of the load.

35. The method as claimed in claim 34, wherein characterization of the load involves determining a relative weight of the object.

36. The method as claimed in claim 34, wherein characterization of the load involves determining a relative balance of the load provided by the object.

37. The method as claimed in claim 31, wherein the method further includes the step of characterizing the load presented by the object.

38. A method of engaging and moving a load presented by an object at an end effector of an articulated arm in a high flow vacuum system, said method comprising the steps of:

providing a high flow vacuum using a blower, said high flow vacuum being provided at all of plural openings at a contact surface of the end effector, the end effector including a flexible bellows and including a central region of the contact surface;

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engaging the object at the contact surface while permitting substantial flow of air through all of the openings, the substantial flow of air being greater at the central region of the contact surface than at regions more radially peripheral to the central region of the contact surface;

lifting the engaged object using the end effector while permitting substantial flow of air through all of the openings and while permitting flexing of the bellows in any of three mutually orthogonal directions; and

moving the engaged object using the end effector and the articulated arm.

39. The method as claimed in claim 38, wherein vacuum pressure is no more than about 50,000 Pascals below atmospheric.

40. The method as claimed in claim 38, wherein a maximum air flow rate is at least about 100 cubic feet per minute.

41. The method as claimed in claim 38, wherein the method further includes the step of determining whether to maintain a grasp on an object responsive to a characterization of the load.

42. The method as claimed in claim 38, wherein the method further includes the step of characterizing a load presented by the object, including determining a relative weight of the object.

43. The method as claimed in claim 38, wherein the method further includes the step of characterizing a load presented by the object, including determining a relative balance of the load provided by the object.

44. A system for providing high flow vacuum control to an end effector of an articulated arm, said system comprising a high flow vacuum source that provides a high flow vacuum at a contact

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surface at a distal side of the end effector such that an object is engageable at the contact surface for movement by the articulated arm while permitting substantial flow of air through the contact surface, wherein the contact surface includes a central region, and wherein the contact surface includes a plurality of openings, said plurality of openings providing more air flow at the central region of the contact surface than at a peripheral region of the contact surface.

45. The system as claimed in claim 44, wherein the plurality of openings include a larger number of openings at the central region than at the peripheral region of the contact surface.

46. The system as claimed in claim 44, wherein the plurality of openings include larger openings at the central region that at the peripheral region of the contact surface.

47. The system as claimed in claim 44, wherein the plurality of openings are more concentrated at the central region than at the peripheral region of the contact surface.

48. The system as claimed in claim 44, wherein the high flow vacuum source includes a blower.

49. The system as claimed in claim 44, wherein vacuum pressure is no more than about 50,000 Pascals below atmospheric.

50. The system as claimed in claim 44, wherein a maximum air flow rate is at least about 100 cubic feet per minute.

51. The system as claimed in claim 44, wherein the contact surface includes a cover that provides the plurality of openings therein.

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52. The system as claimed in claim 44, wherein the system determines whether to maintain a grasp on an object responsive to a load detection system that characterizes a load presented by the object.

53. The system as claimed in claim 52, wherein the load detection system monitors load weight.

54. The system as claimed in claim 52, wherein the load detection system monitors load balance.

55. A system for providing high flow vacuum control to an end effector of an articulated arm, said system comprising a high flow vacuum source that provides a high flow vacuum at a contact surface at a distal side of the end effector such that an object is engageable at the contact surface for movement by the articulated arm while permitting substantial flow of air through the contact surface, wherein the contact surface includes a cover with a central region, and wherein the cover includes a plurality of openings, said plurality of openings providing restricted air flow at a peripheral region of the cover as compared to air flow at the central region of the cover by said plurality of openings providing a larger amount of opening area at the center region of the cover and a smaller amount of opening area at the peripheral region of the cover.

56. The system as claimed in claim 55, wherein the plurality of openings include a larger number of openings at the central region than at the peripheral region of the contact surface.

57. The system as claimed in claim 55, wherein the plurality of openings include larger openings at the central region that at the peripheral region of the contact surface.

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58. The system as claimed in claim 55, wherein the plurality of openings are more concentrated at the central region than at the peripheral region of the contact surface.

59. The system as claimed in claim 55, wherein the high flow vacuum source includes a blower.

60. The system as claimed in claim 55, wherein vacuum pressure is no more than about 50,000 Pascals below atmospheric.

61. The system as claimed in claim 55, wherein a maximum air flow rate is at least about 100 cubic feet per minute.

62. The system as claimed in claim 55, wherein the cover includes a compliant outwardly facing material.

63. The system as claimed in claim 55, wherein the system includes a load detection system that characterizes a load presented by the object.

64. The system as claimed in claim 63, wherein the system determines whether to maintain a grasp on an object responsive to the load detection system that characterizes the load presented by the object.

65. The system as claimed in claim 64, wherein the load detection system monitors load weight.

66. The system as claimed in claim 64, wherein the load detection system monitors load balance.

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67. A method of engaging and moving a load presented by an object at an end effector in a high flow vacuum system, said method comprising:

providing a high flow vacuum at a contact surface of the end effector;

engaging the object at the contact surface while permitting substantial flow or air through the contact surface, wherein the contact surface includes a central region, and wherein the contact surface includes a plurality of openings, said plurality of openings providing more air flow at the central region of the contact surface than at a peripheral region of the contact surface; and

moving the engaged object using the end effector.

68. The method as claimed in claim 67, wherein the plurality of openings include a larger number of openings at the central region than at the peripheral region of the contact surface.

69. The method as claimed in claim 67, wherein the plurality of openings include larger openings at the central region that at the peripheral region of the contact surface.

70. The method as claimed in claim 67, wherein the plurality of openings are more concentrated at the central region than at the peripheral region of the contact surface.

71. The method as claimed in claim 67, wherein the high flow vacuum system includes a blower.

72. The method as claimed in claim 67, wherein vacuum pressure is no more than about 50,000 Pascals below atmospheric.

73. The method as claimed in claim 67, wherein a maximum air flow rate is at least about 100 cubic feet per minute.

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74. The method as claimed in claim 67, wherein the contact surface includes a cover that provides the plurality of openings therein.

75. The method as claimed in claim 67, wherein the method further includes determining whether to maintain a grasp on an object responsive to a load detection system that characterizes a load presented by the object.

76. The method as claimed in claim 75, wherein the load detection system monitors load weight.

77. The method as claimed in claim 75, wherein the load detection system monitors load balance.

78. A method of engaging and moving a load presented by an object at an end effector in a high flow vacuum system, said method comprising:

providing a high flow vacuum at a contact surface of the end effector;

engaging the object at the contact surface while permitting substantial flow of air through the contact surface, wherein the contact surface includes a cover with a central region, and wherein the cover includes a plurality of openings, said plurality of openings providing restricted flow at a peripheral region of the cover as compared to air flow at the central region of the cover by said plurality of openings providing a larger amount of opening area at the center region of the contact surface and a smaller amount of opening area at the peripheral region of the contact surface; and

moving the engaged object using the end effector.

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79. The method as claimed in claim 78, wherein the plurality of openings include a larger number of openings at the central region than at the peripheral region of the cover.

80. The method as claimed in claim 78, wherein the plurality of openings include larger openings at the central region that at the peripheral region of the cover.

81. The method as claimed in claim 78, wherein the plurality of openings are more concentrated at the central region than at the peripheral region of the cover.

82. The method as claimed in claim 78, wherein the high flow vacuum system includes a blower.

83. The method as claimed in claim 78, wherein vacuum pressure is no more than about 50,000 Pascals below atmospheric.

84. The method as claimed in claim 78, wherein a maximum air flow rate is at least about 100 cubic feet per minute.

85. The method as claimed in claim 78, wherein the cover includes a compliant outwardly facing material.

86. The method as claimed in claim 78, wherein the system determines whether to maintain a grasp on an object responsive to a load detection system that characterizes a load presented by the object.

87. The method as claimed in claim 86, wherein the load detection system monitors load weight.

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88. The method as claimed in claim 86, wherein the load detection system monitors load balance.

89. A system for providing high flow vacuum control to an end effector of an articulated arm, said system comprising:

a cover at a distal end of the end effector, said cover allowing air to flow through one or more openings defined therein;

a vacuum source that provides a high flow vacuum at the end effector such that an object is engaged and lifted with a high flow grasp at the one or more openings defined in the cover of the end effector, wherein the one or more openings allow more air to flow near the center of the cover than near the periphery of the cover;

a load detection device attached to the end effector, the load detection device including a magnetic field sensor that senses a magnet mounted on the articulated arm to determine a position of the load detection device responsive to movements of the end effector; and

a flow monitor that monitors changes in air flow within the end effector,

a controller that communicates with the load detection device and the flow monitor to determine whether the high flow grasp of the end effector on the object is sufficient for transport based on the position of the load detection device and the changes in air flow within the end effector.

90. The system as claimed in claim 89, wherein the vacuum source provides a vacuum pressure is no more than 50,000 Pascals below atmospheric.

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91. The system as claimed in claim 89, wherein the vacuum source provides a maximum air flow rate is at least 100 cubic feet per minute.

92. The system as claimed in claim 89, wherein said cover includes a compliant outwardly facing material.

93. The system as claimed in claim 92, wherein the one or more openings defined in the cover provide a larger amount of opening area near the center of the cover than near the periphery of the cover.

94. The system as claimed in claim 89, wherein the controller determines whether the object engaged by the end effector with the high flow grasp is load balanced based on the position of the load detection device.

95. A method of controlling a high flow vacuum acquisition of an object, said method comprising:

attaching a load detection device to an end effector of an articulated arm, wherein the load detection device includes a magnetic field sensor that senses a magnet mounted on the articulated arm;

providing a high flow vacuum from a vacuum source through an opening of the end effector, wherein the opening is configured to allow more air to flow at the center of the opening than at the periphery of the opening;

engaging and lifting an object at the opening of the end effector with a high flow grasp;

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determining a position of the load detection device responsive to movements of the end effector engaging and lifting the object by sensing the magnet on the articulated arm with the magnetic field sensor;

monitoring changes in air flow within the end effector; and

determining whether the high flow grasp of the end effector on the object is sufficient for transport based on the position of the load detection device and the changes in air flow within the end effector.

96. The method as claimed in claim 95, wherein the vacuum source provides a vacuum pressure is no more than 50,000 Pascals below atmospheric.

97. The method as claimed in claim 95, wherein the vacuum source provides a maximum air flow rate is at least 100 cubic feet per minute.

98. The method as claimed in claim 95, further comprising determining a relative weight of the object.

99. The method as claimed in claim 95, further comprising determining a relative balance of the load provided by the object.

100. The method as claimed in claim 95, further comprising

moving the object responsive to determining that the high flow grasp on the object should be maintained; and

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repositioning the end effector on the object responsive to determining that the high flow grasp on the object should not be maintained.

101. The method as claimed in claim 95, further comprises determining whether the object engaged by the end effector is load balanced based on the position of the load detection device.

102. The method as claimed in claim 95, further comprising returning the object in response to determining that the high flow grasp of the end effector on the object is not sufficient for transport.

103. The method as claimed in claim 95, further comprising increasing an air flow through the opening of the end effector in response to determining that the high flow grasp of the end effector on the object is not sufficient for transport.

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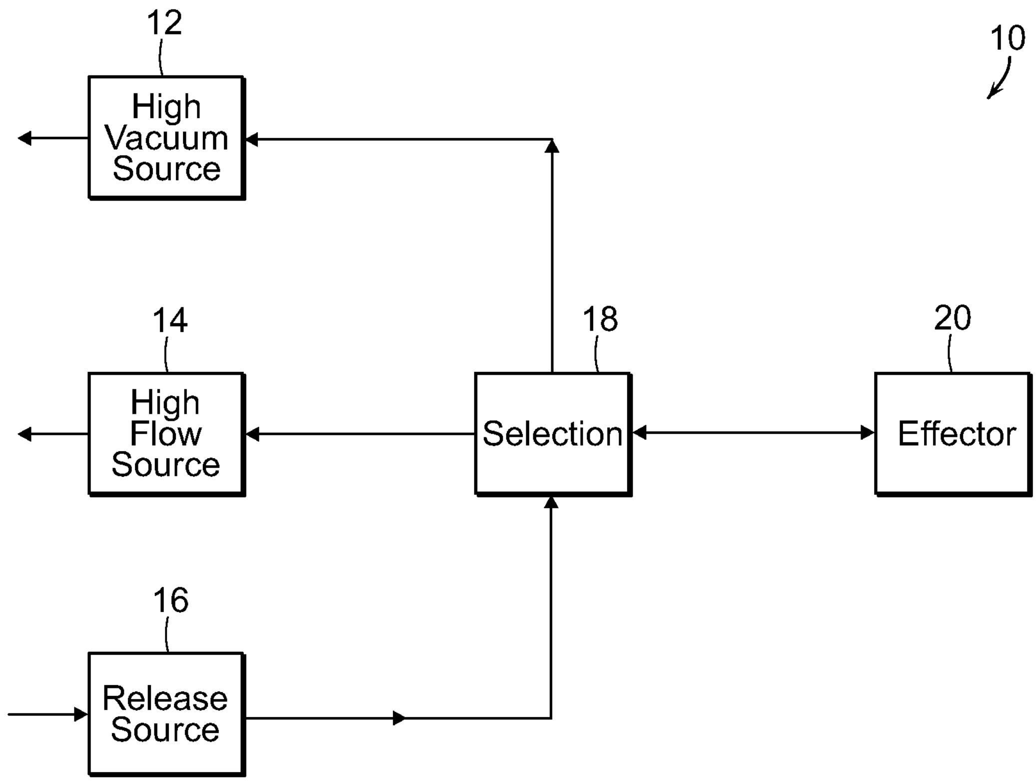

12
High Vacuum Source
10
14
High Flow Source
18
Selection
20
Effector
16
Release Source

FIG. 1

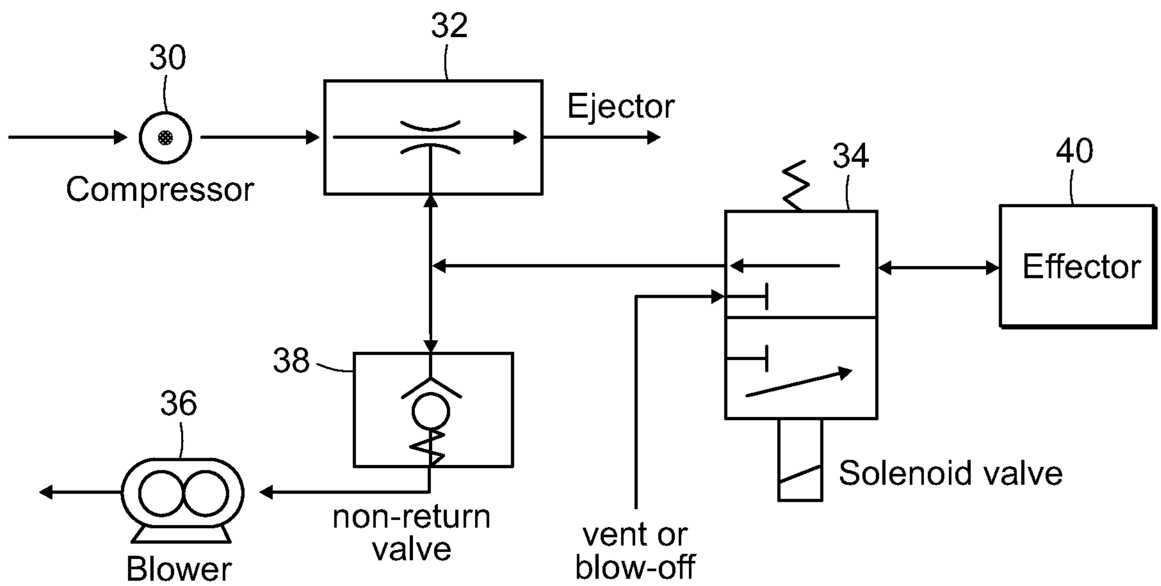

32
30
Compressor
Ejector
34
40
Effector
38
36
Blower
non-return valve
vent or blow-off
Solenoid valve

FIG. 2

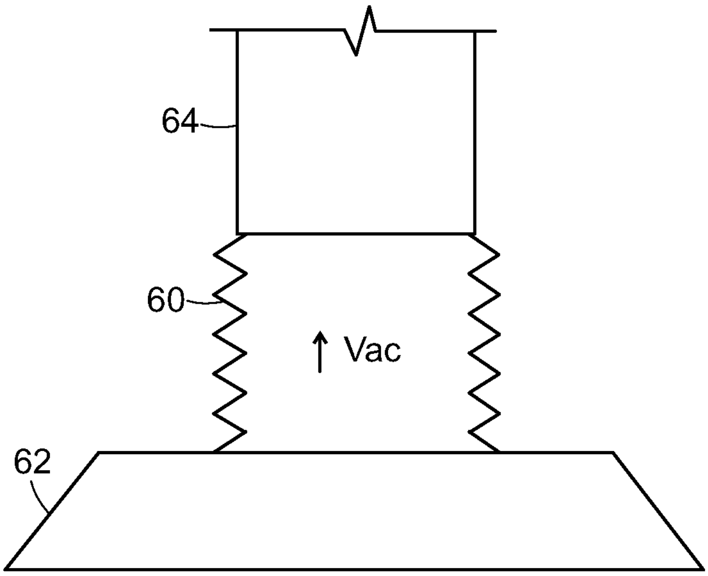


FIG. 3A

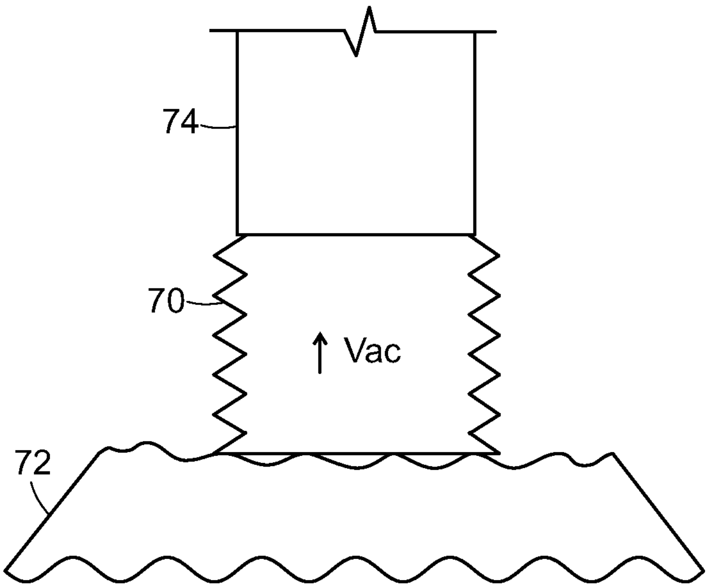


FIG. 3B

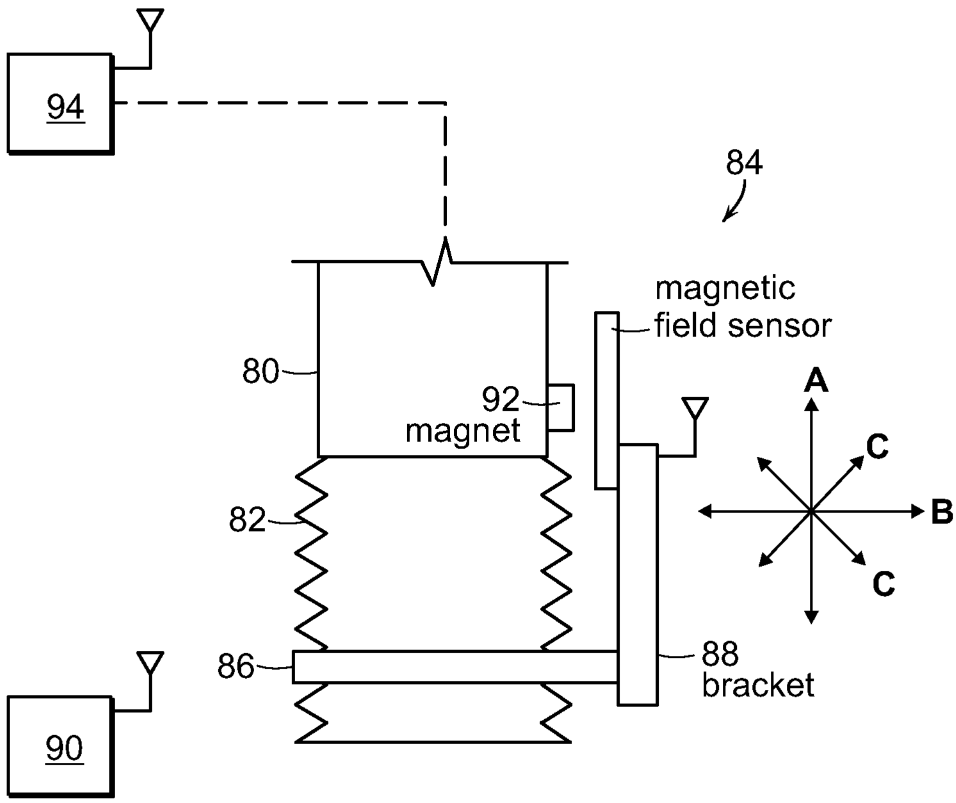

94
84
magnetic
field sensor
80
92
magnet
A
C
B
C
82
86
88
bracket
90

FIG. 4

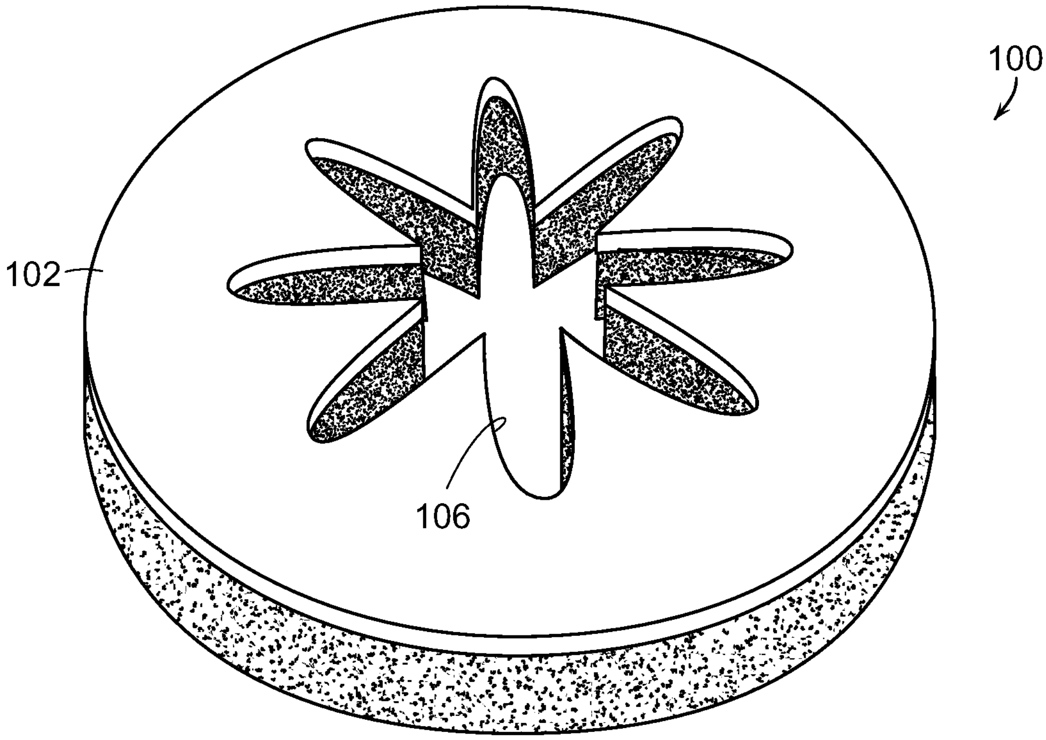


FIG. 5A

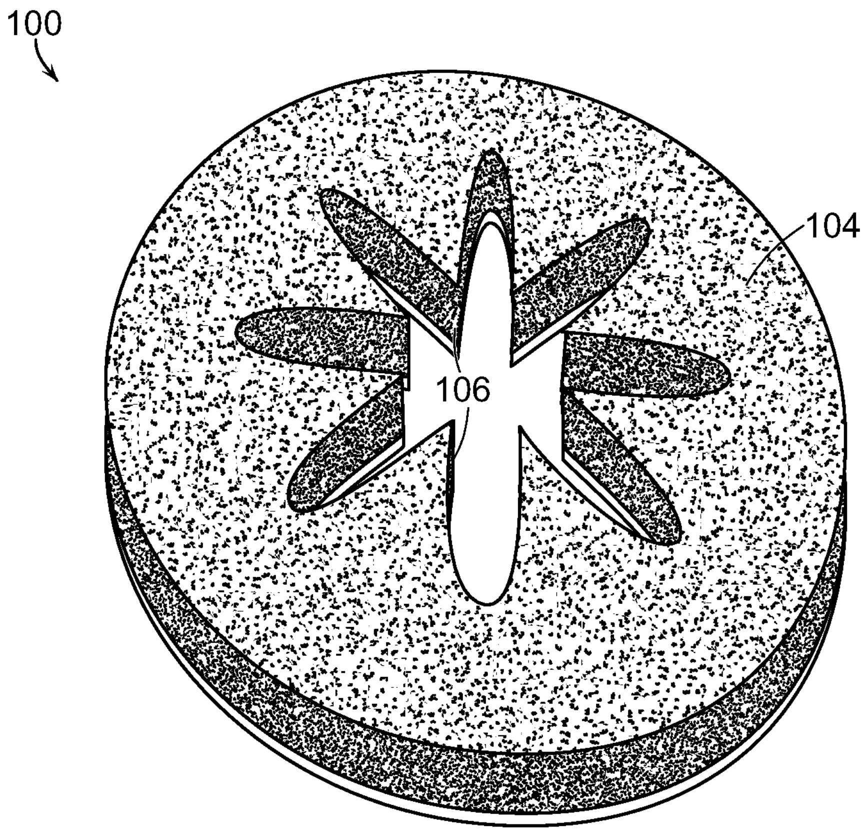


FIG. 5B

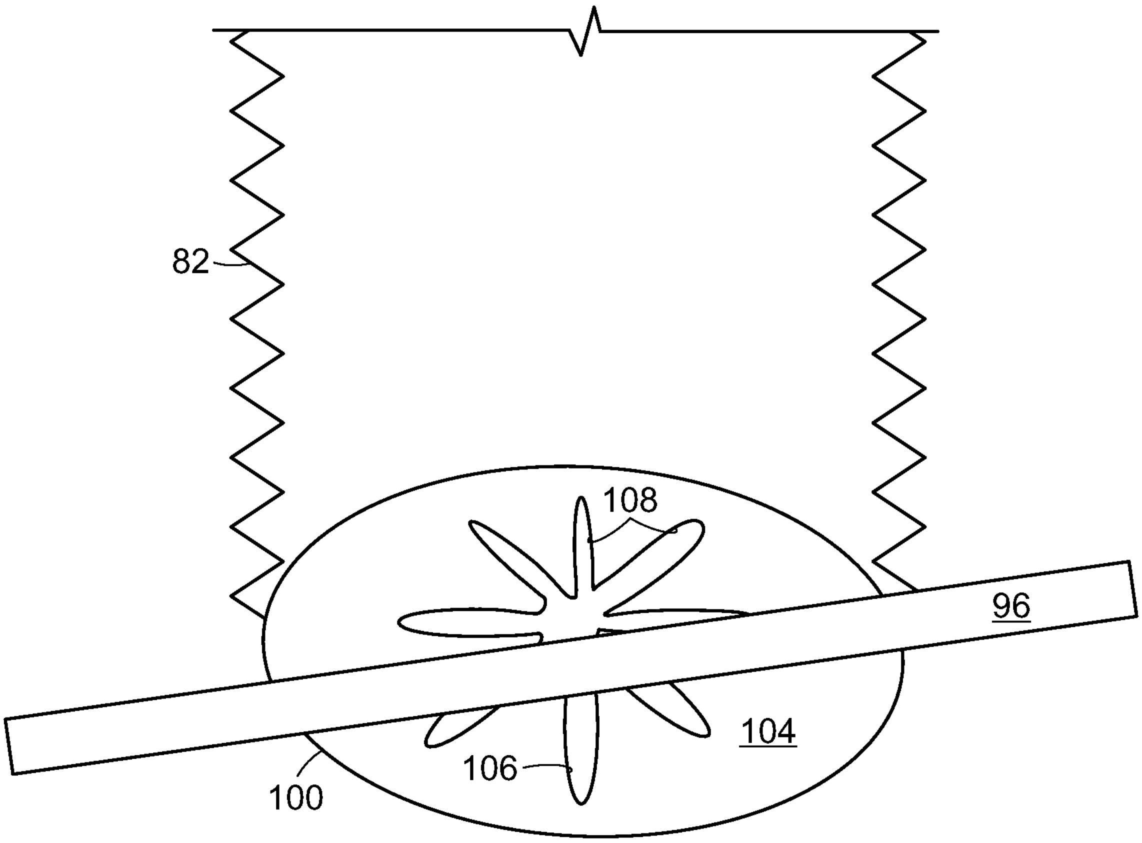


FIG. 6

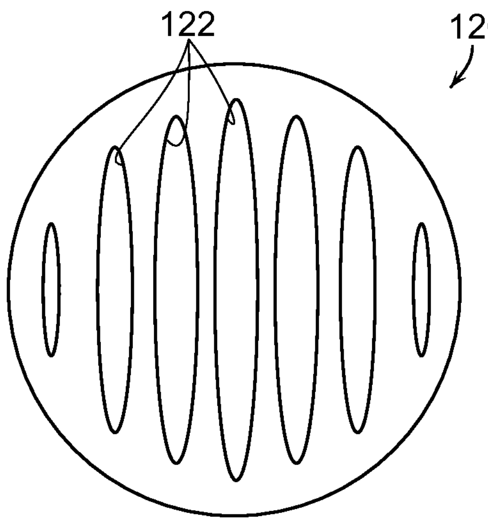


FIG. 7A

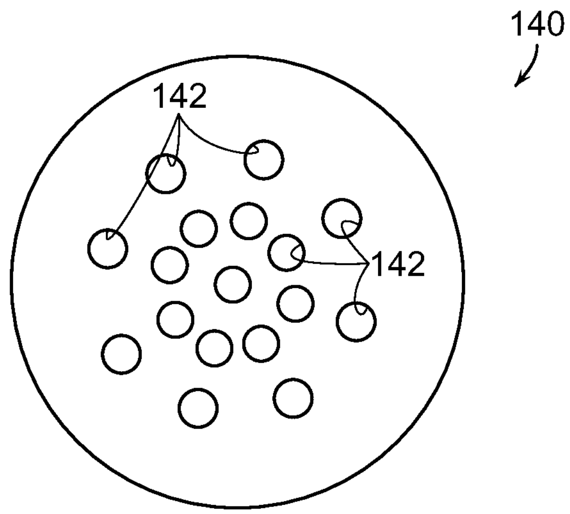


FIG. 7C

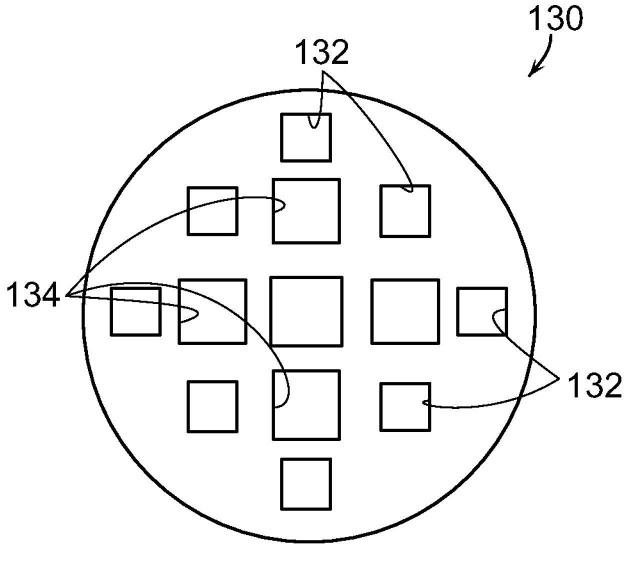


FIG. 7B

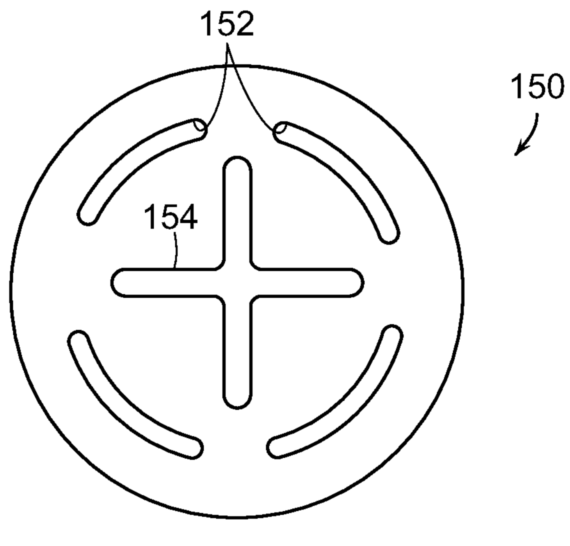


FIG. 7D

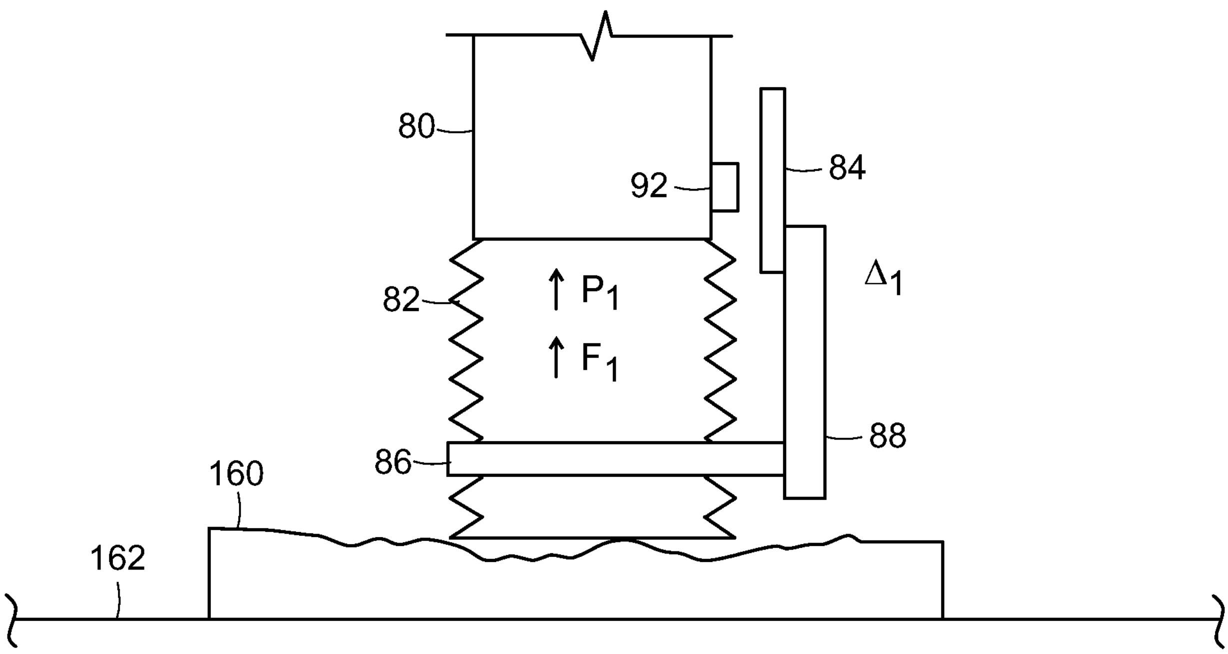

80
92
84
82
P1
F1
Δ1
88
86
160
162

FIG. 8A

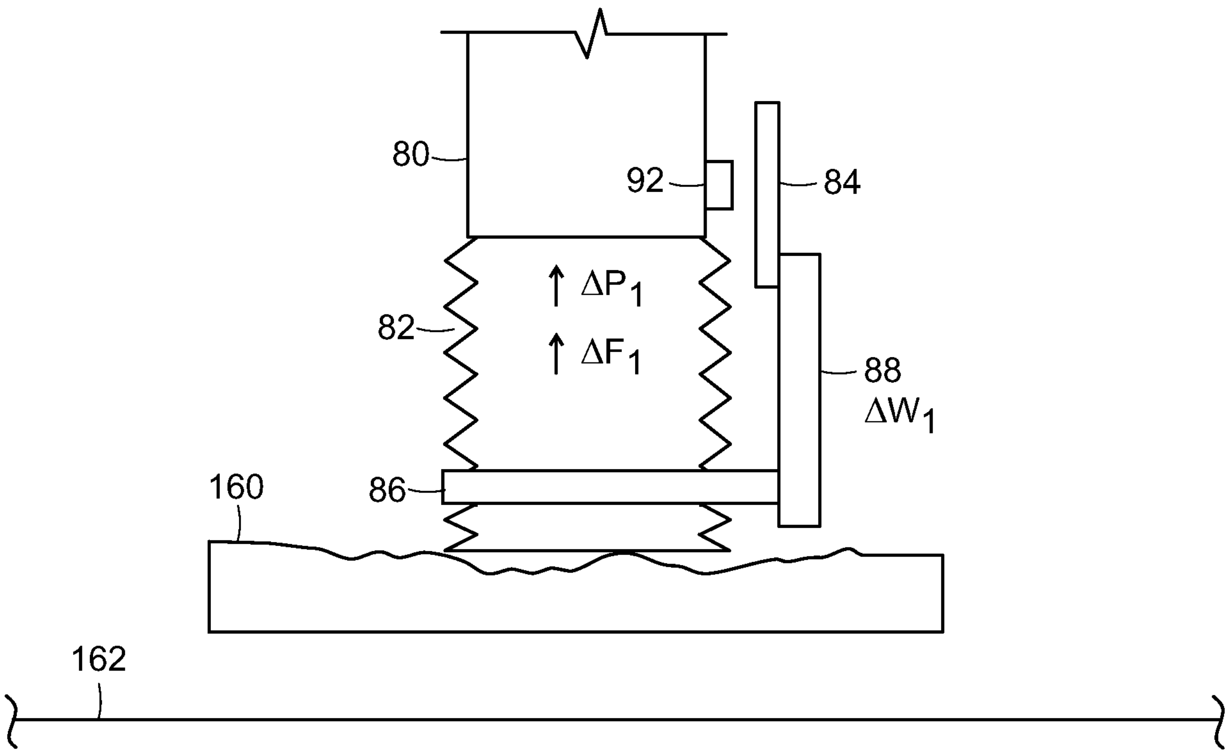

80
92
84
ΔP1
82
ΔF1
88
ΔW1
160
86
162

FIG. 8B

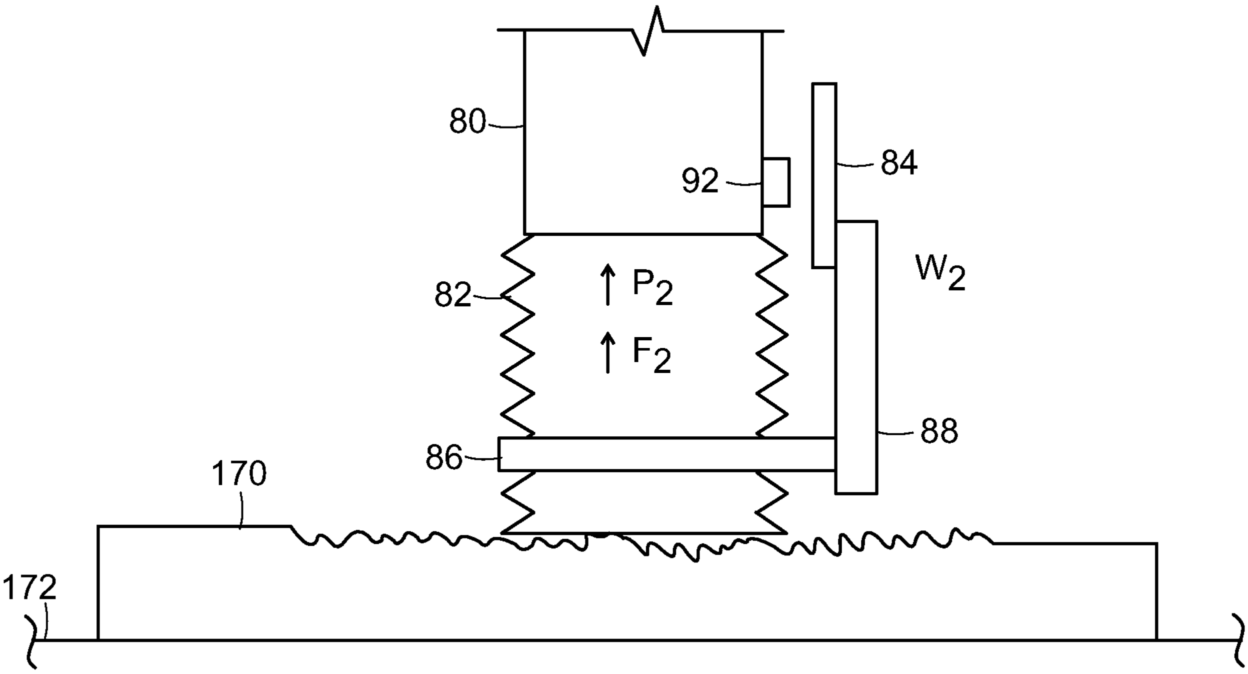


FIG. 9A

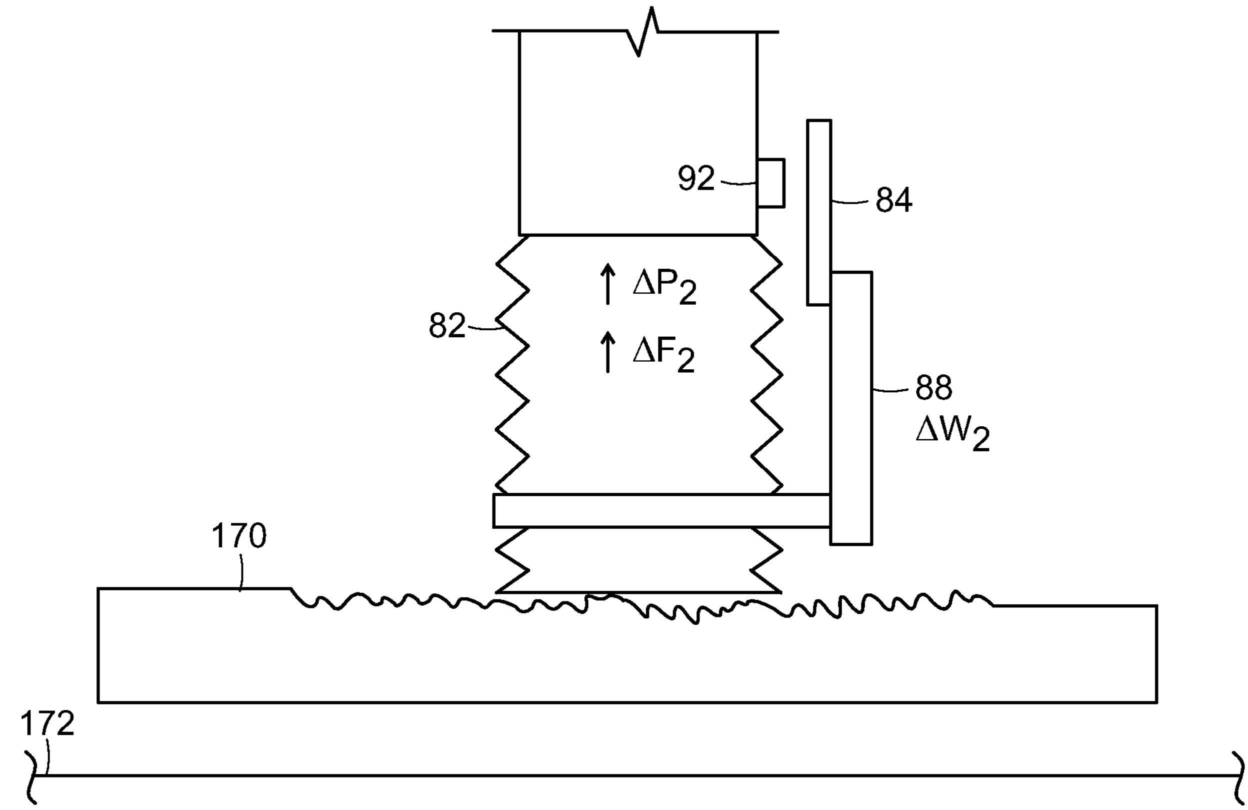


FIG. 9B

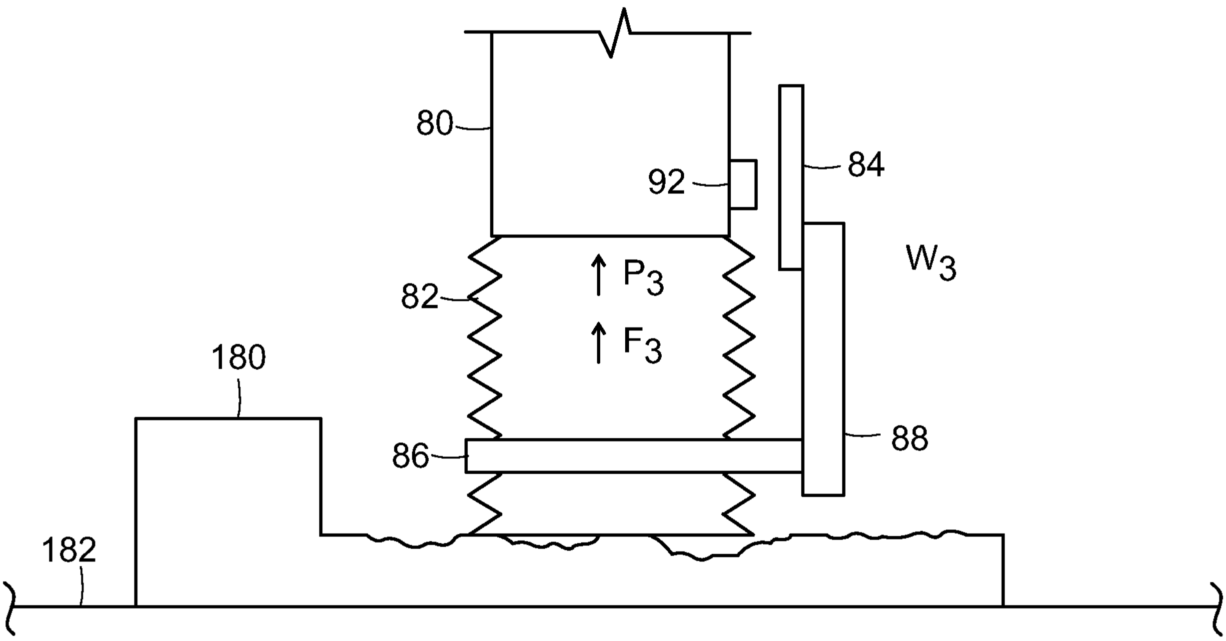


FIG. 10A

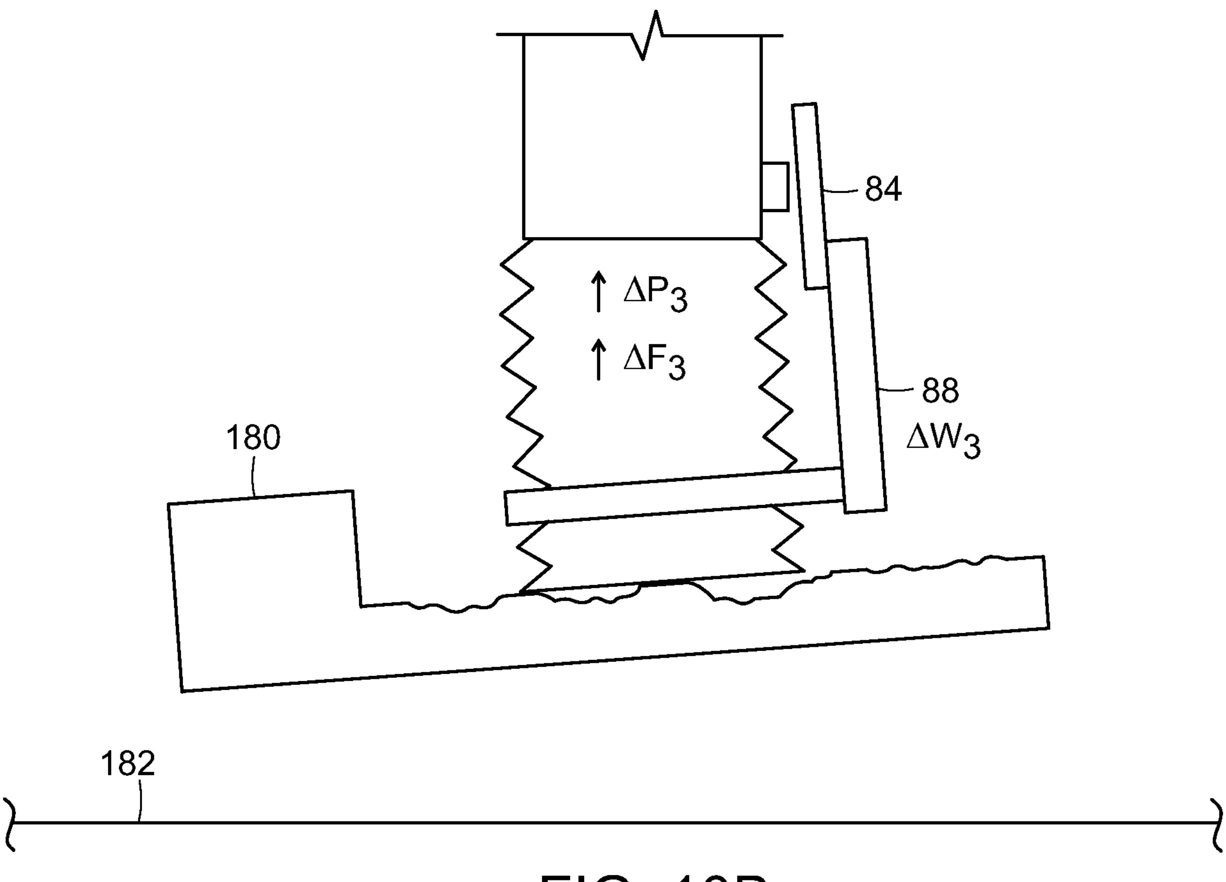


FIG. 10B

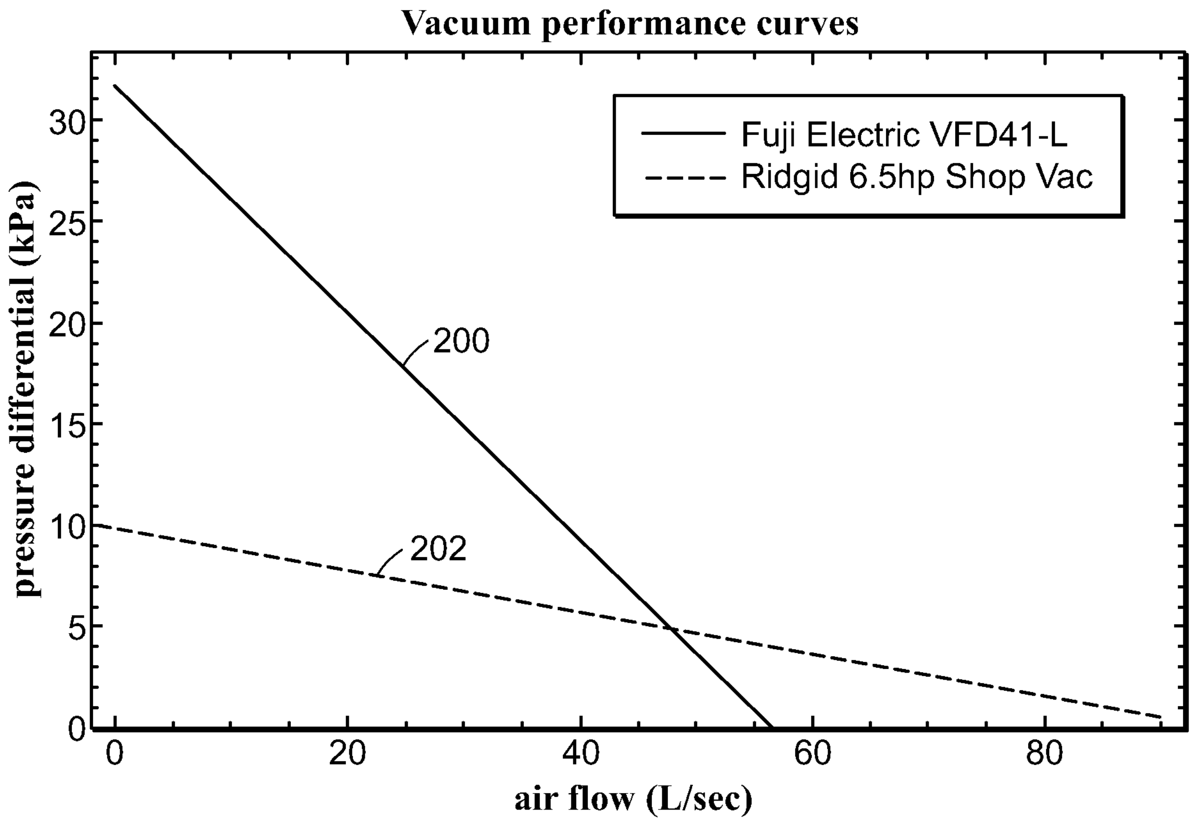

Vacuum performance curves
Fuji Electric VFD41-L
Ridgid 6.5hp Shop Vac
200
202
pressure differential (kPa)
air flow (L/sec)
0
5
10
15
20
25
30
0
20
40
60
80

FIG. 11

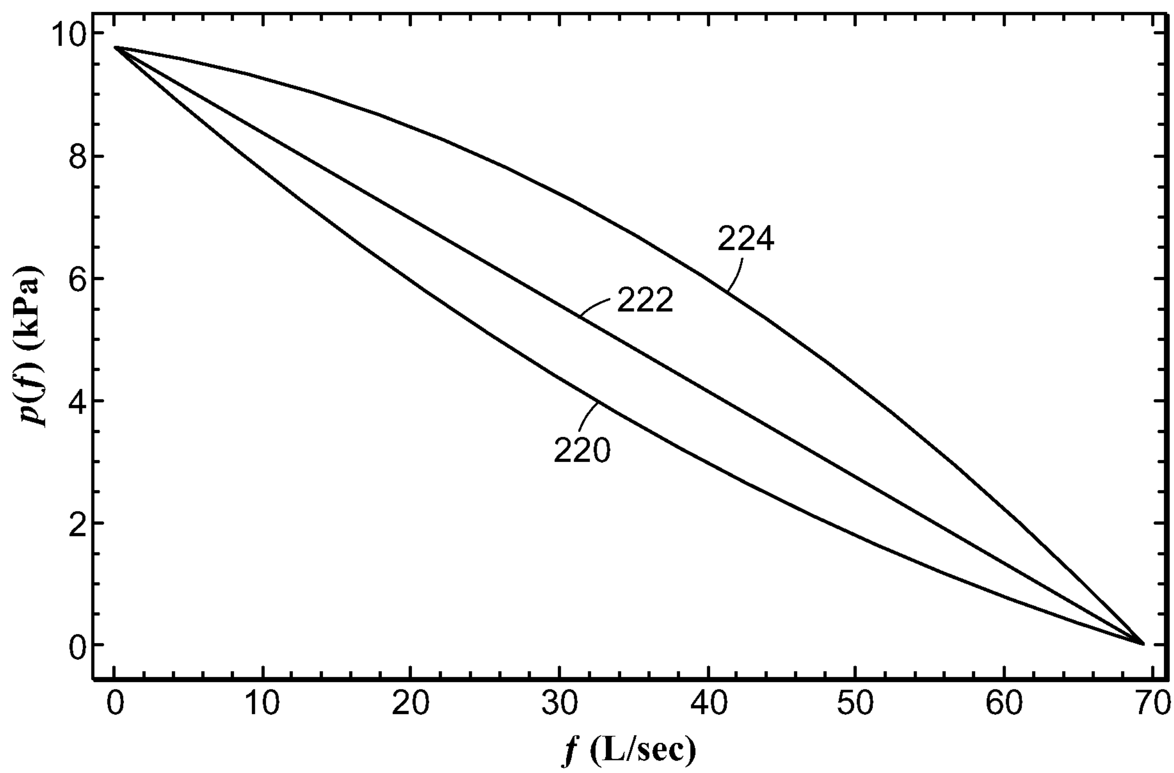

224
222
220
p(f) (kPa)
f (L/sec)
0
2
4
6
8
10
0
10
20
30
40
50
60
70

FIG. 12

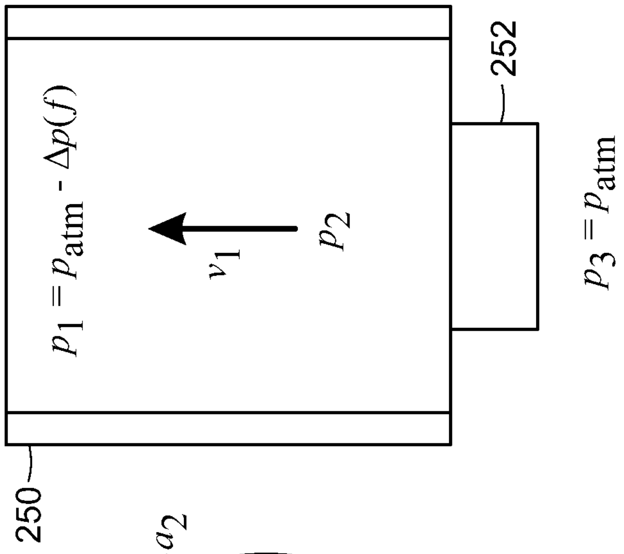


FIG. 15

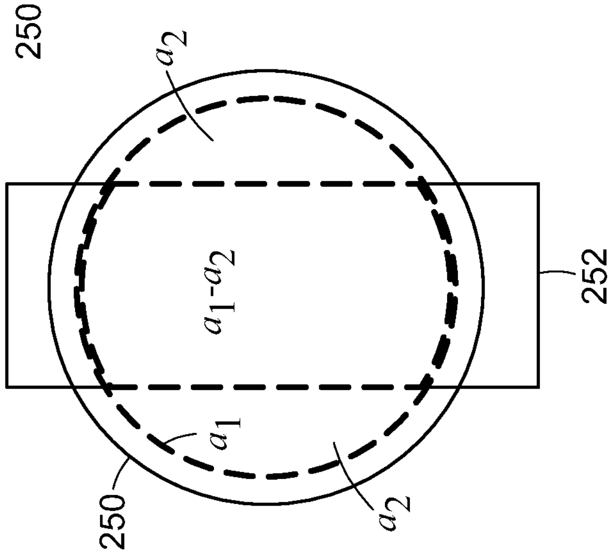


FIG. 14

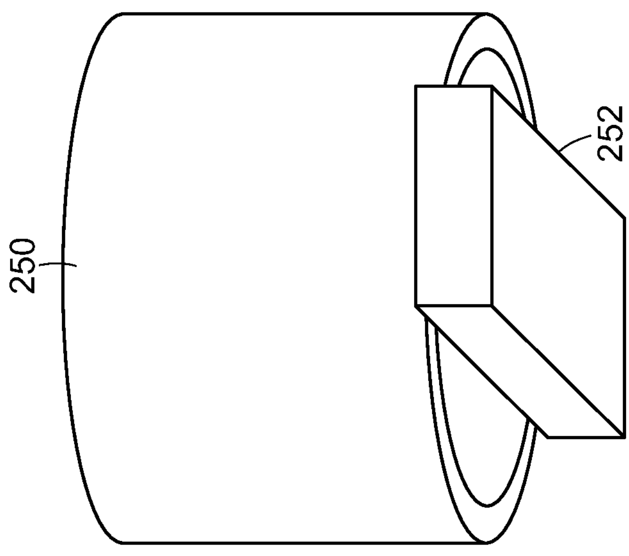


FIG. 13

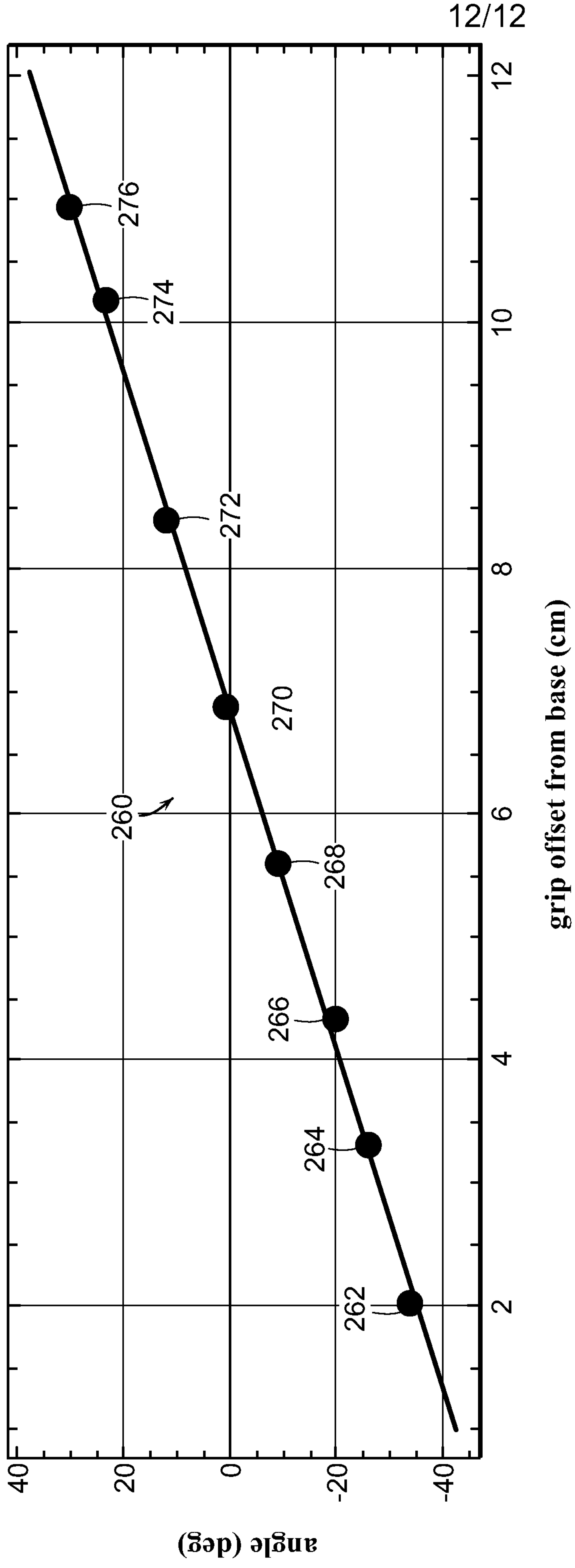

angle (deg)
40
20
0
-20
-40
grip offset from base (cm)
2
4
6
8
10
12
260
262
264
266
268
270
272
274
276

FIG. 16

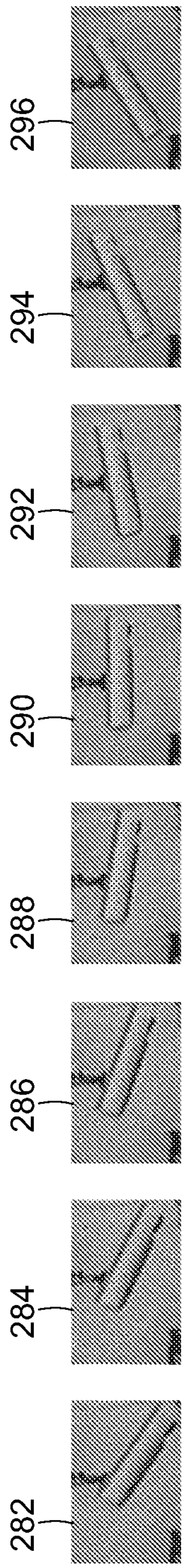
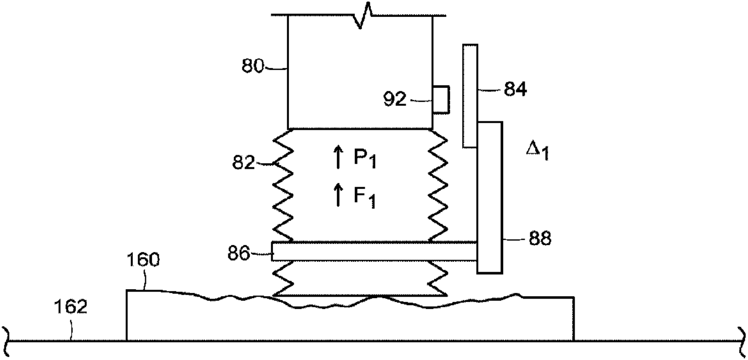

282
284
286
288
290
292
294
296

FIG. 17



80
92
84
82
P1
F1
Δ1
88
86
160
162