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(54) **SYSTEM AND METHOD FOR CONTROLLING A TREATMENT PROCESS**

(57) A system (50) for monitoring and/or controlling a treatment process includes a treatment apparatus (100) for carrying out the treatment process. The treatment apparatus (100) includes a vibratory trough (102) for receiving and retaining treatment media (12) and a component support (104) fixedly attached to the vibratory trough (102). The system (50) includes a plurality of sensor devices (14) respectively and fixedly disposed at a plurality of heights relative to the vibratory trough (102) and configured to respectively measure a plurality of movement parameters of the treatment media (12) at the plurality of heights and generate a plurality of movement signals (16) corresponding to the plurality of movement parameters. The system (50) includes a central controller (18) configured to determine a plurality of process variables (20) corresponding to the plurality of movement signals (16) and control the treatment apparatus (100) based at least on the plurality of process variables (20).

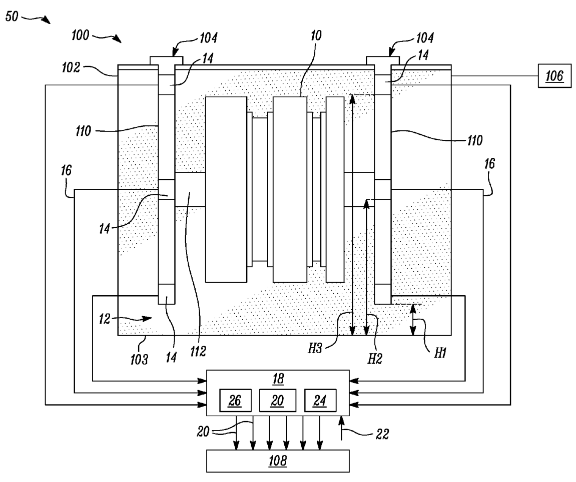

FIG. 1

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Description

Field

[0001] The present invention relates to a system and a method for controlling a treatment process that modifies surface properties of a component.

Background

[0002] Mechanical articles typically degrade in various ways over time especially when operated for long durations of time in extremes of temperature. The degradation often primarily or at least initially tends to occur at one or more surfaces of the articles concerned. It is known in the aerospace industry to treat the surface of components, especially gas turbine components, such as compressor blades, turbine blades, and bladed integrated disks, in order to modify/enhance the performance/life and/or appearance of those components.

[0003] It is well known that polishing a metal surface can improve its appearance. It involves rubbing the surface and/or applying a chemical substance to it to make the surface smooth and shiny. Vibropolishing, aka ball pressure polishing, is a polishing method that involves placing an article in a container of specially shaped pellets and vibrating the container so that the pellets rub against the article to deburr, radius, descale, burnish, clean, and/or brighten its surface. While vibropolishing is useful for improving the surface roughness of aerospace components it can undesirably remove material and detrimentally affect aerofoil geometries.

[0004] The process of working on a metal surface to improve its material properties is known as peening. Certain types of peening reflect the manner in which the metal surface is worked upon. Peening is not restricted to metal surfaces. It is, for example, possible to peen composite materials. Shot peening is a cold working process that involves striking the surface of a metal or a composite with a shot with sufficient force to produce a compressive residual stress layer by plastic deformation. The shot can, for example, be in the form of round metallic, glass, or ceramic particles. The process is intended to modify the mechanical properties of the metal or the composite without removing any appreciable material. It is known to use shot peening to strengthen car crankshafts and connecting rods. While shot peening is useful for providing desired compressive residual stresses in aerospace components, it typically undesirably increases surface roughness.

[0005] Vibropeening is a process that combines vibratory polishing and shot peening to a single polishing process in a vibratory bowl/trough. Also known as ball polishing, it is known to be useful for improving the appearance of car wheels, various types of furniture, and cutlery.

[0006] Tests have shown that vibro-treating, i.e., vibropeening or vibropolishing, a component of a gas turbine engine (e.g., a bladed disk drum and a fan blade) results in a non-uniform residual stress distribution and material properties across the length due to asymmetry of the component. This may undesirably increase treatment time and process cost.

[0007] However, currently there is no validated process control mechanism for vibropeening. This may be because vibropeening is a low energy process and may therefore take significant amount of time to perform process control checks thereby reducing the business case benefit introduced through elimination of shot peening. Further, if a drawing parameter (e.g., a process intensity) for a component is not as per drawing requirement after quantification using Almen strips, then significant time may be again required to revalidate a vibropeening setup to be deemed as fit for obtaining the drawing parameter as per the drawing requirement for the component. Further, if the drawing parameter for the component is not as per drawing requirement after quantification, the component may have to be discarded. Moreover, in conventional vibropeening techniques, human intervention is relatively high as measuring Almen intensity through saturation curves is a very labour-intensive process. Also, conventional vibropeening techniques may cause an excessive amount of cost to be spent on the sacrificial Almen strips in a production plant. Therefore, there exists a need for a system and a method that control such a treatment process in an improved/sustainable manner.

[0008] The present invention provides a method and a system for controlling a treatment process that modifies surface properties of a component that addresses the shortcomings of conventional polishing and peening methods, or at least provides a useful alternative to the same.

Summary

[0009] According to a first aspect there is provided a system for controlling a treatment process that modifies surface properties of a component. The system includes a treatment apparatus for carrying out the treatment process. The treatment apparatus includes a vibratory trough for receiving and retaining treatment media. The treatment apparatus further includes a component support fixedly attached to the vibratory trough. The component support supports the component within the vibratory trough. The treatment apparatus further includes at least one trough vibrating mechanism that causes the vibratory trough to vibrate. The system further includes a plurality of sensor devices respectively and fixedly disposed at a plurality of heights relative to the vibratory trough. The plurality of sensor devices is configured to respectively measure a plurality of movement/vibration parameters of the treatment media at the plurality of heights and generate a plurality of movement/vibration signals corresponding to the plurality of movement/vibration parameters. The vibration parameters may be defined by the oscillating, reciprocating, or any other periodic motion of a rigid or elastic body or medium forced from a position or state of equilibrium. The movement may be timely adjusted according to requirements, for e.g., primarily introduce high residual compressive stresses by other parameters and secondary treatment to smoothen the surface roughness which might both not be periodically. The system further includes a central controller communicably coupled to each of the plurality of sensor devices. The central controller is configured to receive the plurality of movement signals from the plurality of sensor devices. The central controller is further configured to determine a plurality of process variables corresponding to the plurality of movement signals. The central controller is further configured to control the treatment apparatus based at least on the plurality of process variables.

[0010] The central controller controls the treatment apparatus based at least on the plurality of process variables, such as a value of an energy/impulse, a coverage, and/or an intensity at respective heights relative to the vibratory trough. The central controller communicably coupled to the plurality of sensor devices fixedly disposed at the plurality of heights relative to the vibratory trough may enable the system of the present invention to monitor the plurality of movement signals and the plurality of process variables. In other words, the system of the present invention may be used to obtain a desired parameter of the treatment process (i.e., vibropeening) for a specific aerospace component according to the drawing requirement.

[0011] As the controller controls the treatment apparatus based at least on the plurality of process variables corresponding to the plurality of movement signals, the system of the present invention may provide uniform residual stress distribution and material properties across the component during the treatment process (i.e., vibropeening). This may improve fatigue life and/or performance of the component. This is particularly important when the component is large in size. Further, unlike conventional techniques where the component may have to be scrapped if there is any error in obtaining the drawing requirement (e.g., Almen intensity), the system of the present invention may enable monitoring the vibropeening at specific heights and accordingly controlling the vibropeening of the component. As a result, a likelihood of scrapping the component after the treatment process of the component may be reduced by the system of the present invention. Therefore, the central controller and the plurality of sensor devices may validate a process control method and/or mechanism of the treatment process for the component.

[0012] Moreover, as compared to the conventional vibropeening techniques, the system of the present invention may substantially reduce human intervention because of continuous determination of the plurality of process variables corresponding to the plurality of movement signals and subsequently controlling the treatment apparatus based at least on the plurality of process variables. The system of the present invention may enable the vibropeening which is relatively faster with less intensive manual labour which may significantly reduce developmental time and cost for research. This will enable faster optimization of the process to meet a specific drawing requirement for any given component/geometry at a specific location. Such a method also could be used for locally optimizing vibropeening for specific repair process through various fixturing/masking steps. Further, in the proposed system, there are minimal chances of wastage of sacrificial Almen strips or scrapping of components which may not meet the drawing requirements. The system of the present invention may be used for vibropeening of rotationally symmetric as well as asymmetric components.

[0013] In some embodiments, the system further includes a display device communicably coupled to the central controller. The display device is configured to display the plurality of process variables. The display device may display intensity of the treatment process. In some applications, an operator may also adjust or control the treatment apparatus based on the plurality of process variables displayed on the display device. The display device may be a monitor or a screen.

[0014] In some embodiments, the component support includes a support fixture and a support shaft attached to the support fixture. The support fixture fixedly attaches the support shaft to the vibratory trough and the support shaft removably mounts the component within the vibratory trough. Each of the plurality of sensor devices is fixedly attached to the support fixture. The support shaft may be mounted using a bearing assembly. The support shaft may be a substantially hollow shaft that spans across each end of the vibratory trough. The support shaft may be removably locatable within the vibratory trough and shaped to support the component to be treated in the treatment apparatus.

[0015] In some embodiments, the system further includes a frame fixedly attached to the vibratory trough. The frame further includes one or more vertical hangers. Each of the plurality of sensor devices is fixedly attached to the one or more vertical hangers of the frame. The frame may also include a plurality of holders attached to the one or more vertical hangers and configured to receive the respective plurality of sensor devices. The one or more vertical hangers may allow mounting of the plurality of sensor devices at the respective plurality of heights relative to the vibratory trough.

[0016] In some embodiments, each of the one or more vertical hangers extends at least partially into the treatment media. When each of the one or more vertical hangers extends at least partially into the treatment media, the plurality of sensor devices may respectively measure the plurality of movement parameters of the treatment media at the plurality of heights and generate the plurality of movement signals corresponding to the plurality of movement parameters.

[0017] In some embodiments, the central controller is further configured to receive a predetermined process parameter for the treatment process. The central controller is further configured to determine a measured process parameter based on the plurality of process variables. The central controller is further configured to control the treatment apparatus based on the predetermined process parameter and the measured process parameter, such that a difference between the predetermined process parameter and the measured process parameter is reduced. By reducing the difference between the predetermined process parameter and the measured process parameter, a desirable intensity and/or energy of the treatment process (i.e., vibropeening) may be obtained at the plurality of heights. The measured process parameter may be an overall intensity of the treatment process. The predetermined process parameter may be the drawing requirement.

[0018] In some embodiments, the central controller is further configured to, prior to receiving the plurality of movement signals from the plurality of sensor devices, determine a plurality of predicted process variables corresponding to the plurality of heights of the vibratory trough. The central controller is further configured to control the treatment apparatus based on the plurality of predicted process variables and the plurality of process variables, such that a difference between each of the plurality of process variables and a corresponding predicted process variable from the plurality of predicted process variables is reduced. By reducing the difference between each of the plurality of process variables and the corresponding predicted process variable from the plurality of predicted process variables, a desirable value of intensity and/or energy of the treatment process (i.e., vibropeening) may be obtained at the plurality of heights. The plurality of predicted process variables may be predicted intensities of the treatment process at the plurality of heights.

[0019] In some embodiments, the central controller is further configured to control the at least one trough vibrating mechanism of the treatment apparatus based on the plurality of process variables. Therefore, the central controller may adjust the vibration of the vibratory trough based on the plurality of process variables, such as a value of an energy, a coverage, and/ or an intensity of the treatment process.

[0020] In some embodiments, the treatment apparatus further includes at least one trough wall provided in the vibratory trough and configured to adjust a height, a volume, and/or a mass of the treatment media in the vibratory trough. The central controller is further configured to control the at least one trough wall of the treatment apparatus based on the plurality of process variables. By adjusting the height, the volume, and/or the mass of the treatment media in the vibratory trough, various characteristics and the overall intensity of the treatment process may be varied as per desirable application attributes. The trough wall may include a slot to receive the support shaft at various heights depending on application requirements.

[0021] In some embodiments, the treatment apparatus further includes a drive arrangement configured to rotate the component relative to the treatment media. The central controller is further configured to control the drive arrangement of the treatment apparatus based on the plurality of process variables. The drive arrangement may include a motor, a timing belt, and a gearbox with a variable gear ratio. The central controller may adjust a speed of the motor based on the plurality of process variables in order to control the coverage and uniformity of the treatment process (i.e., vibropeening).

[0022] In some embodiments, the treatment apparatus further includes a treatment media inlet for controllably supplying the treatment media into the vibratory trough and a treatment media outlet for controllably emptying the treatment media from the vibratory trough. The central controller is further configured to control the treatment media inlet and/or the treatment media outlet of the treatment apparatus based on the plurality of process variables. The treatment media inlet may be an inlet valve and the treatment media outlet may be an outlet valve. The treatment media inlet and the treatment media outlet may also be used to keep a desirable volume, height, and/or mass of the treatment media in the vibratory trough.

[0023] In some embodiments, each of the plurality of sensor devices includes at least two fixed electrodes for generating an electric field. An electric parameter is applied across the at least two fixed electrodes to induce the electric field between the at least two fixed electrodes. Each of the plurality of sensor devices further includes at least one movable electrode disposed between the at least two fixed electrodes. Upon vibration of the vibratory trough, the at least one movable electrode moves causing the electric field between the at least two fixed electrodes to change. Each of the plurality of sensor devices further includes an electric circuit electrically coupled to the at least two fixed electrodes and the at least one movable electrode. The electric circuit is configured to measure the corresponding movement parameter based on the change in the electric field between the at least two fixed electrodes. Each of the plurality of sensor devices further includes a processor communicably coupled to the electric circuit. The processor is configured to generate the corresponding movement signal based on the corresponding movement parameter. The processor is further configured to transmit the corresponding movement signal to the central controller. Therefore, the plurality of sensor devices generates the plurality of movement signals corresponding to the plurality of movement parameters. In other words, upon movement of the at least one movable electrode by vibration of the vibratory trough, the electric circuit measures the corresponding movement parameter (e.g., acceleration of the treatment media in the vibratory trough) based on the change in the electric field between the at least two fixed electrodes.

[0024] In some embodiments, each of the plurality of sensor devices further includes a casing. The casing includes one or more provisions for removably attaching a test strip to the casing. The test strip may be an Almen test strip that is used to quantify the intensity of the treatment process (i.e., vibropeening). The test strip may be a metal/alloy strip of a predetermined thickness to monitor the intensity of the treatment process being induced on the component.

[0025] According to a second aspect there is provided a method for controlling a treatment process that modifies surface properties of a component. The method includes providing a treatment apparatus for carrying out the treatment process. The treatment apparatus includes a vibratory trough for receiving and retaining treatment media. The treatment apparatus further includes a component support fixedly attached to the vibratory trough. The component support supports the component within the vibratory trough. The treatment apparatus further includes at least one trough vibrating mechanism that causes the vibratory trough to vibrate. The method further includes providing a plurality of sensor devices respectively and fixedly disposed at a plurality of heights relative to the vibratory trough. The plurality of sensor devices is configured to respectively measure a plurality of movement/vibration parameters of the treatment media at the plurality of heights and generate a plurality of movement/vibration signals corresponding to the plurality of movement parameters. The method further includes receiving the plurality of movement signals from the plurality of sensor devices. The method further includes determining a plurality of process variables corresponding to the plurality of movement signals. The method further includes controlling the treatment apparatus based at least on the plurality of process variables.

[0026] In some embodiments, the method further includes receiving a predetermined process parameter of the treatment process. The method further includes determining a measured process parameter based on the plurality of process variables. Controlling the treatment apparatus further includes controlling the treatment apparatus based on the predetermined process parameter and the measured process parameter, such that a difference between the predetermined process parameter and the measured process parameter is reduced.

[0027] In some embodiments, the method further includes, prior to receiving the plurality of movement signals from the plurality of sensor devices, determining a plurality of predicted process variables corresponding to the plurality of heights of the vibratory trough. Controlling the treatment apparatus further includes controlling the treatment apparatus based on the plurality of predicted process variables and the plurality of process variables, such that a difference between each of the plurality of process variables and a corresponding predicted process variable from the plurality of predicted process variables is reduced.

[0028] In some embodiments, controlling the treatment apparatus further includes controlling the at least one trough vibrating mechanism based on the plurality of process variables.

[0029] In some embodiments, controlling the treatment apparatus further includes adjusting a height, a volume, and/or a mass of the treatment media in the vibratory trough based on the plurality of process variables.

[0030] In some embodiments, controlling the treatment apparatus further includes controlling a rotation of the component relative to the treatment media based on the plurality of process variables.

[0031] In some embodiments, controlling the treatment apparatus further includes controllably supplying the treatment media into the vibratory trough and/or controllably emptying of the treatment media from the vibratory trough based on the plurality of process variables.

[0032] In some embodiments, the component is a gas turbine engine component.

[0033] In some embodiments, the gas turbine engine component is a bladed disk drum, compressor airfoils made of conventional/ additive manufacture methods or a fan blade.

[0034] The term "shot peening", as used herein, is a method of modifying the mechanical properties of an article that involves striking the surface of the article, typically made of metal or composite, with shot with sufficient force to produce a compressive residual stress layer in the article by plastic deformation. The method tends to result in the article having a rough surface.

[0035] The term "vibrofinishing" (aka vibratory finishing), as used herein, is a method for polishing the surface of an article, typically made of metal or composite, which involves vibrating the article amongst certain specially shaped pellets to decrease the surface roughness of the article. Shot peened articles are often vibrofinished to reduce their surface roughness, with the vibrofinishing typically removing some material from the article but typically not affecting the residual stress created during the shot peening process. It is typically advisable to minimise any vibropolishing in order to minimise the removal of material. Indeed excessive vibropolishing shot peened articles can remove the compressive residual stress layer formed by the shot peening.

[0036] The term "vibropeening" (aka vibratory peening), as used herein, is a method of modifying the mechanical and surface properties of an article, typically made of metal of composite, that involves vibrating the article within a treatment media to polish the article, reduce its surface roughness, and to induce compressive residual stress on the article. Vibropeening tends to provide a superior surface finish to shot peening. It also tends to provide a deeper layer of compression than shot peening albeit typically providing somewhat less residual stress than shot peening.

[0037] The term "fatigue life", as used herein, means the time by which a component or material will last before completely failing because of concentrated stresses.

[0038] Throughout this specification and in the claims that follow, unless the context requires otherwise, the word "comprise" or variations such as "comprises" and "comprising", will be understood to imply the inclusion of a stated integer or group of integers but not the exclusion of any other stated integer or group of integers.

[0039] The skilled person will appreciate that except where mutually exclusive, a feature or parameter described in relation to any one of the above aspects may be applied to any other aspect. Furthermore, except where mutually exclusive, any feature or parameter described herein may be applied to any aspect and/or combined with any other feature or parameter described herein.

Brief description of the drawings

[0040] Embodiments will now be described by way of example only, with reference to the Figures, in which:

Figure 1 is a schematic diagram of a system for controlling a treatment process that modifies surface properties of a component, according to a first embodiment of the present invention;

Figure 2 is a top perspective view of a treatment apparatus of the system of Figure 1;

Figure 3A is a perspective view of the treatment apparatus with some components removed;

Figure 3B is a top view of the treatment apparatus;

Figure 3C is a front view of the treatment apparatus;

Figure 4A is a detailed schematic view of a sensor device from a plurality of sensor devices of the system of Figure 1;

Figure 4B is a perspective view of a sensor device from the plurality of sensor devices of Figure 4A;

Figure 5A is a perspective view of a system for controlling a treatment process that modifies surface properties of a component, according to a second embodiment of the present invention;

Figure 5B is a perspective view of a frame of the system of Figure 5A; and

Figure 6 is a flowchart illustrating a method for controlling the treatment process that modifies the surface properties of the component.

[0041] The following table lists the reference numerals used in the drawings with the features to which they refer:

Ref no.	Feature	Figure
10	Component	1 2 3A 3B 3C 5A
12	Treatment media	1
14	Sensor device(s)	1 2 3A 3C 4A 4B 5A 5B
16	Movement signal(s)	1 4A 5A
18	Central controller	1 4A 5A
20	Process variables	1 5A
22	Predetermined process parameter	1
24	Measured process parameter	1 5A
26	Predicted process variables	1 5A
28	Fixed electrode(s)	4A
30	Movable electrode	4A
32	Electric circuit	4A
34	Processor	4A
35	Communication unit	4A

(continued)

Ref no.	Feature	Figure
36	Power supply circuit	4A
38	Data storage unit	4A
39	Receiver	4A
40	Digital display	4A
41	User input interface	4A
42	Casing	4A 4B
44	Provision for removably attaching a test strip to the casing	4B
46	Test strip	4B
50	System	1
50’	System	5A
100	Treatment apparatus	1 2 3A 3B 3C 5A
102	Vibratory trough	1 2 5A
103	Base	1
104	Component support	1 2 3A 3B 3C 5A
106	Trough vibrating mechanism	1
108	Display device	5A
110	Support fixture	1 2 3A 3B 3C 5A
112	Support shaft	1 2 3A 3B 3C 5A
114	Frame	5A 5B
116	Vertical hanger(s)	5A 5B
118	Trough wall	3A
118a	First trough wall	3A
118b	Second trough wall	3A
120	Drive arrangement	2 3A 3B 3C 5A
122	Gearbox	2 3A 3B 3C 5A
124	Motor	2 3B 3C 5A
126	Timing belt	2 3A 3C 5A
128	Bearing assembly	3C
130	Treatment media inlet	3C
132	Treatment media outlet	3C
200	Method	6
202	Step	6
204	Step	6
206	Step	6
208	Step	6
210	Step	6
F	Electric field	4A
H1	Height	1

(continued)

Ref no.	Feature	Figure
H2	Height	1
H3	Height	1

Detailed description

[0042] Aspects and embodiments of the present invention will now be discussed with reference to the accompanying figures. Further aspects and embodiments will be apparent to those skilled in the art.

[0043] **Figure 1** is a schematic diagram of a system 50 for controlling a treatment process that modifies surface properties of a component 10, according to an embodiment of the present invention. In some embodiments, the treatment process modifies mechanical properties of the component 10. In some embodiments, the component 10 is a part of a gas turbine engine (not shown). In some embodiments, the component 10 of the gas turbine engine is a bladed disk drum or a fan blade. The system 50 includes a treatment apparatus 100 for carrying out the treatment process.

[0044] **Figure 2** is a top perspective view of the treatment apparatus 100. Some portions of the treatment apparatus 100 are shown as transparent in Figure 2 for illustrative purposes. The treatment apparatus 100 is used to modify the mechanical and the surface properties of the component 10 in order to prolong its useful life and/or performance. In some embodiments, the treatment process for modifying the surface properties of the component 10 is vibropeening. Vibropeening is a process combining vibratory polishing and shot peening to a single polishing process in a vibratory bowl or a vibratory trough.

[0045] Referring to Figures 1 and 2, the treatment apparatus 100 includes a vibratory trough 102 for receiving and retaining treatment media 12. The vibratory trough 102 may take a variety of forms with respect to inter alia construction, shape, and materials. In the illustrated embodiment of Figure 2, the vibratory trough 102 has a substantially u-shaped cross-section. The substantially u-shaped cross-section may enable a substantially uniform flow of the treatment media 12 in a desired direction when the vibratory trough 102 is in operation. For example, this may be useful when treating pressure and suction sides of aerofoils. The treatment media 12 may include steel media or shot, although ceramic, metallic, polymeric, composite, or any such material of appropriate hardness, size, or shape may be used depending on the component 10 and the treatment process.

[0046] In some embodiments, the vibratory trough 102 may be composed of a metal, e.g., aluminium or steel, and lined with a polyurethane layer (not shown) to protect the vibratory trough 102 and avoid any chemical reaction with the construction material of the vibratory trough 102. The polyurethane layer may ensure a smooth flow of the treatment media 12 within the vibratory trough 102. It may also be useful to apply a layer of polyurethane to metal parts of the treatment apparatus 100 for which any polishing is not required or is undesirable. Instead of polyurethane, other materials may be used to fulfil the same or similar purpose, e.g., the vibratory trough 102 may be lined with another polymeric material.

[0047] The treatment apparatus 100 further includes a component support 104 fixedly attached to the vibratory trough 102. In some embodiments, the component support 104 may be fixedly attached to the vibratory trough 102 via fasteners, such as screws, rivets, or nut and bolts. The component support 104 supports the component 10 within the vibratory trough 102. The component support 104 is located at least partially within the vibratory trough 102. The component 10 is removably attached to the component support 104. The component support 104 may take a variety of forms so as to support the component 10 to be treated in the treatment apparatus 100.

[0048] **Figure 3A** is a perspective view of the treatment apparatus 100 with some components removed. **Figure 3B** is a top view of the treatment apparatus 100 with some components removed. **Figure 3C** is a side view of the treatment apparatus 100 with some components removed. Referring to Figures 1 to 3C, in some embodiments, the component support 104 includes a support fixture 110 and a support shaft 112 attached to the support fixture 110. In some embodiments, the support fixture 110 of the component support 104 is fixedly attached to the vibratory trough 102 by the fasteners. The support fixture 110 fixedly attaches the support shaft 112 to the vibratory trough 102 and the support shaft 112 removably mounts the component 10 within the vibratory trough 102. The support shaft 112 may be mounted using a bearing assembly 128 (shown in Figure 3C). In some embodiments, the support shaft 112 may be a substantially hollow shaft that spans across each end of the vibratory trough 102.

[0049] In the illustrated embodiment of FIGS. 1 to 3C, the treatment apparatus 100 includes a pair of component supports 104 spaced apart from each other. The pair of component supports 104 includes respective support fixtures 110 opposing each other. The support shaft 112 extends at least between the support fixtures 110 of the pair of component supports 104.

[0050] In some embodiments, the treatment apparatus 100 further includes at least one trough wall 118 provided in the vibratory trough 102. The at least one trough wall 118 is configured to adjust a height, a volume, and/or a mass of the treatment media 12 in the vibratory trough 102. In the illustrated embodiment of Figure 3A, the at least one trough wall 118 includes a first trough wall 118a and an opposing second trough wall 118b provided in the vibratory trough 102. Each of the first and second trough walls 118a, 118b has an aperture (not shown) through which the support shaft 112 can pass. The first trough wall 118a is disposed proximal to one of the support fixtures 110, while the second trough wall 118b is disposed proximal to the other one of the support fixtures 110. During the treatment process, the support shaft 112 passes through the component 10. Further, during the treatment process, the first trough wall 118a and the second trough wall 118b are located on the support shaft 112 on either side of the component 10 in order to support the component 10 in a desired position within the vibratory trough 102. In this way, the support shaft 112 may be removably locatable within the vibratory trough 102 and shaped to support the component 10 in the treatment apparatus 100. In some cases, the component 10 includes a channel (not shown) through which the support shaft 112 may pass to support the component 10 within the vibratory trough 102 of the treatment apparatus 100. If the component 10 includes a pair of recesses rather than the channel, the support shaft 112 may include a pair of support shafts 112 and the component 10 may be supported within the vibratory trough 102 using the pair of support shafts rather than a single support shaft. The first trough wall 118a and the second trough wall 118b may be formed, shaped, angled and/or positioned in accordance with different application requirements.

[0051] The treatment apparatus 100 further includes at least one trough vibrating mechanism 106 (schematically shown in Figure 1) that causes the vibratory trough 102 to vibrate. The at least one trough vibrating mechanism 106 includes suitable equipment for the vibratory trough 102 to be rocked or otherwise oscillated, as desired. In some embodiments, the at least one trough vibrating mechanism 106 may include a plurality of actuators (not shown) and corresponding actuator extension rods (not shown). The actuator extension rods may be individually extendable, as required. The actuators may be powered pneumatically or hydraulically.

[0052] In some embodiments, the treatment apparatus 100 further includes a drive arrangement 120 configured to rotate the component 10 relative to the treatment media 12 (schematically shown in Figure 1). The drive arrangement 120 includes a motor 124, a timing belt 126 (e.g., a chain drive), and a gearbox 122 with a variable gear ratio. Therefore, the support shaft 112 is rotated by the drive arrangement 120 during the treatment process. A speed of rotation of the support shaft 112 and the component 10 may be controlled by the gearbox 122 of the drive arrangement 120 in order to control the coverage and uniformity of the treatment process (i.e., vibropeening).

[0053] In some embodiments, the treatment apparatus 100 further includes a treatment media inlet 130 (shown in Figure 3C) for controllably supplying the treatment media 12 into the vibratory trough 102. In some embodiments, the treatment media inlet 130 may include an inlet valve (not shown) that is in fluid communication with a reservoir (not shown) storing the treatment media 12. In some embodiments, the treatment apparatus 100 further includes a treatment media outlet 132 (shown in Figure 3C) for controllably emptying the treatment media 12 from the vibratory trough 102. In some embodiments, the treatment media outlet 132 may include an outlet valve (not shown) to remove the treatment media 12 from the vibratory trough 102 after the treatment process is completed.

[0054] The system 50 further includes a plurality of sensor devices 14 respectively and fixedly disposed at a plurality of heights relative to the vibratory trough 102. Some of the sensor devices 14 from the plurality of sensor devices 14 may be fixedly disposed at a height H1 from a base 103 of the vibratory trough 102. Some other sensor devices 14 from the plurality of sensor devices 14 may be fixedly disposed at a height H2 from the base 103 of the vibratory trough 102. Further, some other sensor devices 14 from the plurality of sensor devices 14 may be fixedly disposed at a height H3 from the base 103 of the vibratory trough 102. The plurality of sensor devices 14 is configured to respectively measure a plurality of movement parameters of the treatment media 12 at the plurality of heights (i.e., H1, H2, H3, and so on) and generate a plurality of movement signals 16 corresponding to the plurality of movement parameters. The plurality of movement parameters of the treatment media 12 may include an acceleration and/or a speed of the treatment media 12 at the plurality of heights. In some embodiments, the plurality of movement parameters may be a plurality of vibration parameters. Therefore, the plurality of movement signals 16 may be a plurality of vibration signals. In some embodiments, each of the plurality of sensor devices 14 is fixedly attached to the support fixture 110. Therefore, each of the plurality of sensor devices 14 may measure a relative movement parameter of the treatment media 12 with respect to the vibratory trough 102 at a corresponding height from the plurality of heights. In some embodiments, each of the plurality of sensor devices 14 may include an intensity prediction unit, a vibration monitoring sensor, an accelerometer, an ultrasonic senor, an infrared sensor, and/or any other sensor capable of measuring the plurality of movement parameters of the treatment media 12 at the plurality of heights.

[0055] The system 50 further includes a central controller 18 communicably coupled to each of the plurality of sensor devices 14. The central controller 18 may be a control circuit, a computer, a microprocessor, a microcomputer, a central processing unit, or any suitable device or apparatus. The central controller 18 may include one or more of a digital processor, an analog processor, a digital circuit designed to process information, an analog circuit designed to process information, a state machine, and/or other mechanisms for electronically processing information. In some embodiments, the central controller 18 is communicably coupled to each of the plurality of sensor devices 14 via at least one of a wired connection and a wireless connection. Functional details of the central controller 18 will be described later in the description.

[0056] **Figure 4A** is a detailed schematic view of a sensor device 14 from the plurality of sensor devices 14. In some embodiments, each of the plurality of sensor devices 14 includes a casing 42 (e.g., a metal housing). In some embodiments, the casing 42 may be a cuboidal casing. In some embodiments, each of the plurality of sensor devices 14 further includes at least two fixed electrodes 28 for generating an electric field F. Further, an electric parameter (e.g., an electric current, an electric voltage, etc.) is applied across the at least two fixed electrodes 28 to induce the electric field F between the at least two fixed electrodes 28. Each of the plurality of sensor devices 14 further includes at least one movable electrode 30 disposed between the at least two fixed electrodes 28. Upon vibration of the vibratory trough 102 (shown in Figure 1) by the at least one trough vibrating mechanism 106 (shown in Figure 1), the at least one movable electrode 30 moves causing the electric field F between the at least two fixed electrodes 28 to change.

[0057] In some embodiments, each of the plurality of sensor devices 14 further includes an electric circuit 32 electrically coupled to the at least two fixed electrodes 28 and the at least one movable electrode 30. The electric circuit 32 is configured to measure the corresponding movement parameter based on the change in the electric field F between the at least two fixed electrodes 28. In some embodiments, each of the plurality of sensor devices 14 further includes a processor 34 communicably coupled to the electric circuit 32. The processor 34 is configured to generate the corresponding movement signal 16 based on the corresponding movement parameter. The processor 34 is further configured to transmit the corresponding movement signal 16 to the central controller 18.

[0058] In some embodiments, each of the plurality of sensor devices 14 further includes a data storage unit 38 configured to store the plurality of movement signals 16 and a set of instructions or a genetic algorithm that is executable by the processor 34. In some embodiments, each of the plurality of sensor devices 14 further includes a communication unit 35 to transfer data in real-time to an external unit or to connect to an external digital device. For example, the communication unit 35 of each of the plurality of sensor devices 14 may transfer the corresponding movement signal 16 to the central controller 18. The communication unit 35 may be a Wi-Fi or Bluetooth unit. In some embodiments, each of the plurality of sensor devices 14 further includes a power supply circuit 36 that enables charging of a battery of the corresponding sensor device 14.

[0059] In some embodiments, each of the plurality of sensor devices 14 further includes a receiver 39 that may receive data from the central controller 18. In some cases, the receiver 39 may receive data (e.g., the plurality of movement parameters) from other sensors from the plurality of sensors 14. In some embodiments, each of the plurality of sensor devices 14 further includes a digital display 40. In some embodiments, the digital display 40 is communicably coupled to the processor 34 and configured to display the corresponding movement signal 16. In some embodiments, the digital display 40 is communicably coupled to the receiver 39 and configured to display one or more values corresponding to the received data to a user. The receiver 39 includes a digital display 40 to display the values corresponding to the received data. In some embodiments, each of the plurality of sensor devices 14 further includes a user input interface 41 (e.g., one or more buttons) to configure one or more settings of the sensor device 14 or the digital display 40 of the sensor device 14.

[0060] **Figure 4B** is a perspective view (i.e., outer view) of a sensor device 14 from the plurality of sensor devices 14. In the illustrated embodiment of Figure 4B, the casing 42 of each of the plurality of sensor devices 14 includes one or more provisions/devices 44 for removably attaching a test strip 46 to the casing 42. The test strip 46 may be a metal or alloy strip of a predetermined thickness to determine an intensity of the treatment process being induced on the component 10. For example, the test strip may include Almen test strip (thin strip of SAE 1070 steel) used to quantify the intensity of the vibropeening of the component 10 (shown in Figures 1 and 2). The intensity of the treatment process may correspond to an arc height of Almen test strip measured at a coverage of 98% using an Almen gauge. In some embodiments, the provisions 44 may include fasteners for removably holding the test strip 46 on the casing 42. In some other embodiments, the provisions 44 may include mechanisms, latching mechanisms, or any other suitable attachment mechanisms capable of removably attaching the test strip 46 to the casing 42.

[0061] Referring to Figures 1 to 4B, the central controller 18 is configured to receive the plurality of movement signals 16 from the plurality of sensor devices 14. The central controller 18 is further configured to determine a plurality of process variables 20 corresponding to the plurality of movement signals 16. The plurality of process variables 20 may include values of energy, coverage, and intensity of the treatment process.

[0062] In some embodiments, the system 50 further includes a display device 108 (shown in Figure 1) communicably coupled to the central controller 18. The display device 108 is configured to display the plurality of process variables 20. The display device 108 may display the energy, the intensity, and/or coverage of the treatment process at the plurality of heights. In some applications, an operator may also adjust or control the treatment apparatus 100 based on the plurality of process variables 20 displayed on the display device 108. In some examples, the display device 108 may be a monitor or a screen.

[0063] The central controller 18 is further configured to control the treatment apparatus 100 based at least on the plurality of process variables 20. In some embodiments, the central controller 18 is further configured to control the at least one trough vibrating mechanism 106 (shown in Figure 1) of the treatment apparatus 100 based on the plurality of process variables 20. In other words, the central controller 18 may control the at least one trough vibrating mechanism 106 so as to adjust the amount of vibration of the vibratory trough 102. For example, the central controller 18 may control one or more of the plurality of actuators and corresponding actuator extension rods.

[0064] In some embodiments, the central controller 18 is further configured to control the drive arrangement 120 (shown in Figure 2) of the treatment apparatus 100 based on the plurality of process variables 20. For example, according to desired application requirements, the central controller 18 may adjust a speed of rotation of the support shaft 112 and thereby, the rotation of the component 10 by controlling the gearbox 122 of the drive arrangement 120. In some embodiments, the central controller 18 is further configured to control the at least one trough wall 118 (shown in Figure 3A) of the treatment apparatus 100 based on the plurality of process variables 20. For example, the central controller 18 may adjust the height, the volume, and/or the mass of the treatment media 12 in the vibratory trough 102 by controlling the first trough wall 118a and the second trough wall 118b. In some embodiments, the central controller 18 is further configured to control the treatment media inlet 130 and/or the treatment media outlet 132 (shown in Figure 3C) of the treatment apparatus 100 based on the plurality of process variables 20 to further adjust the height, the volume and/or the mass of the treatment media 12 in the vibratory trough 102.

[0065] In some embodiments, the central controller 18 is further configured to receive a predetermined process parameter 22 (shown in Figure 1) for the treatment process. For example, the predetermined process parameter 22 may be a drawing requirement of the treatment process for the component 10. In some examples, the predetermined process parameter 22 may be manually provided by the user via one or more input devices (not shown). In some embodiments. The predetermined process parameter 22 may be retrieved from a memory (not shown) communicably coupled to the central controller 18. In some embodiments, the central controller 18 may include the memory. In some embodiments, the memory may include an external database or a library.

[0066] The central controller 18 is further configured to determine a measured process parameter 24 (shown in Figure 1) based on the plurality of process variables 20. For example, the measured process parameter 24 may be an overall intensity of the treatment process which may be determined by the central controller 18 using the plurality of process variables 20 (e.g., a plurality of intensities) measured at the plurality of heights. In some embodiments, the central controller 18 is further configured to control the treatment apparatus 100 based on the predetermined process parameter 22 and the measured process parameter 24, such that a difference between the predetermined process parameter 22 and the measured process parameter 24 is reduced. By reducing the difference between the predetermined process parameter 22 and the measured process parameter 24, desirable intensity and/or energy (e.g., the predetermined process parameter 22) of the treatment process (i.e., vibropeening) may be obtained.

[0067] In some embodiments, the central controller 18 is further configured to, prior to receiving the plurality of movement signals 16 from the plurality of sensor devices 14, determine a plurality of predicted process variables 26 corresponding to the plurality of heights of the vibratory trough 102. The plurality of predicted process variables 26 may be predicted intensities of the treatment process (i.e., vibropeening) at the plurality of heights. In some embodiments, the plurality of predicted process variables 26 may be predicted based on one or more machine-learning models and/or algorithms.

[0068] In some embodiments, the central controller 18 is further configured to control the treatment apparatus 100 based on the plurality of predicted process variables 26 and the plurality of process variables 20, such that a difference between each of the plurality of process variables 20 and a corresponding predicted process variable 26 from the plurality of predicted process variables 26 is reduced. By reducing the difference between each of the plurality of process variables 20 and the corresponding predicted process variable 26 from the plurality of predicted process variables 26, desirable value of intensity and/or energy of the treatment process (i.e., vibropeening) may be obtained at the plurality of heights (i.e., H1, H2, H3, and so on, as shown in Figure 1).

[0069] Referring again to Figures 1 to 4B, the central controller 18 controls the treatment apparatus 100 based at least on the plurality of process variables 20, such as a value of the energy, the coverage, and/or the intensity at the respective heights (i.e., H1, H2, H3, and so on) relative to the vibratory trough 102. The central controller 18 communicably coupled to the plurality of sensor devices 14 fixedly disposed at the plurality of heights relative to the vibratory trough 102 may enable the system 50 to monitor the plurality of movement signals 16 and the plurality of process variables 20 in specific sections of the vibratory trough 102. In other words, the system 50 may be used to obtain a desired parameter of the treatment process (i.e., vibropeening) for a specific aerospace component according to the drawing requirement.

[0070] As the controller 18 controls the treatment apparatus 100 based at least on the plurality of process variables 20 corresponding to the plurality of movement signals 16, the system 50 may provide uniform residual stress distribution and material properties across the component 10 during the treatment process (i.e., vibropeening). This may improve fatigue life and/or performance of the component 10. This is particularly important when the component 10 is large in size. Further, unlike conventional techniques where a component (subject part) may have to be scrapped if there is any error in obtaining the drawing requirement (e.g., Almen intensity), the system 50 may enable monitoring the vibropeening at specific heights and accordingly controlling the vibropeening of the component 10. As a result, a likelihood of scrapping the component 10 after the treatment process of the component 10 may be reduced by the system 50 of the present invention. Therefore, the central controller 18 and the plurality of sensor devices 14 may validate a process control method and/or mechanism for the treatment process for the component 10.

[0071] Moreover, as compared to the conventional vibropeening techniques, the system 50 may substantially reduce human intervention because of continuous determination of the plurality of process variables 20 corresponding to the plurality of movement signals 16 and subsequently controlling the treatment apparatus 100 based at least on the plurality of process variables 20. The system 50 may enable the vibropeening which is relatively faster with less intensive manual labour. Further, in the system 50, there are minimal chances of wastage of sacrificial Almen strips or scrapping of components which may not meet the drawing requirements. The system 50 may be used for vibropeening of rotationally symmetric as well as asymmetric components.

[0072] **Figure 5A** is a perspective view of a system 50' for controlling the treatment process that modifies surface properties of the component 10, according to an embodiment of the present invention. The system 50' is substantially similar and functionally equivalent to the system 50 of Figure 1, with common components being referred to by the same numerals. Some portions of the treatment apparatus 100 are shown as transparent in Figure 5A for illustrative purposes. Some of the components are not shown in Figure 5A for illustrative purposes. However, in the illustrated embodiment of Figure 5A, the system 50' further includes a frame 114 fixedly attached to the vibratory trough 102. **Figure 5B** is a perspective view of the frame 114. Functional advantages of the system 50' is the same as that of the system 50 of Figure 1.

[0073] Referring to Figures 5A and 5B, the frame 114 includes one or more vertical hangers 116. Each of the one or more vertical hangers 116 extends at least partially into the treatment media 12. In the illustrated embodiment of Figures 5A and 5B, a total of four vertical hangers 116 are shown. However, in other embodiments, the frame 114 may include any number of the vertical hangers 116. Each of the plurality of sensor devices 14 is fixedly attached to the one or more vertical hangers 116 of the frame 114. In the illustrated embodiment of Figures 5A and 5B, a total of three sensor devices 14 are fixedly attached to each vertical hanger 116. In other embodiments, any number of sensor devices 14 may be fixedly attached to each vertical hanger 116, as per application requirements.

[0074] **Figure 6** is a flowchart illustrating a method 200 for controlling the treatment process that modifies the surface properties of the component 10 (shown in Figures 1 and 2), according to an embodiment of the present invention.

[0075] Referring to Figures 1 to 6, at step 202, the method 200 includes providing the treatment apparatus 100 (shown in Figures 1 and 2) for carrying out the treatment process. At step 204, the method 200 includes providing the plurality of sensor devices 14 (shown in Figures 1 and 2) respectively and fixedly disposed at the plurality of heights (i.e., H1, H2, H3, and so on, shown in Figure 1) relative to the vibratory trough 102.

[0076] At step 206, the method 200 includes receiving the plurality of movement signals 16 (shown in Figure 1) from the plurality of sensor devices 14. At step 208, the method 200 includes determining the plurality of process variables 20 (shown in Figure 1) corresponding to the plurality of movement signals 16. At step 210, the method 200 includes controlling the treatment apparatus 100 based at least on the plurality of process variables 20. In some embodiments, the central controller 18 may include a memory (not shown) storing computer executable instructions or computer code that may be executed by the central controller 18 to perform the step 210 of the method 200.

[0077] In some embodiments, controlling the treatment apparatus 100 further includes controlling the at least one trough vibrating mechanism 106 based on the plurality of process variables 20. For example, the central controller 18 may control one or more of the plurality of actuators and the corresponding actuator extension rods of the treatment apparatus 100 based at least on the plurality of process variables 20 to adjust the amount of vibration of the vibratory trough 102. In some embodiments, controlling the treatment apparatus 100 further includes adjusting the height, volume, and/or mass of the treatment media 12 in the vibratory trough 102 based on the plurality of process variables 20. For example, the central controller 18 may control the first trough wall 118a and/or the second trough wall 118b of the treatment apparatus 100 based at least on the plurality of process variables 20 to adjust the height, volume, and/or mass of the treatment media 12 in the vibratory trough 102. In some embodiments, controlling the treatment apparatus 100 further includes controlling a rotation of the component 10 relative to the treatment media 12 based on the plurality of process variables 20. For example, the central controller 18 may adjust a speed of rotation of the support shaft 112 and thereby, the rotation of the component 10 by controlling the gearbox 122 of the drive arrangement 120. In some embodiments, controlling the treatment apparatus 100 further includes controllably supplying the treatment media 12 into the vibratory trough 102 and/or controllably emptying of the treatment media 12 from the vibratory trough 102 based on the plurality of process variables 20. For example, the central controller 18 may control the treatment media inlet 130 and/or the treatment media outlet 132 of the treatment apparatus 100 based at least on the plurality of process variables 20 to adjust the height, volume, and/or mass of the treatment media 12 in the vibratory trough 102.

[0078] In some embodiments, the method 200 further includes receiving the predetermined process parameter 22 (shown in Figure 1) of the treatment process. The method 200 further includes determining the measured process parameter 24 (shown in Figure 1) based on the plurality of process variables 20. In some embodiments, controlling the treatment apparatus 100 further includes controlling the treatment apparatus 100 based on the predetermined process parameter 22 and the measured process parameter 24, such that the difference between the predetermined process parameter 22 and the measured process parameter 24 is reduced.

[0079] In some embodiments, the method 200 further includes, prior to receiving the plurality of movement signals 16 from the plurality of sensor devices 14, determining the plurality of predicted process variables 26 (shown in Figure 1) corresponding to the plurality of heights of the vibratory trough 102. In some embodiments, controlling the treatment apparatus 100 further includes controlling the treatment apparatus 100 based on the plurality of predicted process variables 26 and the plurality of process variables 20, such that the difference between each of the plurality of process variables 20 and the corresponding predicted process variable 26 from the plurality of predicted process variables 26 is reduced.

Claims

1. A system (50, 50') for controlling a treatment process that modifies surface properties of a component (10), the system (50, 50') comprising:

a treatment apparatus (100) for carrying out the treatment process, the treatment apparatus (100) comprising:

a vibratory trough (102) for receiving and retaining treatment media (12);
a component support (104) fixedly attached to the vibratory trough (102), wherein the component support (104) supports the component (10) within the vibratory trough (102); and
at least one trough vibrating mechanism (106) that causes the vibratory trough (102) to vibrate;

a plurality of sensor devices (14) respectively and fixedly disposed at a plurality of heights relative to the vibratory trough (102), wherein the plurality of sensor devices (14) is configured to respectively measure a plurality of movement parameters of the treatment media (12) at the plurality of heights and generate a plurality of movement signals (16) corresponding to the plurality of movement parameters; and
a central controller (18) communicably coupled to each of the plurality of sensor devices (14), the central controller (18) configured to:

receive the plurality of movement signals (16) from the plurality of sensor devices (14);
determine a plurality of process variables (20) corresponding to the plurality of movement signals (16); and
control the treatment apparatus (100) based at least on the plurality of process variables (20).

2. The system (50, 50') of claim 1, further comprising a display device (108) communicably coupled to the central controller (18), wherein the display device (108) is configured to display the plurality of process variables (20).

3. The system (50) of claim 1 or 2, wherein the component support (104) comprises a support fixture (110) and a support shaft (112) attached to the support fixture (110), wherein the support fixture (110) fixedly attaches the support shaft (112) to the vibratory trough (102) and the support shaft (112) removably mounts the component (10) within the vibratory trough (102), and wherein each of the plurality of sensor devices (14) is fixedly attached to the support fixture (110).

4. The system (50') of claim 1 or 2, further comprising a frame (114) fixedly attached to the vibratory trough (102), wherein the frame (114) comprises one or more vertical hangers (116), and wherein each of the plurality of sensor devices (14) is fixedly attached to the one or more vertical hangers of the frame.

5. The system (50') of claim 4, wherein each of the one or more vertical hangers (116) extends at least partially into the treatment media (12).

6. The system (50, 50') of any preceding claim, wherein the central controller (18) is further configured to:

receive a predetermined process parameter (22) for the treatment process;
determine a measured process parameter (24) based on the plurality of process variables (20); and
control the treatment apparatus (100) based on the predetermined process parameter (22) and the measured process parameter (24), such that a difference between the predetermined process parameter (22) and the measured process parameter (24) is reduced.

7. The system (50, 50') of any preceding claim, wherein the central controller (18) is further configured to:

prior to receiving the plurality of movement signals (16) from the plurality of sensor devices (14), determine a plurality of predicted process variables (26) corresponding to the plurality of heights of the vibratory trough (102); and

control the treatment apparatus (100) based on the plurality of predicted process variables (26) and the plurality of process variables (20), such that a difference between each of the plurality of process variables (20) and a corresponding predicted process variable (26) from the plurality of predicted process variables (26) is reduced.

8. The system (50, 50') of any preceding claim, wherein the central controller (18) is further configured to control the at least one trough vibrating mechanism (106) of the treatment apparatus (100) based on the plurality of process variables (20).

9. The system (50, 50') of any preceding claim, wherein the treatment apparatus (100) further comprises at least one trough wall (118) provided in the vibratory trough (102) and configured to adjust a height, a volume, and/or a mass of the treatment media (12) in the vibratory trough (102), and wherein the central controller (18) is further configured to control the at least one trough wall (118) of the treatment apparatus (100) based on the plurality of process variables (20).

10. The system (50, 50') of any preceding claim, wherein the treatment apparatus (100) further comprises a drive arrangement (120) configured to rotate the component (10) relative to the treatment media (12), and wherein the central controller (18) is further configured to control the drive arrangement (120) of the treatment apparatus (100) based on the plurality of process variables (20).

11. The system (50, 50') of any preceding claim, wherein the treatment apparatus (100) further comprises a treatment media inlet (130) for controllably supplying the treatment media (12) into the vibratory trough (102) and a treatment media outlet (132) for controllably emptying the treatment media (12) from the vibratory trough (102), and wherein the central controller (18) is further configured to control the treatment media inlet (130) and/or the treatment media outlet (132) of the treatment apparatus (100) based on the plurality of process variables (20).

12. The system (50, 50') of any preceding claim, wherein each of the plurality of sensor devices (14) comprises:

at least two fixed electrodes (28) for generating an electric field (F), wherein an electric parameter is applied across the at least two fixed electrodes (28) to induce the electric field (F) between the at least two fixed electrodes (28);

at least one movable electrode (30) disposed between the at least two fixed electrodes (28), wherein upon vibration of the vibratory trough (102), the at least one movable electrode (30) moves thereby causing the electric field (F) between the at least two fixed electrodes (28) to change;

an electric circuit (32) electrically coupled to the at least two fixed electrodes (28) and the at least one movable electrode (30), wherein the electric circuit (32) is configured to measure the corresponding movement parameter based on the change in the electric field (F) between the at least two fixed electrodes (28); and

a processor (34) communicably coupled to the electric circuit (32), wherein the processor (34) is configured to:

generate the corresponding movement signal (16) based on the corresponding movement parameter; and

transmit the corresponding movement signal (16) to the central controller (18).

13. The system (50, 50') of any preceding claim, wherein each of the plurality of sensor devices (14) further comprises a casing (42), and wherein the casing (42) comprises one or more provisions (44) for removably attaching a test strip (46) to the casing (42).

14. A method (200) for controlling a treatment process that modifies surface properties of a component (10), the method (200) comprising the steps of:

providing a treatment apparatus (100) for carrying out the treatment process, the treatment apparatus (100) comprising:

a vibratory trough (102) for receiving and retaining treatment media (12),

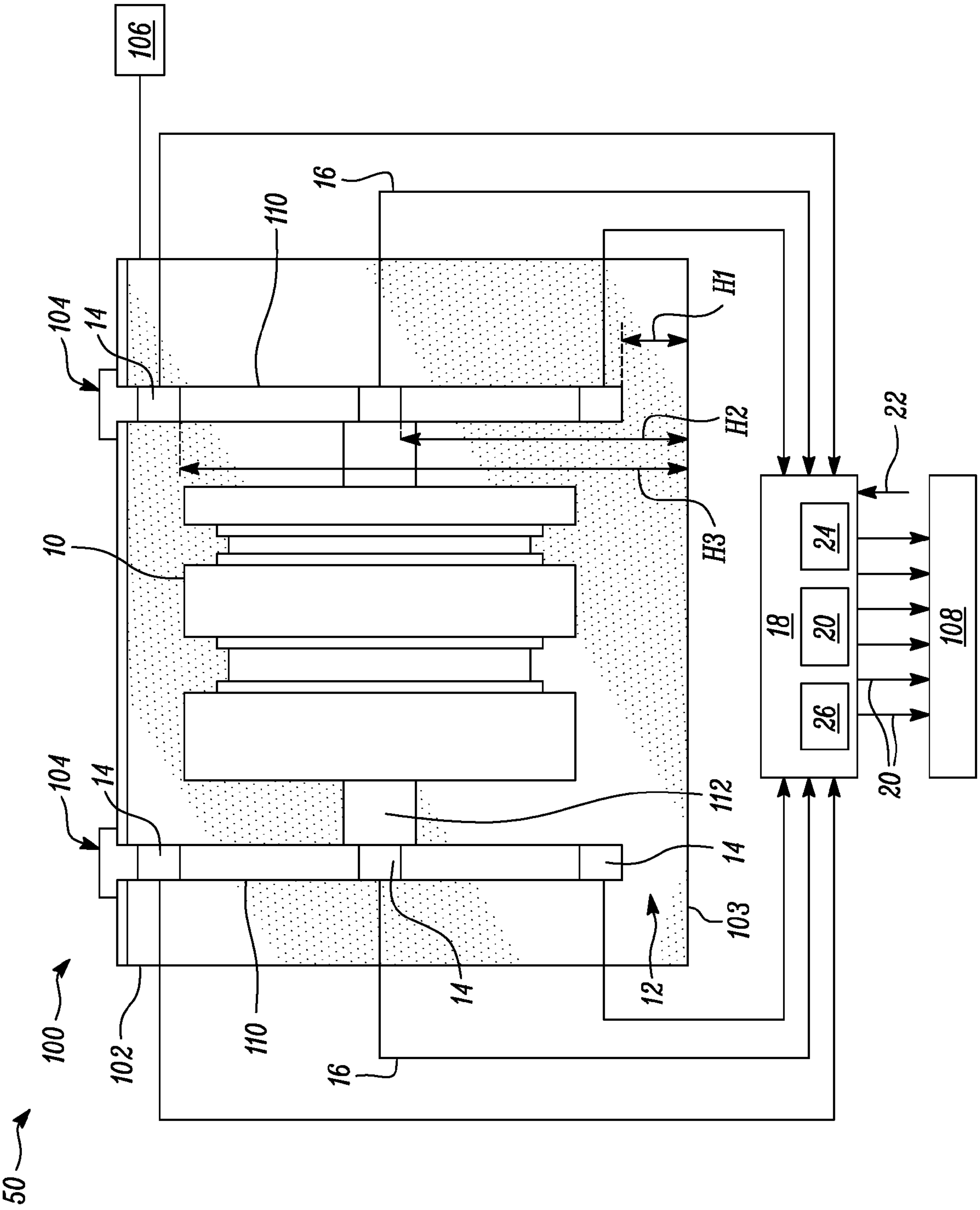
a component support (104) fixedly attached to the vibratory trough (102), wherein the component support (104) supports the component (10) within the vibratory trough (102); and

at least one trough vibrating mechanism (106) that causes the vibratory trough (102) to vibrate;

providing a plurality of sensor devices (14) respectively and fixedly disposed at a plurality of heights relative to the vibratory trough (102), wherein the plurality of sensor devices (14) is configured to respectively measure a plurality of movement parameters of the treatment media (12) at the plurality of heights and generate a plurality of movement signals (16) corresponding to the plurality of movement parameters;
receiving the plurality of movement signals (16) from the plurality of sensor devices (14);
determining a plurality of process variables (20) corresponding to the plurality of movement signals (16); and
controlling the treatment apparatus (100) based at least on the plurality of process variables (20).

15. The method of claim 14, further comprising:

receiving a predetermined process parameter (22) of the treatment process; and
determining a measured process parameter (24) based on the plurality of process variables (20);
wherein controlling the treatment apparatus (100) further comprises controlling the treatment apparatus (100) based on the predetermined process parameter (22) and the measured process parameter (24), such that a difference between the predetermined process parameter (22) and the measured process parameter (24) is reduced.


50
100
102
103
104
106
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H1
H2
H3

FIG. 1

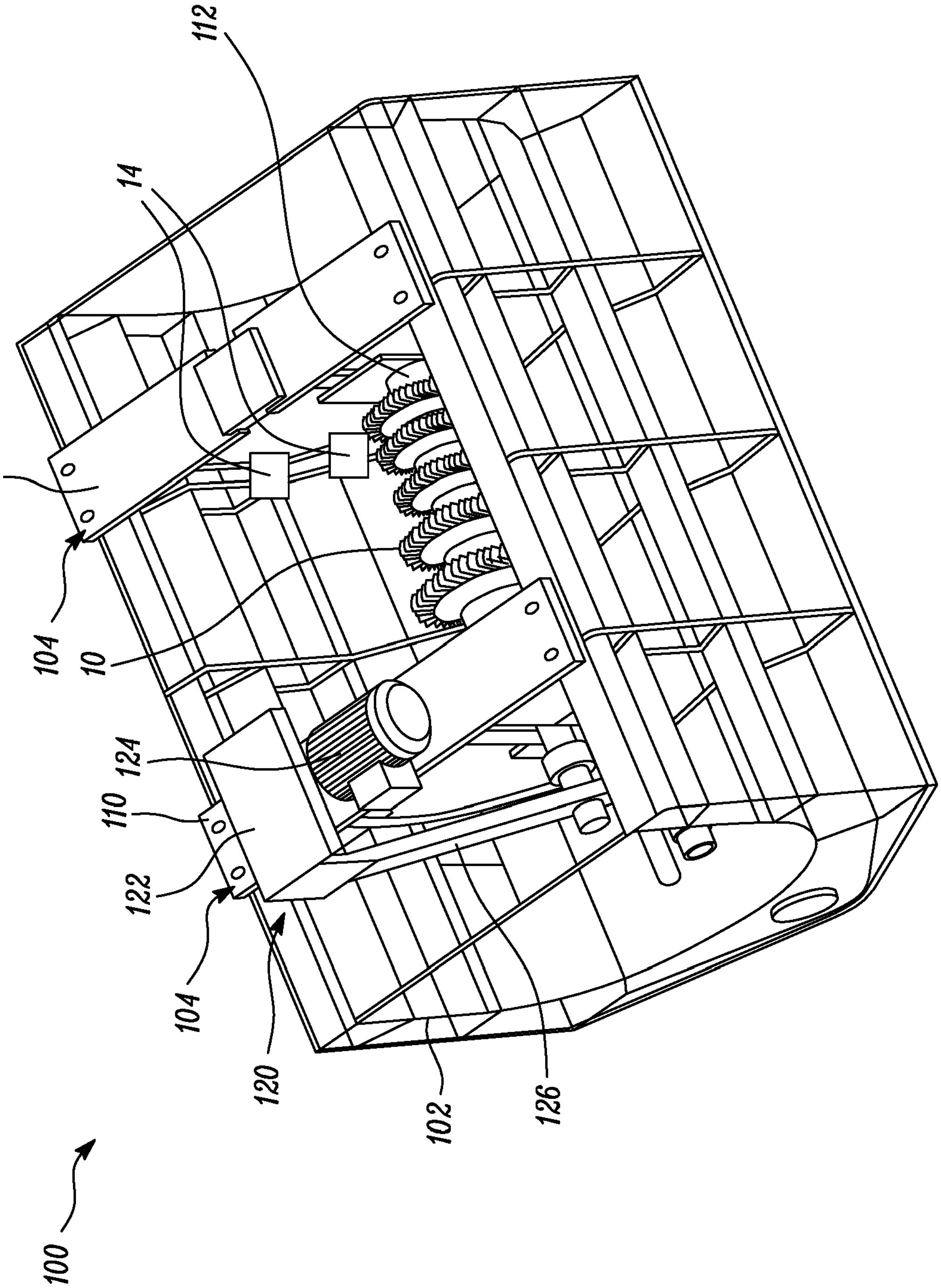


FIG. 2

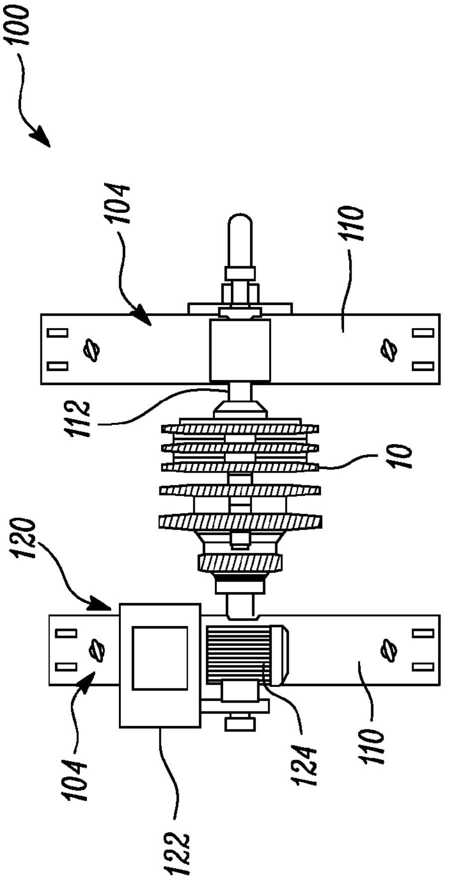


FIG. 3B

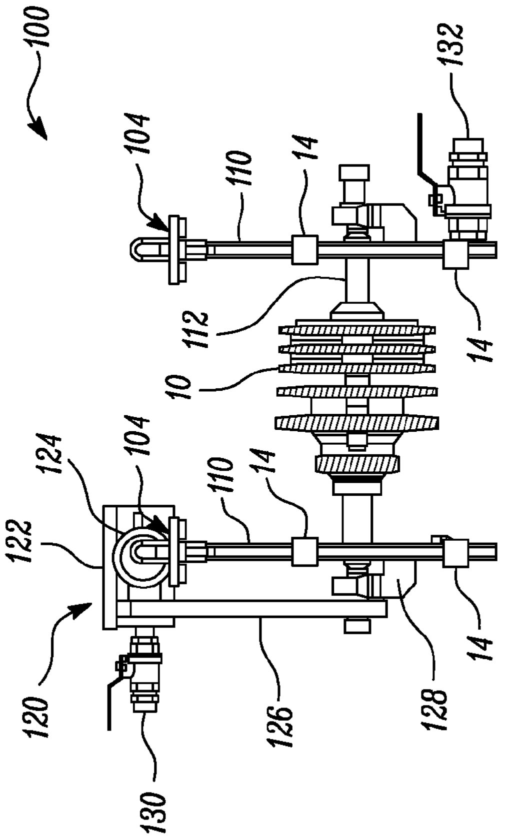


FIG. 3C

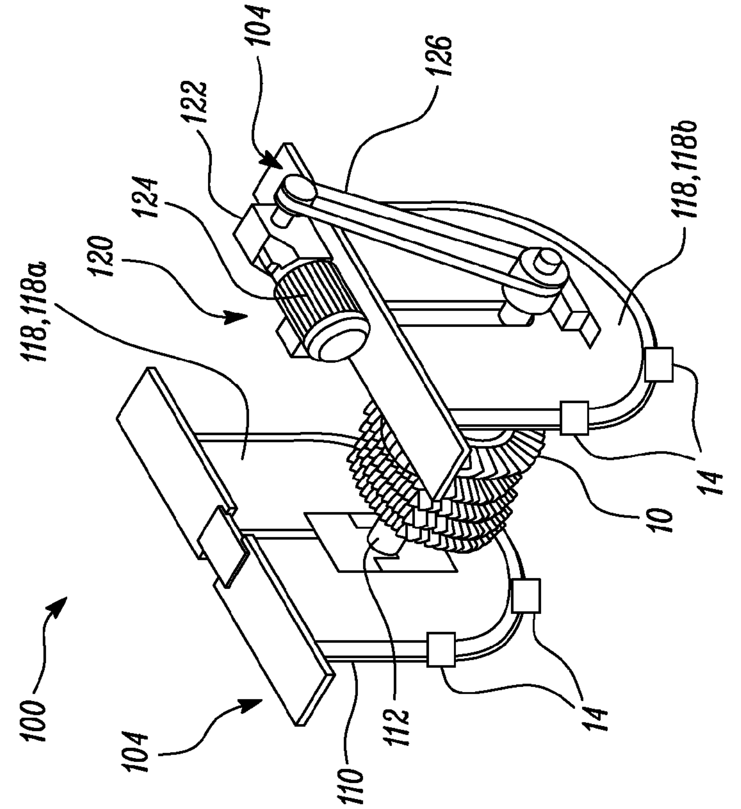


FIG. 3A

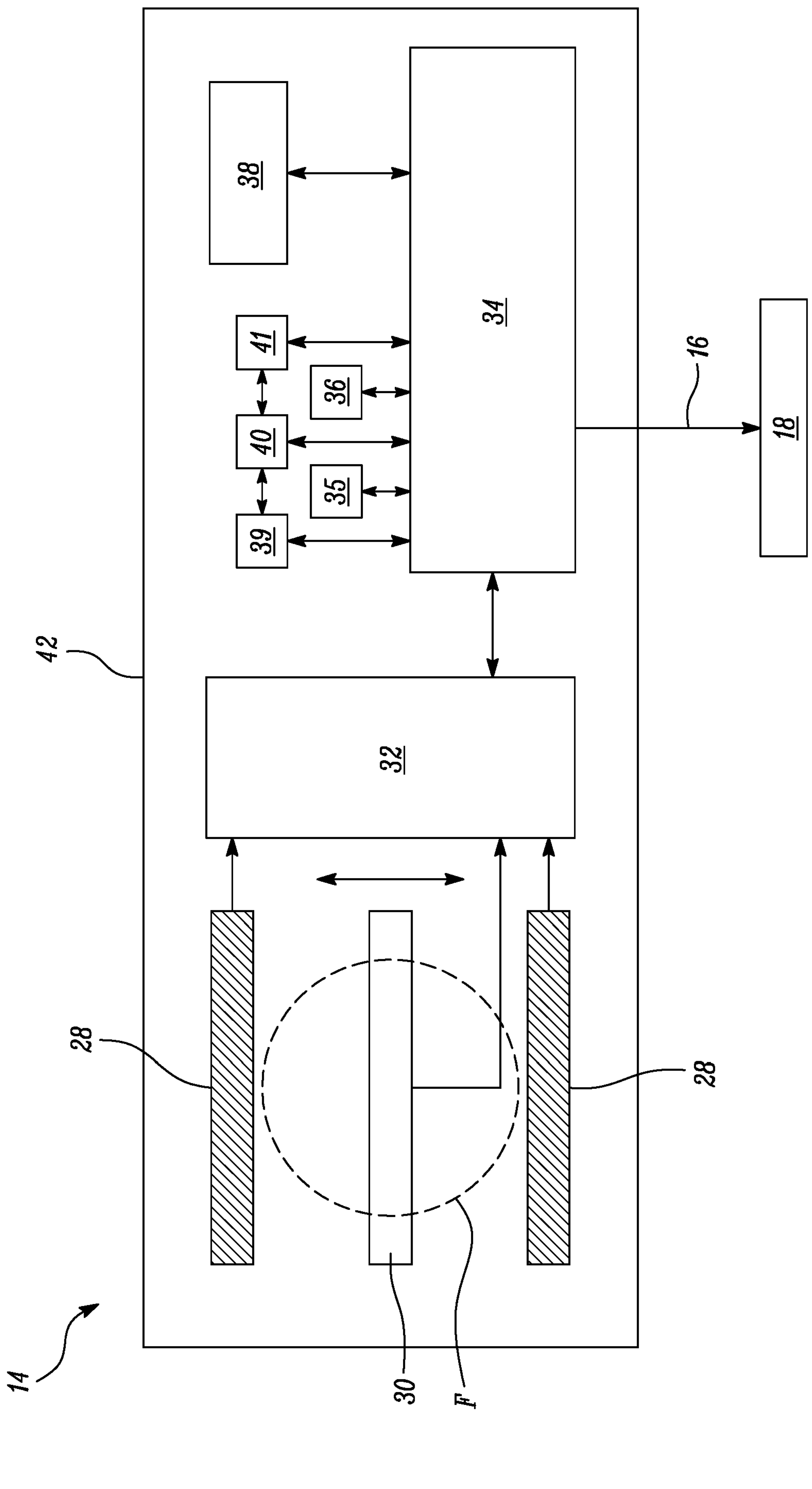


FIG. 4A

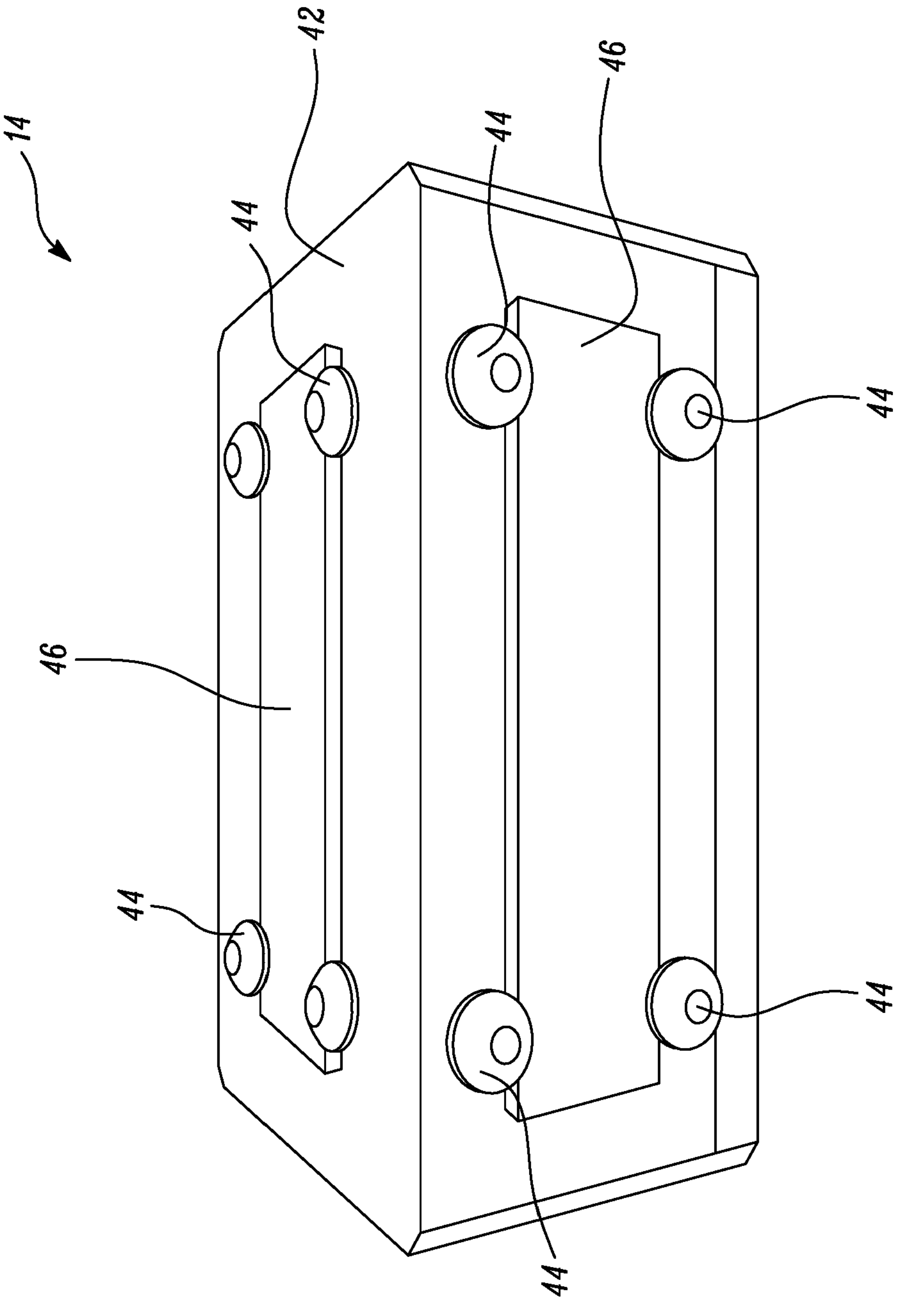
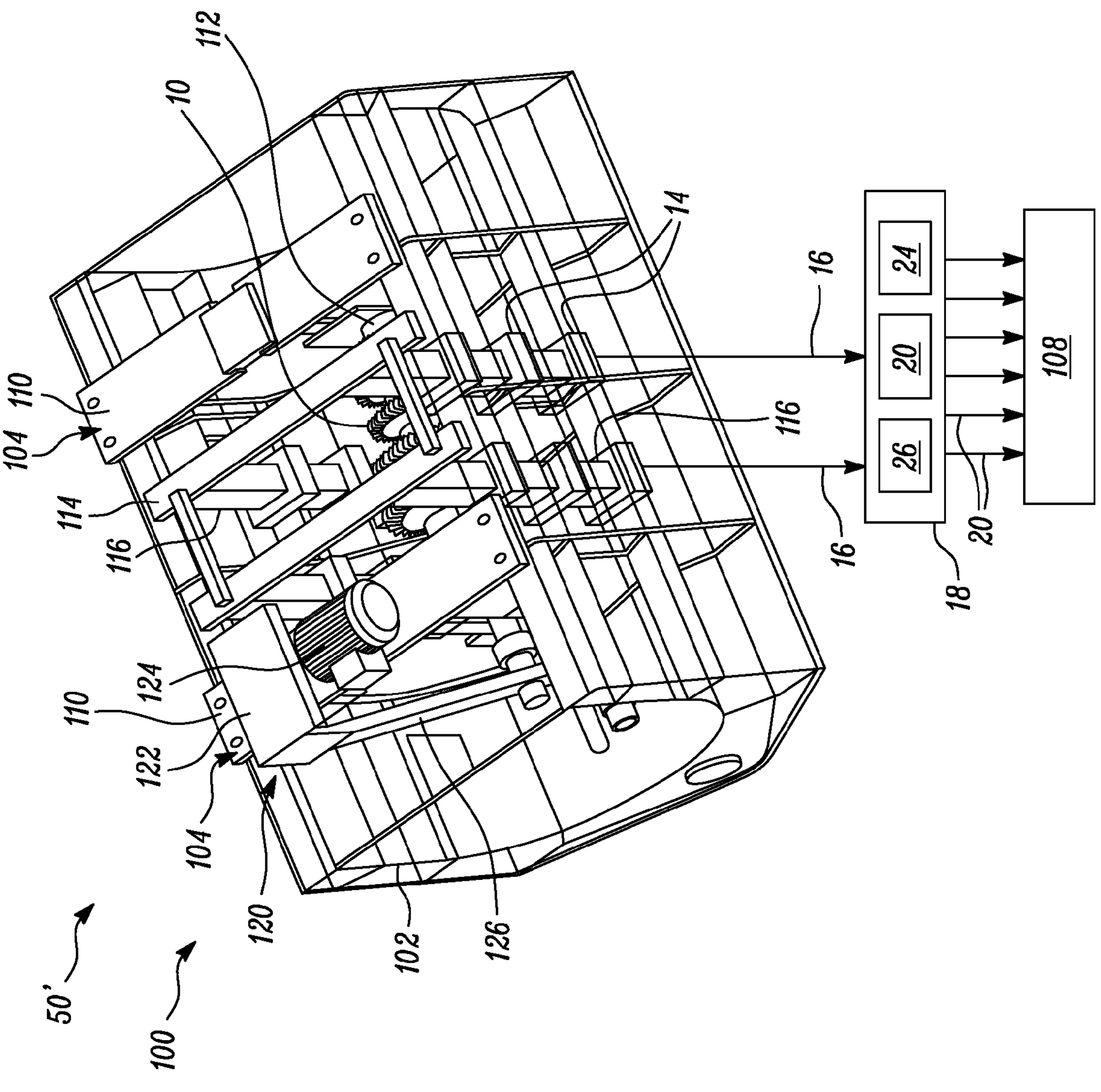


FIG. 4B


50'
100
102
126
120
104
122
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116
16
18
26
20
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20
108

FIG. 5A

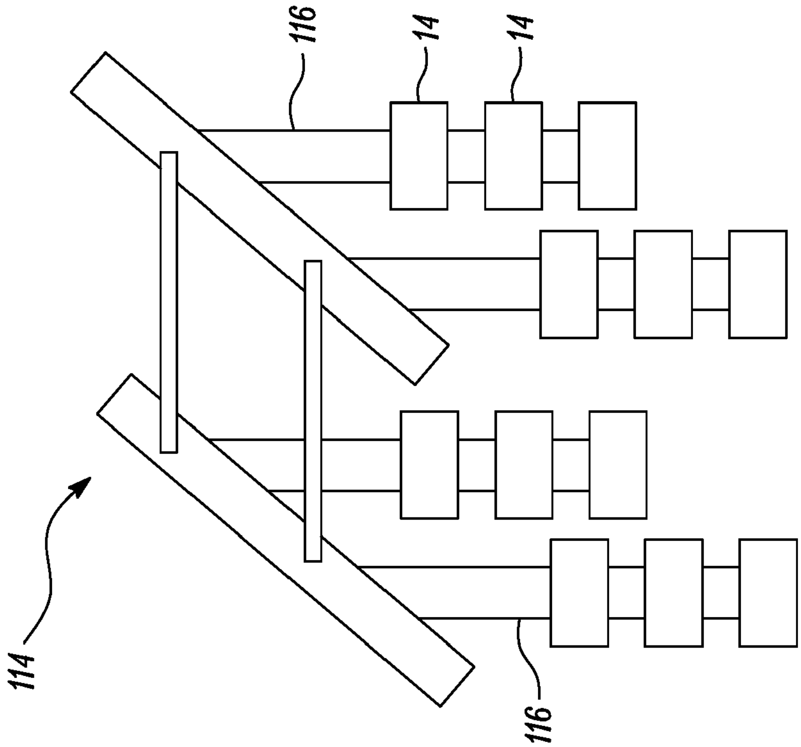

FIG. 5B

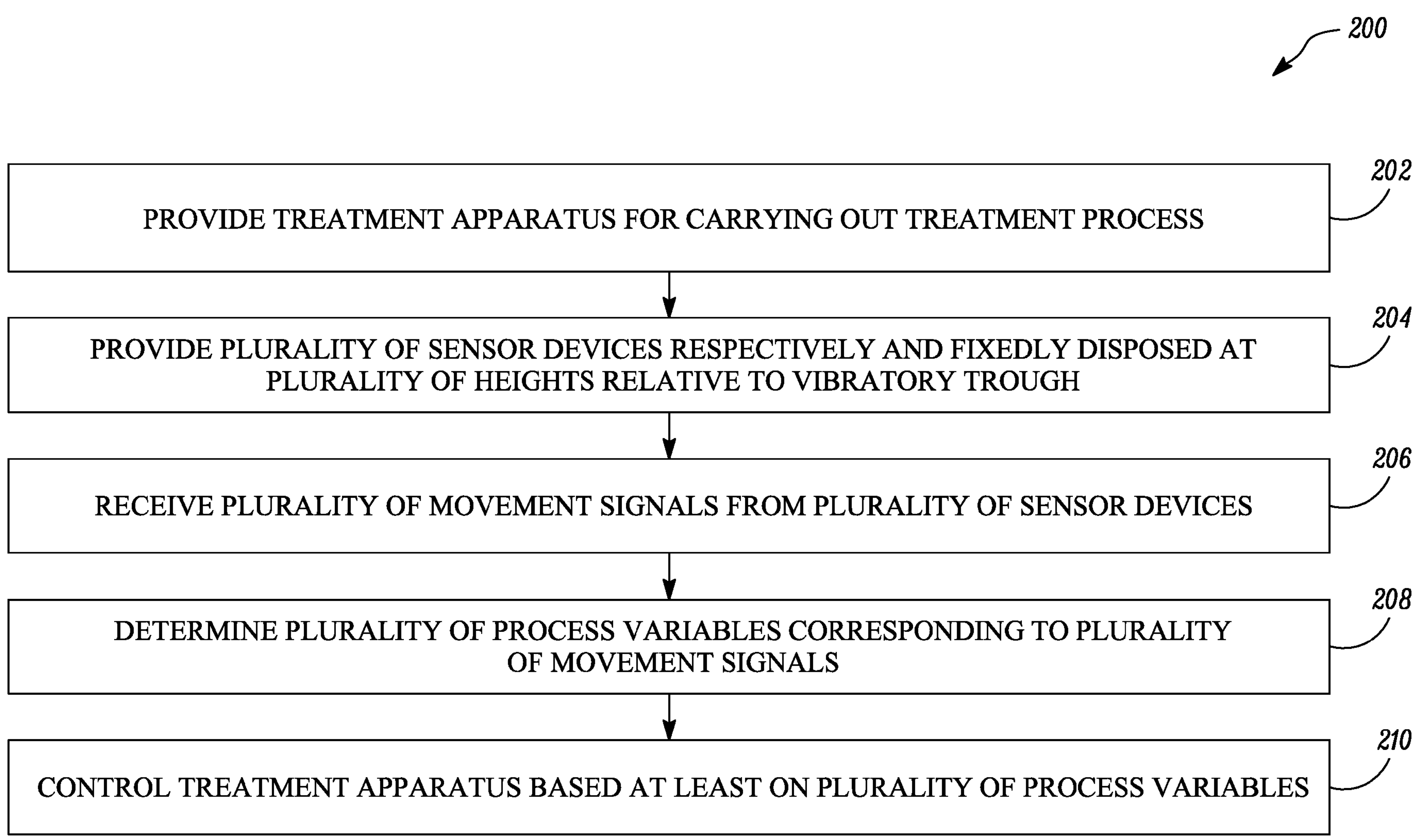
200
PROVIDE TREATMENT APPARATUS FOR CARRYING OUT TREATMENT PROCESS
202
PROVIDE PLURALITY OF SENSOR DEVICES RESPECTIVELY AND FIXEDLY DISPOSED AT PLURALITY OF HEIGHTS RELATIVE TO VIBRATORY TROUGH
204
RECEIVE PLURALITY OF MOVEMENT SIGNALS FROM PLURALITY OF SENSOR DEVICES
206
DETERMINE PLURALITY OF PROCESS VARIABLES CORRESPONDING TO PLURALITY OF MOVEMENT SIGNALS
208
CONTROL TREATMENT APPARATUS BASED AT LEAST ON PLURALITY OF PROCESS VARIABLES
210

FIG. 6

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EUROPEAN SEARCH REPORT

Application Number
EP 23 20 3961

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The present search report has been drawn up for all claims

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Place of search	Date of completion of the search	Examiner
Munich	7 March 2024	Koller, Stefan

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