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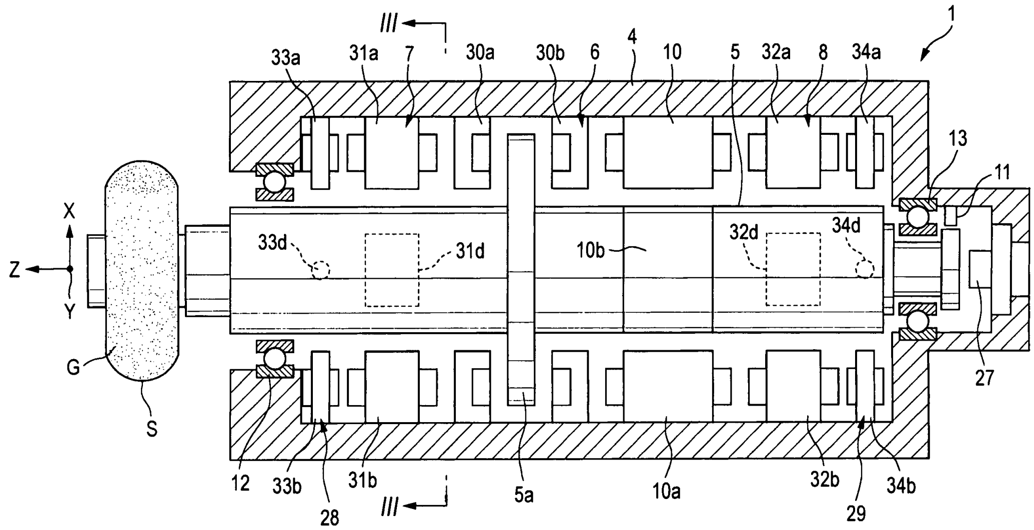
(54) **Grinding apparatus and method of controlling grinding apparatus**

(57) A grinding wheel formed on an outer peripheral surface with a grinding surface is attached to a grinding wheel spindle supported by axial active magnetic bearings and radial active magnetic bearings in a noncontact manner axially and radially and rotated by an electric motor. A casing is axially positioned and then is radially moved and a ground part of a workpiece is ground. Before the casing moves radially and the grinding wheel comes in contact with the workpiece, the stiffness value of the radial magnetic bearings is set to an initialization value lower than a value at the usual grinding time and after the grinding surface of the grinding wheel comes in contact with the workpiece, the stiffness value of the radial magnetic bearings is set to a value higher than the initialization value for grinding the workpiece.

FIG. 2



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Description

BACKGROUND OF THE INVENTION

[0001] This invention relates to a grinding wheel for grinding a workpiece on a grinding surface of the outer peripheral surface of the grinding wheel attached to a grinding wheel spindle and in particular to a grinding apparatus adapted to grind a groove formed on a cylindrical peripheral surface of a workpiece, such as a raceway groove formed on the inner peripheral surface of an outer ring of a ball bearing, for example, using a grinding wheel formed on the outer peripheral surface with a center-high grinding surface, and relates to a method of controlling the grinding apparatus.

[0002] An internal cylindrical grinding machine is known as a grinding apparatus for performing finishing grinding of a raceway groove formed on the inner peripheral surface of an inner ring of a ball bearing or the inner peripheral surface of an outer ring.

[0003] In a usual internal cylindrical grinding machine, a grinding wheel formed on the outer peripheral surface with a grinding surface is attached to a grinding wheel spindle supported on a casing for rotation. To grind a cylindrical surface such as the inner peripheral surface of an inner ring, the grinding surface is shaped like a cylindrical surface; to grind a groove of the inner peripheral surface of an outer ring, etc., the grinding surface is formed like a center-high shape.

[0004] In such an internal cylindrical grinding machine in a related art, a contact rolling bearing is used as a bearing for supporting a grinding wheel spindle to which a grinding wheel is attached on a casing of a spindle unit for rotation. (For example, refer to Japanese Patent Publication No. 2001-159421, Japanese Patent Publication No. 27660/1982)

[0005] The internal cylindrical grinding machine in the related art involves the following problems because a rolling bearing is used to support the grinding wheel spindle for rotation as mentioned above:

[0006] To use the internal cylindrical grinding machine for grinding, a workpiece is rotated in a state in which it is gripped with a proper grip device such as a chuck, and the casing is positioned in the axial direction of the grinding wheel spindle and then is moved radially, the grinding wheel is brought into contact with the workpiece, and a ground portion is ground.

[0007] In this case, when the casing is moved radially and the grinding wheel is brought into contact with the workpiece, a radial impact force acts on the grinding wheel.

[0008] To grind a groove formed on a cylindrical peripheral surface of a workpiece, such as a raceway groove formed on the inner peripheral surface of an outer ring of a ball bearing, for example, the following problem exists in addition to occurrence of an impact force:

[0009] To perform finishing grinding of a raceway groove of an outer ring using the internal cylindrical grinding machine, the workpiece formed on the inner peripheral surface with a groove in the preceding step is rotated in a state in which it is gripped with a grip device, and a groove is ground in a similar manner to that described above.

[0010] At this time, if the axial position of the groove formed on the inner peripheral surface of the workpiece in the preceding step does not involve any error, an impact force only acts; however, if an error occurs and the axial position of the groove deviates axially from the correct position, not only an impact force, but also so-called grinding wheel wear of extreme wearing (or chip) of a part of the grinding surface of the grinding wheel occurs and the grinding wheel life is shortened.

[0011] For example, if the position of a groove R of a workpiece W is correct as in FIG. 6A, when a casing is moved radially, a grinding surface S of a grinding wheel G comes in contact with the whole groove R almost at the same time and thus the grinding surface S does not locally wear or chip. In contrast, if the position of the groove R deviates axially to the left of the figure as in FIG. 6B, when the casing is moved radially, first only the right edge of the groove R comes in contact with the grinding surface S of the grinding wheel and only the edge portion is ground. Thus, only the portion of the grinding surface S of the grinding wheel coming in contact with the right edge of the groove R wears locally. If the position of the groove R deviates axially to the right of the figure as in FIG. 6C, likewise, only the portion of the grinding surface S of the grinding wheel coming in contact with the left edge of the groove R wears (or chips) locally.

[0012] In addition to finishing grinding of the raceway groove on the inner peripheral surface of the outer ring, to grind a groove formed on the cylindrical peripheral surface (inner peripheral surface or outer peripheral surface) of the workpiece, a similar problem is involved.

SUMMARY OF THE INVENTION

[0013] It is therefore an object of the invention to provide a grinding apparatus capable of lightening an impact force and making grinding wheel wear hard to occur if the axial position of a groove deviates when the groove formed on the peripheral surface of a workpiece is worked on, and to provide a method of controlling the grinding apparatus.

[0014] A grinding apparatus according to a first aspect of the invention is a grinding apparatus comprising:

a casing movable relative to a workpiece to be ground;
a grinding wheel spindle disposed in the casing;
a axial active magnetic bearing that axially supports the grinding wheel spindle relative to the casing in a noncontact manner;
a radial active magnetic bearing that radially supports the grinding wheel spindle relative to the casing in a noncontact manner;

an electric motor that rotates the grinding wheel spindle; and

a grinding wheel that includes a grinding surface, for grinding the workpiece, formed on an outer peripheral surface thereof and is attached to the grinding wheel spindle,

wherein the casing is first positioned axially and is then positioned radially to grind the workpiece,

wherein before the casing moves radially and the grinding wheel comes in contact with the workpiece, a stiffness value of the radial magnetic bearing is set to an initialization value lower than a value at a usual grinding time, and

wherein after the grinding surface of the grinding wheel comes in contact with the workpiece, the stiffness value of the radial magnetic bearings is set to a value higher than the initialization value for grinding the workpiece.

[0015] The grinding apparatus is provided with radial magnetic bearing controller for controlling the radial magnetic bearings based on radial displacement of the grinding wheel spindle. The stiffness value of the radial magnetic bearings is changed by changing the control constant of the radial magnetic bearing controller, for example. The radial magnetic bearing controller usually performs PID control. In this case, the stiffness value of the radial magnetic bearings is changed by changing the control constant of at least any one of a proportional (P) operation section, an integration (I) operation section, or a differentiation (D) operation section.

[0016] The fact that the grinding surface of the grinding wheel comes in contact with the workpiece is detected based on change in the excitation current supplied to the electromagnets of the radial magnetic bearings, for example.

[0017] When the grinding surface of the grinding wheel comes in contact with the workpiece, the reaction force backward in the cutting direction for the grinding wheel spindle increases and the excitation current supplied to the electromagnets forward in the cutting direction of the radial magnetic bearings increases. Therefore, the fact that the grinding surface of the grinding wheel comes in contact with the workpiece can be detected based on the excitation current of the electromagnets of the radial magnetic bearings.

[0018] Before the casing moves radially and the grinding wheel comes in contact with the workpiece, the stiffness value of the radial magnetic bearings is set to the initialization value lower than the value at the usual grinding time and after the grinding surface of the grinding wheel comes in contact with the workpiece, the stiffness value of the radial magnetic bearings is set to a value higher than the initialization value for grinding the workpiece. Thus, the grinding wheel comes in contact with the workpiece in a state in which the stiffness value of the radial magnetic bearings is low; when the grinding wheel comes in contact with the workpiece, it can get away radially. Thus, the impact force produced when the grinding wheel comes in contact with the workpiece is lightened.

[0019] A grinding apparatus according to a second aspect of the invention is a grinding apparatus comprising:

a casing movable relative to a workpiece to be ground;

a grinding wheel spindle disposed in the casing;

a axial active magnetic bearing that axially supports the grinding wheel spindle relative to the casing in a noncontact manner;

a radial active magnetic bearing that radially supports the grinding wheel spindle relative to the casing in a noncontact manner;

an electric motor that rotates the grinding wheel spindle;

a grinding wheel that includes a grinding surface, for grinding the workpiece, formed on an outer peripheral surface thereof and is attached to the grinding wheel spindle;

a radial magnetic bearing controller that includes an integration operation section for integrating radial displacement of the grinding wheel spindle using an integration constant and controls the radial magnetic bearing, wherein when integration output of the integration operation section is smaller than a predetermined reference value, the radial magnetic bearing controller sets the integration constant of the integration operation section to an initialization value lower than the value at the usual grinding time and when the integration output exceeds the reference value, the radial magnetic bearing controller increases the integration constant in response to the integration output,

wherein the casing is first positioned axially and is then positioned radially to grind the workpiece.

[0020] An external force in the radial direction does not act on the grinding wheel or the grinding wheel spindle before the grinding wheel comes in contact with the workpiece. Thus, in the integration operation section of the bearing controller, the integration output is smaller than the reference value, the integration constant is set to the initialization value lower than the value at the usual grinding time, and the stiffness value in the radial direction is set to a value lower than the value at the usual grinding time. When the grinding wheel comes in contact with the workpiece, an external force in the radial direction acts on the grinding wheel and the grinding wheel spindle. Thus, in the integration operation section, the integration output becomes larger than the reference value and accordingly the integration constant becomes larger than the initialization value and the stiffness value of the radial magnetic bearings becomes larger than the value before the grinding wheel comes in contact with the workpiece. Thus, the impact force produced when the grinding wheel comes in contact with the workpiece is lightened as with the first aspect of the invention.

[0021] In the first and second aspects of the invention, the grinding surface of the grinding wheel is a center-high grinding surface and the ground part of the workpiece is a groove formed on the cylindrical peripheral surface of the workpiece, for example.

[0022] The cross-sectional shape of the center-high grinding surface of the grinding wheel and the cross-sectional shape of the groove of the workpiece are each a curve as a whole.

[0023] As for the cross-sectional shapes of the grinding surface of the grinding wheel and the groove of the workpiece, the cross section refers to the cross section (longitudinal section) in the plane passing through the axis of the grinding wheel, namely, the grinding wheel spindle and the axis of the cylindrical peripheral surface where the groove is formed. To grind the groove, the axis of the grinding wheel spindle and the axis of the cylindrical peripheral surface of the workpiece where the groove is formed are parallel with each other.

[0024] If the groove R is formed at the correct position by pre-working and the groove R and the grinding wheel G match in the axial position as in FIG. 6A, when the casing 4 is moved radially and the grinding wheel G is brought close to the workpiece W, the grinding surface S of the grinding wheel comes in contact with the whole groove R almost at the same time. After the grinding surface S of the grinding wheel comes in contact with the whole groove R, the stiffness value of the radial magnetic bearings is set to a value higher than the initialization value. When the casing 4 is moved radially, the grinding surface S of the grinding wheel comes in contact with the whole groove R almost at the same time and moreover the stiffness value of the radial magnetic bearings at this time is lower than the value at the usual grinding time and the grinding wheel can get away in the axial direction. Thus, the impact is lightened and the grinding surface S does not locally wear (or chip).

[0025] If the position of the groove R by pre-working shifts axially to the left of the drawing as in FIG. 6B, when the casing 4 is moved radially and the grinding wheel G is brought close to the workpiece W, first only the right edge of the groove R comes in contact with the grinding surface S of the grinding wheel. However, the stiffness value of the radial magnetic bearings at this time is lower than the value at the usual grinding time and the grinding wheel can get away in the radial direction. Thus, the impact is lightened and the grinding surface S does not locally wear (or chip).

[0026] Similar comments apply if the position of the groove R by pre-working shifts axially to the right of the drawing as in FIG. 6C.

[0027] Usually, two pairs of radial magnetic bearings are provided. In this case, changing the stiffness value in the first aspect of the invention and changing the integration constant in the second aspect of the invention may be executed for the two pairs of radial magnetic bearings or may be executed only for either of the two pairs of radial magnetic bearings. For example, changing the stiffness value and changing the integration constant may be executed only for the radial magnetic bearings close to the grinding wheel.

[0028] The radial magnetic bearing has two radial control axes orthogonal to each other and preferably one control shaft is matched with the cutting direction (the move direction of the casing at the cutting time). In this case, changing the stiffness value and changing the integration constant may be executed only for the control shaft matching the cutting direction.

[0029] According to the grinding apparatus according to the first and second aspects of the invention, the impact force produced when the grinding wheel comes in contact with the workpiece is lightened as described above.

[0030] According to the third aspect of the invention, the impact force produced when the grinding wheel comes in contact with the portion of the groove of the workpiece is lightened as described above and moreover if the axial position of the groove deviates, grinding wheel wear is hard to occur and occurrence of local wear of the grinding wheel can be prevented.

According to a method of a fourth aspect for controlling a grinding apparatus which comprises: a casing movable relative to a workpiece to be ground; a grinding wheel spindle disposed in the casing; a axial active magnetic bearing that axially supports the grinding wheel spindle relative to the casing in a noncontact manner; a radial active magnetic bearing that radially supports the grinding wheel spindle relative to the casing in a noncontact manner; an electric motor that rotates the grinding wheel spindle; and a grinding wheel that includes a grinding surface, for grinding the workpiece, formed on an outer peripheral surface thereof and is attached to the grinding wheel spindle, the method comprises:

axially positioning the casing;
setting a stiffness value of the radial magnetic bearing to an initialization value lower than a value at a usual grinding time before the grinding wheel comes in contact with the workpiece;
radially positioning the casing so that the grinding surface of the grinding wheel comes in contact with the workpiece; and
setting the stiffness value of the radial magnetic bearings to a value higher than the initialization value for grinding the workpiece after the grinding surface of the grinding wheel comes in contact with the workpiece.

According to a method of a fifth embodiment for controlling a grinding apparatus which comprises: a casing movable relative to a workpiece to be ground; a grinding wheel spindle disposed in the casing; a axial active magnetic bearing that axially supports the grinding wheel spindle relative to the casing in a noncontact manner; a radial active magnetic bearing that radially supports the grinding wheel spindle relative to the casing in a noncontact manner; an electric motor that rotates the grinding wheel spindle; a grinding wheel that includes a grinding surface, for grinding the workpiece, formed on an outer peripheral surface thereof and is attached to the grinding wheel spindle; and a radial magnetic bearing controller that includes an integration operation section for integrating radial displacement of the grinding wheel spindle using an integration constant and controls the radial magnetic bearing, the method comprises:

setting the integration constant of the integration operation section to an initialization value lower than the value at the usual grinding time when integration output of the integration operation section is smaller than a predetermined reference value;
increasing the integration constant in response to the integration output when the integration output exceeds the reference value;
axially positioning the casing; and
radially positioning the casing to grind the workpiece.

BRIEF DESCRIPTION OF THE DRAWINGS

[0031]

FIG. 1 is a plan view of the main part of a grinding apparatus to show an embodiment of the invention;
FIG. 2 is an enlarged longitudinal sectional view seeing the grinding apparatus in FIG. 1 from the same direction;
FIG. 3 is an enlarged sectional view (transverse sectional view) taken on line III-III in FIG. 2;
FIG. 4 is a block diagram to show the main part of the electric configuration of the spindle unit in FIG. 2;
FIG. 5 is a block diagram to show a part of FIG. 4 in detail; and
FIGS. 6A to 6C are schematic illustrations to show how a groove of a workpiece is worked on using a grinding wheel.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0032] Referring now to the accompanying drawings, there is shown an embodiment of the invention.

[0033] FIG. 1 is a plan view to show a portion of a magnetic bearing spindle unit of the main part of a grinding apparatus, FIG. 2 is an enlarged sectional view of FIG. 1, FIG. 3 is a sectional view taken on line III-III in FIG. 2, and FIG. 4 is a block diagram to show the main part of the electric configuration of the spindle unit. The surface of the plane of the drawing of each of FIGs. 1 and 2 is the top, the rear of the plane of the drawing is the bottom, the upper side of the plane of the drawing is the back, the lower side of the plane of the drawing is the front, the left of the plane of the drawing is the grinding wheel side, and the right of the plane of the drawing is the grinding wheel opposite side. The top and bottom of the plane of the drawing of FIG. 3 are the top and bottom (up and down), the right is the back, and the left is the front.

[0034] Although not shown in detail in the figures, a spindle unit 1 is moved in a grinding wheel side/grinding wheel opposite side direction by a grinding wheel side/grinding wheel opposite side direction drive 2 and is moved in a back/front direction by a back/front direction drive 3 and is positioned at any desired position. The spindle unit 1 is moved in the grinding wheel side/grinding wheel opposite side direction and in the back/front direction and is positioned under the control of a known numerical control (not shown), for example.

[0035] The spindle unit 1 is of a horizontal type wherein a horizontal grinding wheel spindle 5 rotates inside a horizontal casing 4, and is placed so that the grinding wheel spindle 5 points in the grinding wheel side/grinding wheel opposite side direction.

[0036] A control axis (axial control axis) in the axial direction of the grinding wheel spindle 5, namely, in the grinding wheel side/grinding wheel opposite side direction is Z axis and of control axes (radial control axes) in two radial directions orthogonal to the Z axis and also orthogonal to each other, the control axis in the back/front direction is X axis and the control axis in an up and down direction is Y axis. The positive side of the Z axis is the grinding wheel side, the positive side of the X axis is the back side, and the positive side of the Y axis is the upper side.

[0037] The spindle unit 1 is provided with a pair of axial active magnetic bearings 6 for noncontact supporting the grinding wheel spindle 5 axially, two pairs of radial active magnetic bearings 7 and 8 on the grinding wheel side and the grinding wheel opposite side for noncontact supporting the grinding wheel spindle 5 radially, a displacement detection section 9 for detecting axial and radial displacements of the grinding wheel spindle 5, a built-in electric motor 10 for rotating the grinding wheel spindle 5 at high speed, a rotation sensor 11 for detecting the number of revolutions of the grinding wheel spindle 5, and two pairs of protective bearings 12 and 13 for touch down on the grinding wheel side and the grinding wheel opposite side for regulating the axial and radial moving ranges of the grinding wheel spindle 5 and mechanically supporting the grinding wheel spindle 5 when the grinding wheel spindle 5 is not supported on the magnetic bearings 6, 7 and 8.

[0038] A controller 14 for controlling the magnetic bearings 6, 7 and 8 and the electric motor 10 is electrically connected to the spindle unit 1 by a cable. The spindle unit 1 and the controller 14 make up a magnetic bearing unit for noncontact supporting and rotating the grinding wheel spindle 5 relative to the casing 4.

[0039] The controller 14 is provided with sensor circuits 15 and 16, an electromagnet drive circuit 17, an inverter 18, and a DSP board 19. The DSP board 19 is provided with a software programmable DSP 20 as digital processing means, ROM 21, RAM 22 as nonvolatile memory, AD converters 23 and 24, and DA converters 25 and 26.

[0040] The displacement detection section 9 includes an axial displacement sensor 27 for detecting axial displacement of the grinding wheel spindle 5 and two pairs of front and back radial displacement sensor units 28 and 29 for detecting radial displacement of the grinding wheel spindle 5.

[0041] Each axial magnetic bearing 6 includes a pair of axial electromagnets 30a and 30b on the grinding wheel side and the grinding wheel opposite side so as to sandwich a flange part 5a formed in one piece in an intermediate part of the grinding wheel spindle 5 from both sides in the Z axis direction. The axial.magnetic bearings are collectively denoted by reference numeral 30.

[0042] The axial displacement sensor 27 is placed so as to face the end face of the grinding wheel spindle 5 on the grinding wheel opposite side from the back in the Z axis direction, and outputs a distance signal proportional to the distance (gap) between the sensor and the end face.

[0043] Each radial magnetic bearing 7 on the grinding wheel side is placed at a near position on the grinding wheel side of the axial magnetic bearing 6, and each radial magnetic bearing 8 on the grinding wheel opposite side is placed at a distant position on the grinding wheel opposite side of the axial magnetic bearing 6. The radial magnetic bearings 7 on the grinding wheel side include a pair of back and front radial electromagnets 31a and 31b placed so as to sandwich the grinding wheel spindle 5 from both sides in the X axis direction and a pair of up and down radial electromagnets 31c and 31d placed so as to sandwich the grinding wheel spindle 5 from both sides in the Y axis direction. The radial electromagnets are collectively denoted by reference numeral 31. Likewise, the radial magnetic bearings 8 on the grinding wheel opposite side include two pairs of radial electromagnets 32a, 32b, 32c and 32d. The radial electromagnets are also collectively denoted by reference numeral 32.

[0044] The radial displacement sensor units 28 on the grinding wheel side are placed just on the grinding wheel side of the radial magnetic bearings 7 on the grinding wheel side and include a pair of back and front radial displacement sensors 33a and 33b placed so as to sandwich the grinding wheel spindle 5 from both sides in the X axis direction in the proximity of the electromagnets 31a and 31b in the X axis direction and a pair of up and down radial displacement sensors 33c and 33d placed so as to sandwich the grinding wheel spindle 5 from both sides in the Y axis direction in the proximity of the electromagnets 31c and 31d in the Y axis direction. The radial displacement sensors are collectively denoted by reference numeral 33. The radial displacement sensor units 29 on the grinding wheel opposite side are placed just on the grinding wheel opposite side of the radial magnetic bearings 8 on the grinding wheel opposite side and likewise include two pairs of radial displacement sensors 34a, 34b, 34c and 34d. The radial displacement sensors are also collectively denoted by reference numeral 34. Each of the radial displacement sensors 33 and 34 outputs a distance signal proportional to the distance between the sensor and the outer peripheral surface of the grinding wheel spindle 5.

[0045] The electric motor 10 is placed between the axial magnetic bearings 6 and the radial magnetic bearings 8 on the grinding wheel opposite side and is made up of a stator 10a on the side of the casing 4 and a rotor 10b on the side of the grinding wheel spindle 5.

[0046] The electromagnets 30, 31 and 32, the displacement sensors 27, 33 and 34, and the stator 10a of the electric motor 10 are fixed to the casing 4.

[0047] Each of the protective bearings 12 and 13 is made of a rolling bearing such as an angular contact ball bearing; the outer rings of the protective bearings 12 and 13 are fixed to the casing 4 and the inner rings are placed with a predetermined spacing in the surrounding of the grinding wheel spindle 5. The two pairs of protective bearings 12 and 13 can support in the radial direction and at least one pair can also support in the axial direction.

[0048] The sensor circuit 15 drives the displacement sensors 27, 33, and 34 of the displacement detection section 9 and outputs an output signal of each displacement sensor to the DSP 20 through the AD converter 23.

[0049] The sensor circuit 16 drives the rotation sensor 11, converts output of the rotation sensor 11 into a number-of-revolution signal corresponding to the number of revolutions of the grinding wheel spindle 5, and outputs the signal to the DSP 20 through the AD converter 24.

[0050] The DSP 20 finds a control electric current value for each of the electromagnets 30, 31 and 32 of the magnetic bearings 6, 7 and 8 based on the output signal of each of the displacement sensors 27, 33 and 34 input through the AD converter 23, adds the control electric current value to a given stationary current value to generate an excitation current signal, and outputs the excitation current signal to the electromagnet drive circuit 17 through the DA converter 25. The electromagnet drive circuit 17 supplies an excitation current based on the excitation current signal from the DSP 20 to the corresponding the electromagnet 30, 31 and 32 of the magnetic bearing 6, 7 and 8, whereby the grinding wheel spindle 5 is supported in a noncontact manner at a predetermined floating target position. The DSP 20 also outputs a number-of-revolution command signal for the electric motor 10 through the DA converter 26 to the inverter 18 based on the number-of-revolution signal from the rotation sensor 11. The inverter 18 controls the number of revolutions of the electric motor 10 based on the signal. Consequently, the grinding wheel spindle 5 is rotated at high speed by the electric motor 10 in a state in which it is supported in a noncontact manner at the target position by the magnetic bearings 6, 7 and 8.

[0051] In the described spindle unit, the stiffness value can be controlled about the paired electromagnets 31a, 31b, 32a and 32b in the X direction in the radial magnetic bearings 7 and 8 on the grinding wheel side and the grinding wheel opposite side.

[0052] FIG. 5 shows only the portion of the configuration of the controller 14 concerning control of the pair of electromagnets 31a and 31b in the X direction in the radial magnetic bearings 7 on the grinding wheel side, and represents only the portion of radial magnetic bearing controller of the DSP 20 concerning control of the pair of electromagnets 31a and 31b as a functional block. Next, the control of the pair of electromagnets 31a and 31b by the controller 14 will be discussed with reference to FIG. 5.

[0053] To begin with, the sensor circuit 15 subtracts an output signal of the other from an output signal of one of the paired radial displacement sensors 33a and 33b in the X direction in the radial magnetic bearings 7 on the grinding wheel side, thereby finding displacement for the target position (=0) in the X axis direction of the grinding wheel spindle 5 in the portion of the radial magnetic bearings 7 on the grinding wheel side, and outputs a displacement signal ΔX proportional to the displacement. The displacement signal ΔX from the sensor circuit 15 is converted into a digital value (digital displacement signal) ΔX by the AD converter 23 and the digital displacement signal ΔX is input to the DSP 19. The DSP 19 outputs a pair of excitation current signals Ia and Ib as control signals corresponding to the pair of electromagnets 31a and 31b to the DA converter 25 based on the digital displacement signal ΔX as described later. The first excitation current signal Ia is converted into an analog signal by the DA converter 25 and then the analog signal is amplified by a first current amplifier of the electromagnet drive circuit 17 and is supplied to one electromagnet 33a as the first excitation current Ia. The second excitation current signal Ib is converted into an analog signal by the DA converter 25 and then the analog signal is amplified by a second current amplifier of the electromagnet drive circuit 17 and is supplied to the other electromagnet 33b as the second excitation current Ib.

[0054] The DSP 19 functionally includes a control current computation section 35 and an excitation current generation section 36. The control current computation section 35 computes a control current value Ic for the electromagnets 31a and 31b by performing PID computation based on the displacement signal ΔX from the AD converter 23 and is made up of a proportional operation section 37, an integration operation section 38, a differentiation operation section 39, an integration constant change section 40, and an addition section 41. The proportional operation section 37 uses a proportionality constant to compute a proportion component Icp of the control current value Ic based on the displacement signal ΔX. The integration operation section 38 uses an integration constant to compute an integration component Ici of the control current value Ic based on the displacement signal ΔX. The differentiation operation section 39 uses a differentiation constant to compute a differentiation component Icd of the control current value Ic based on the displacement signal ΔX. The addition section 41 adds the proportion component Icp, the integration component Ici, and the differentiation component Icd, thereby finding the control current value Ic, and outputs the control current value Ic to the excitation current generation section 36. The excitation current generation section 36 adds the control current value Ic to a given bias current value Io and outputs the resultant value (Io+Ic) to the DA converter 25 as the first excitation current signal Ia and also subtracts the control current value Ic from the bias current value Io and outputs the resultant value (Io-Ic) to the DA converter 25 as the second excitation current signal Ib.

[0055] The integration constant change section 40 controls the integration constant in the integration operation section 38 based on the integration output Ici of the integration operation section 38. In the example, when the integration output Ici is smaller than a predetermined reference value, the integration constant is set to an initialization value lower than the value at the usual grinding time and when the integration output Ici exceeds the reference value, the integration constant is increased in response to the integration output Ici.

[0056] The configuration of the portion concerning control of the pair of electromagnets 32a and 32b in the X direction in the radial magnetic bearings 8 on the grinding wheel opposite side is also similar to that in FIG. 5.

[0057] The configuration of the portion concerning control of the paired electromagnets 31c, 31d, 32c and 32d in the Y direction in the radial magnetic bearings 7 and 8 and the pair of axial electromagnets 30a and 30b of each axial magnetic bearing 6 is the same as that in FIG. 5 or is similar to that in FIG. 5 from which the integration constant change section 40 is removed.

[0058] The grinding wheel side portion of the grinding wheel spindle 5 projects to the grinding wheel side from the casing 4 and the grinding wheel G is fixed to the tip of the grinding wheel spindle 5.

[0059] To grind a groove R formed on the inner peripheral surface of a workpiece W, such as a raceway groove on the inner peripheral surface of an outer ring of a ball bearing, a grinding wheel G formed on the outer peripheral surface with a center-high grinding surface S which is a curve in cross section is attached to the grinding wheel spindle 5.

[0060] To grind a groove R formed on the inner peripheral surface of a workpiece W as in FIG. 1 using the described grinding apparatus, the casing 4 is moved in the Z axis direction and is positioned at a position where the grinding surface S of the grinding wheel is opposed to the groove R and then the casing 4 is moved in the X axis direction (cutting direction) at predetermined cutting speed.

[0061] An external force in the X axis direction does not act on the grinding wheel G or the grinding wheel spindle 5 before the grinding wheel G comes in contact with the workpiece W. Thus, in the integration operation section 38 of the controller 14, the integration output Ici is smaller than the reference value, the integration constant is set to the initialization value lower than the value at the usual grinding time, and the stiffness value in the X axis direction is set to a value lower than the value at the usual grinding time. When the grinding wheel G comes in contact with the workpiece W, an external force in the X axis direction acts on the grinding wheel G and the grinding wheel spindle 5. Thus, in the integration operation section 38, the integration output Ici becomes larger than the reference value and accordingly the integration constant becomes larger than the initialization value and the stiffness value of the radial magnetic bearings 7 and 8 in the X axis direction becomes larger than the value before the grinding wheel G comes in contact with the workpiece W. Thus, the grinding wheel G comes in contact with the workpiece W in a state in which the stiffness value of the radial magnetic bearings 7 and 8 in the X axis direction is low; when the grinding wheel G comes in contact with the workpiece W, it can get away in the X axis direction. Thus, the impact force produced when the grinding wheel G comes in contact with the workpiece W is lightened.

[0062] If the groove R is formed at the correct position by pre-working and the groove R and the grinding wheel G match in the axial position as in FIG. 6A, when the casing 4 is moved radially and the grinding wheel G is brought close to the workpiece W, the grinding surface S of the grinding wheel comes in contact with the whole groove R almost at the same time. After the grinding surface S of the grinding wheel comes in contact with the whole groove R, the stiffness value of the radial magnetic bearings is set to a value higher than the initialization value. When the casing 4 is moved radially, the grinding surface S of the grinding wheel comes in contact with the whole groove R almost at the same time and moreover the stiffness value of the radial magnetic bearings at this time is lower than the value at the usual grinding time and the grinding wheel G can get away downward in the X axis direction. Thus, the impact is lightened and the grinding surface S does not locally wear (or chip).

[0063] If the position of the groove R by pre-working shifts axially to the left of the drawing as in FIG. 6B, when the casing 4 is moved radially and the grinding wheel G is brought close to the workpiece W, first only the right edge of the groove R comes in contact with the grinding surface S of the grinding wheel. However, the stiffness value of the radial magnetic bearings at this time is lower than the value at the usual grinding time and the grinding wheel G can get away downward in the X axis direction. Thus, the impact is lightened and the grinding surface S does not locally wear (or chip).

[0064] Similar comments apply if the position of the groove R by pre-working shifts axially to the right of the drawing as in FIG. 6C.

[0065] In the example, when the integration output Ici is smaller than the predetermined reference value, the integration constant is set to the initialization value lower than the value at the usual grinding time and when the integration output Ici exceeds the reference value, the integration constant is increased in response to the integration output Ici. However, before the casing 4 moves in the X axis direction and the grinding wheel G comes in contact with the workpiece W, the stiffness value of the radial magnetic bearings 7 and 8 in the X axis direction may be set to the initialization value lower than the value at the usual grinding time and after the grinding surface S of the grinding wheel G comes in contact with the workpiece W, the stiffness value of the radial magnetic bearings 7 and 8 in the X axis direction may be set to a value higher than the initialization value for grinding the workpiece.

[0066] In this case, the stiffness value of the radial magnetic bearings 7 and 8 in the X axis direction is changed by changing the control constant of at least any one of the proportional operation section, the integration operation section, or the differentiation operation of radial magnetic bearing controller for controlling the electromagnets 31a, 31b, 32a, and 32b in the X direction, for example. The stiffness value in the X axis direction is changed by changing the integration constant of the integration operation section, for example.

[0067] The fact that the grinding surface S of the grinding wheel G comes in contact with the workpiece W is detected based on change in the excitation current supplied to the electromagnets 31a, 31b, 32a and 32b in the X direction in the radial magnetic bearings 7 and 8, for example.

[0068] When the grinding surface S of the grinding wheel G comes in contact with the workpiece W, the reaction force backward in the cutting direction (pointing in the negative side of the X axis direction) for the grinding wheel spindle 5, namely, the downward reaction force increases and the excitation current supplied to the electromagnets 31a and 32a forward in the cutting direction of the radial magnetic bearings 7 and 8 (the positive side of the X axis direction) , namely, the upper electromagnets 31a and 32a increases. Therefore, the fact that the grinding surface S of the grinding wheel G comes in contact with the workpiece W can be detected based on the excitation current of the electromagnets 31a, 31b, 32a and 32b in the X direction in the radial magnetic bearings 7 and 8.

[0069] In the example, the stiffness value in the X axis direction is changed for both of the two pairs of radial magnetic bearings 7 and 8 on the grinding wheel side and the grinding wheel opposite side. However, the stiffness value in the X axis direction may be changed for either of them, preferably for only the radial magnetic bearings 7 on the grinding wheel side near to the grinding wheel G. The stiffness value in the Y axis direction may be operatively associated with the X axis.

[0070] The described grinding apparatus can also grind a groove formed on the outer peripheral surface of a workpiece. The inner peripheral surface, the outer peripheral surface of a workpiece, and other surfaces can also be ground using a grinding wheel formed on the outer peripheral surface with a grinding surface shaped like a cylindrical surface.

[0071] The general configuration of the grinding apparatus and the magnetic bearing unit forming it or the configuration of each section is not limited to that of the embodiment described above and may be changed as required.

Claims

1. A grinding apparatus comprising:

a casing movable relative to a workpiece to be ground;
a grinding wheel spindle disposed in the casing;
a axial active magnetic bearing that axially supports the grinding wheel spindle relative to the casing in a noncontact manner;
a radial active magnetic bearing that radially supports the grinding wheel spindle relative to the casing in a noncontact manner;
an electric motor that rotates the grinding wheel spindle; and
a grinding wheel that includes a grinding surface, for grinding the workpiece, formed on an outer peripheral surface thereof and is attached to the grinding wheel spindle,
wherein the casing is first positioned axially and is then positioned radially to grind the workpiece,
wherein before the casing moves radially and the grinding wheel comes in contact with the workpiece, a stiffness value of the radial magnetic bearing is set to an initialization value lower than a value at a usual grinding time, and
wherein after the grinding surface of the grinding wheel comes in contact with the workpiece, the stiffness value of the radial magnetic bearings is set to a value higher than the initialization value for grinding the workpiece.

2. The grinding apparatus according to claim 1, wherein the grinding surface of the grinding wheel is a center-high grinding surface and a part of the workpiece to be ground is a groove formed on a cylindrical peripheral surface of the workpiece.

3. A grinding apparatus comprising:

a casing movable relative to a workpiece to be ground;
a grinding wheel spindle disposed in the casing;
a axial active magnetic bearing that axially supports the grinding wheel spindle relative to the casing in a noncontact manner;
a radial active magnetic bearing that radially supports the grinding wheel spindle relative to the casing in a noncontact manner;
an electric motor that rotates the grinding wheel spindle;
a grinding wheel that includes a grinding surface, for grinding the workpiece, formed on an outer peripheral surface thereof and is attached to the grinding wheel spindle; and
a radial magnetic bearing controller that includes an integration operation section for integrating radial displacement of the grinding wheel spindle using an integration constant and.controls the radial magnetic bearing, wherein when integration output of the integration operation section is smaller than a predetermined reference value, the radial magnetic bearing controller sets the integration constant of the integration operation section to an initialization value lower than the value at the usual grinding time and when the integration output exceeds the reference value, the radial magnetic bearing controller increases the integration constant in response to the integration output,
wherein the casing is first positioned axially and is then positioned radially to grind the workpiece.

4. The grinding apparatus according to claim 3, wherein the grinding surface of the grinding wheel is a center-high grinding surface and a part of the workpiece to be ground is a groove formed on a cylindrical peripheral surface of the workpiece.

5. A method of controlling a grinding apparatus which comprises: a casing movable relative to a workpiece to be ground; a grinding wheel spindle disposed in the casing; a axial active magnetic bearing that axially supports the grinding wheel spindle relative to the casing in noncontact manner; a radial active magnetic bearing that radially supports the grinding wheel spindle relative to the casing in a noncontact manner; an electric motor that rotates the grinding wheel spindle; and a grinding wheel that includes a grinding surface, for grinding the workpiece, formed on an outer peripheral surface thereof and is attached to the grinding wheel spindle, the method comprising:

axially positioning the casing;
setting a stiffness value of the radial magnetic bearing to an initialization value lower than a value at a usual grinding time before the grinding wheel comes in contact with the workpiece;
radially positioning the casing so that the grinding surface of the grinding wheel comes in contact with the workpiece; and
setting the stiffness value of the radial magnetic bearings to a value higher than the initialization value for grinding the workpiece after the grinding surface of the grinding wheel comes in con-

tact with the workpiece.

6. A method of controlling a grinding apparatus which comprises: a casing movable relative to a workpiece to be ground; a grinding wheel spindle disposed in the casing; a axial active magnetic bearing that axially supports the grinding wheel spindle relative to the casing in a noncontact manner; a radial active magnetic bearing that radially supports the grinding wheel spindle relative to the casing in a noncontact manner; an electric motor that rotates the grinding wheel spindle; a grinding wheel that includes a grinding surface, for grinding the workpiece, formed on an outer peripheral surface thereof and is attached to the grinding wheel spindle; and a radial magnetic bearing controller that includes an integration operation section for integrating radial displacement of the grinding wheel spindle using an integration constant and controls the radial magnetic bearing, the method comprising:

setting the integration constant of the integration operation section to an initialization value lower than the value at the usual grinding time when integration output of the integration operation section is smaller than a predetermined reference value;
increasing the integration constant in response to the integration output when the integration output exceeds the reference value;
axially positioning the casing; and
radially positioning the casing to grind the workpiece.

FIG. 1

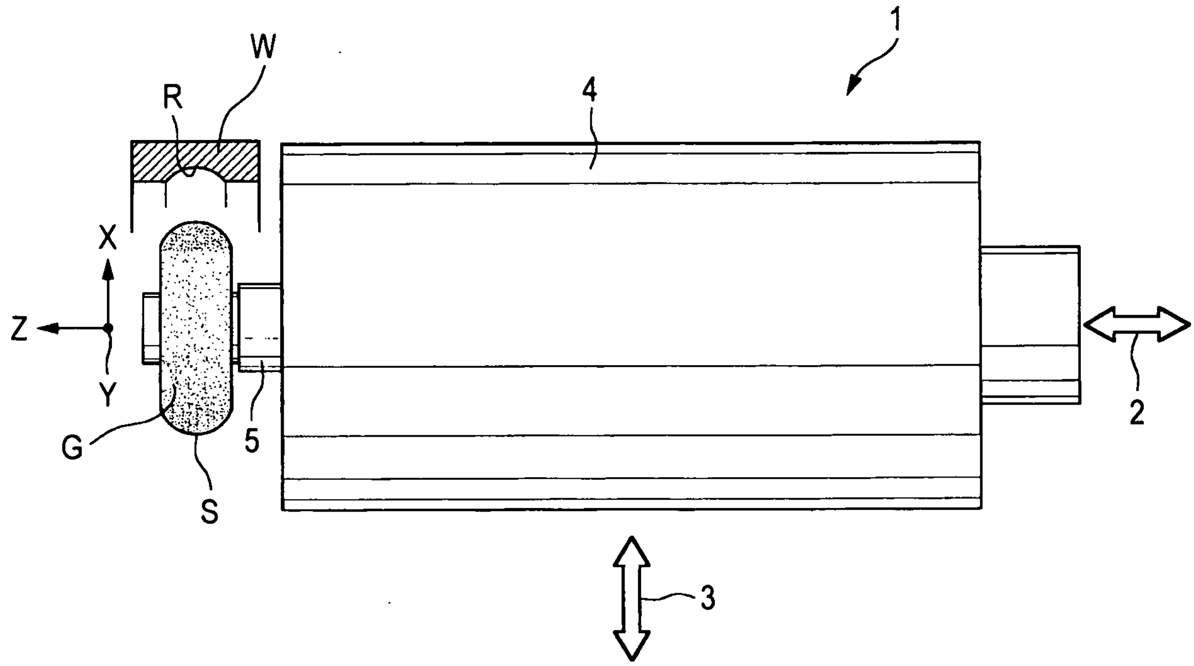
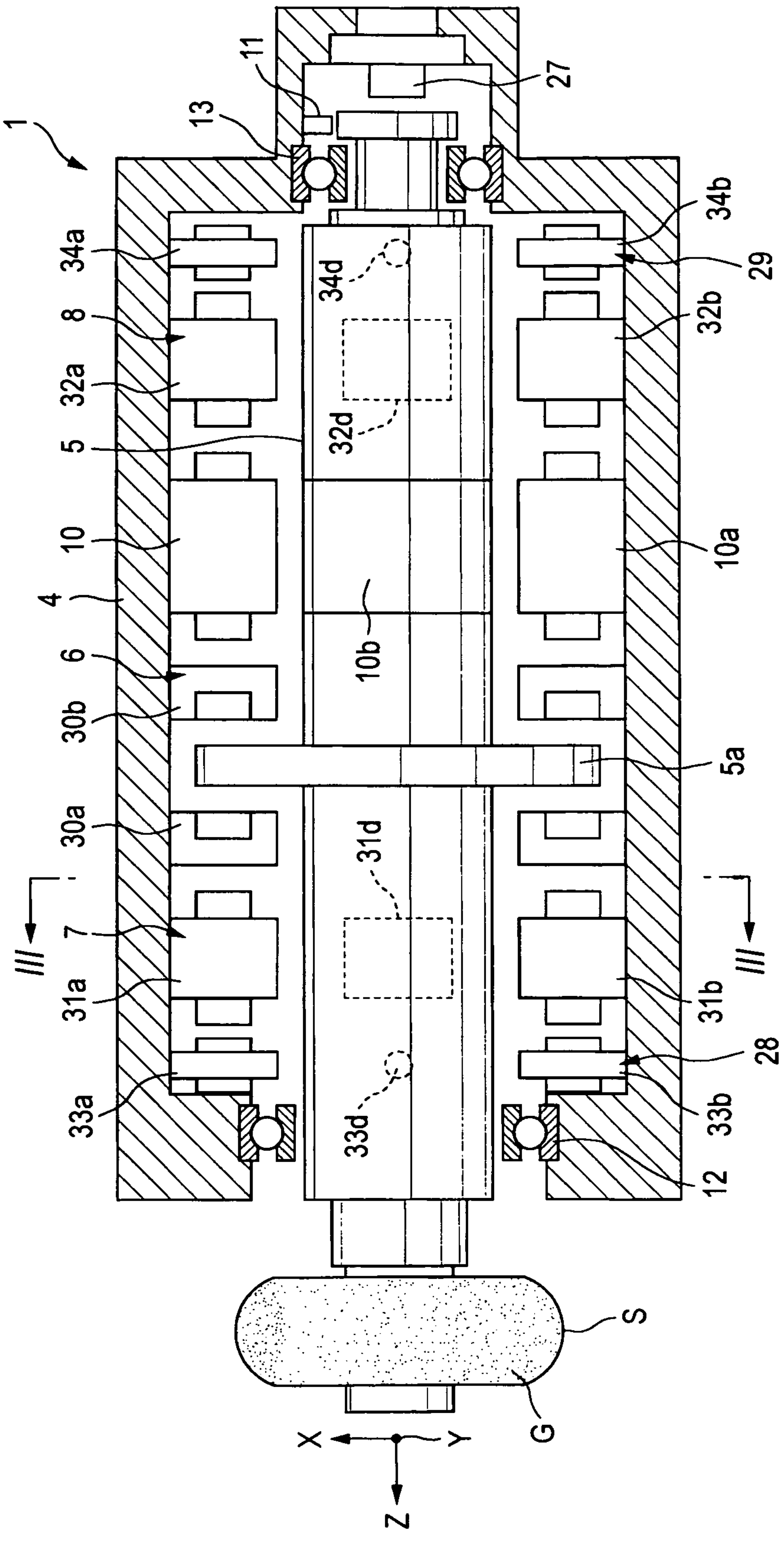


FIG. 2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13
27
34a
34b
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34d
8
32a
32b
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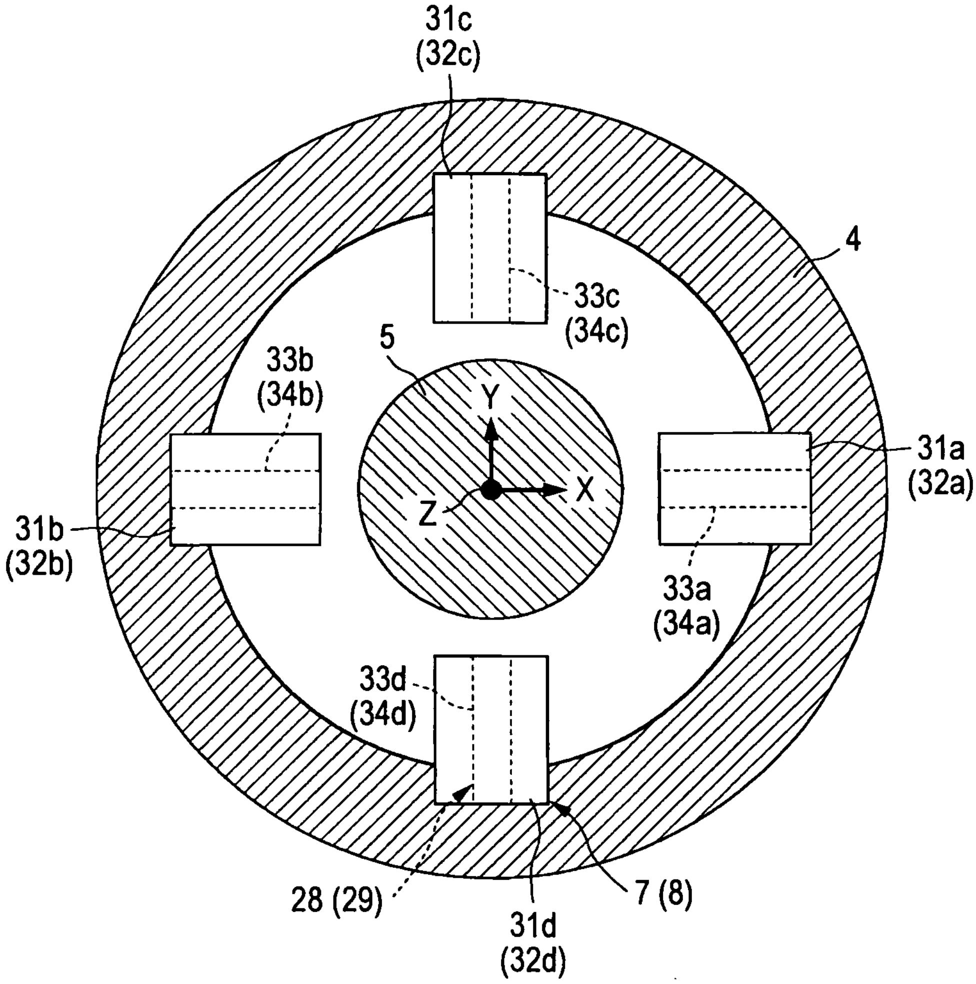
5a
30a
31d
III
7
31a
31b
III
33a
33b
28
33d
12
S
G
X
Y
Z

FIG. 3


31c
(32c)
4
33c
(34c)
5
33b
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Y
X
Z
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33a
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33d
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28 (29)
31d
(32d)
7 (8)

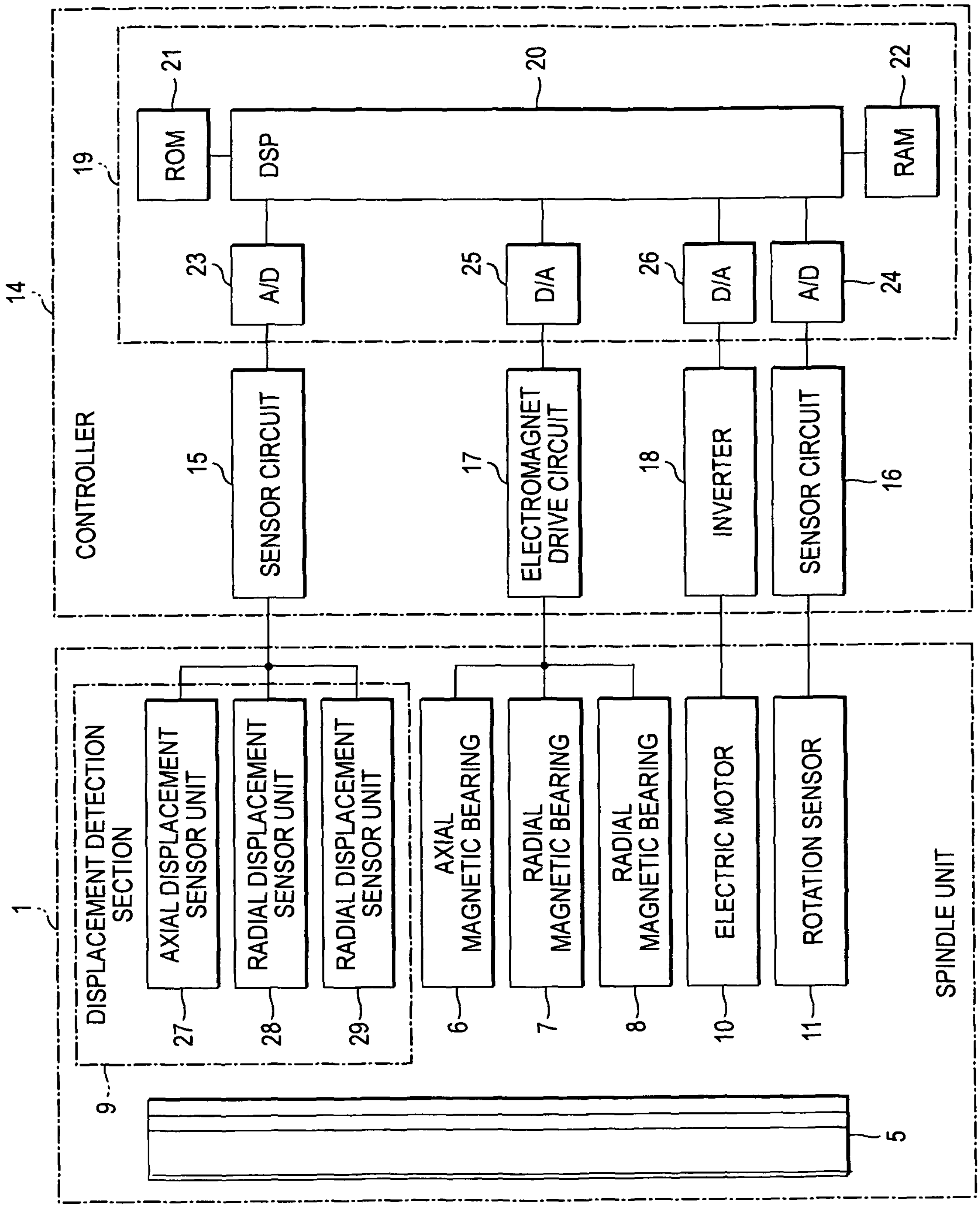
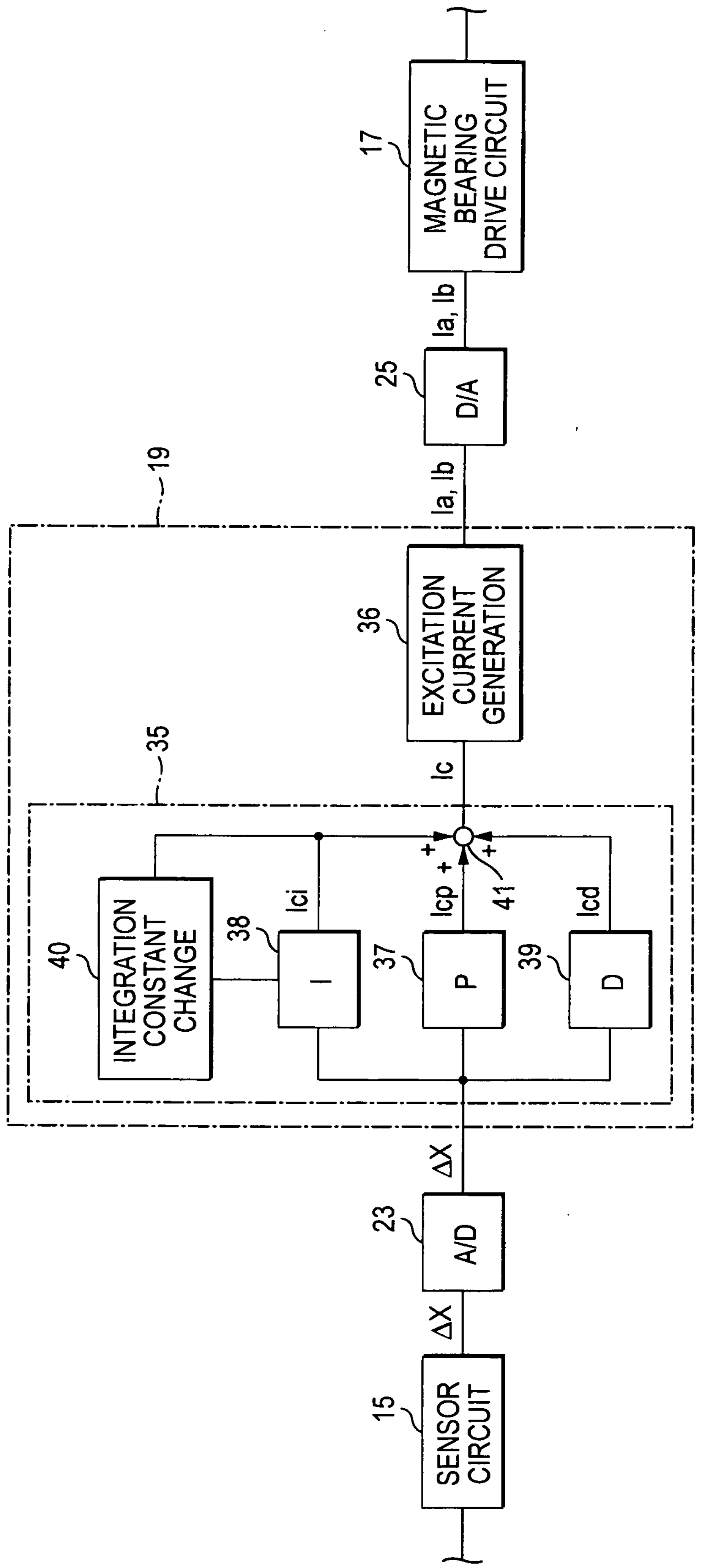

CONTROLLER
14
19
ROM
21
DSP
20
RAM
22
A/D
23
D/A
25
D/A
26
A/D
24
SENSOR CIRCUIT
15
ELECTROMAGNET DRIVE CIRCUIT
17
INVERTER
18
SENSOR CIRCUIT
16
1
DISPLACEMENT DETECTION SECTION
9
AXIAL DISPLACEMENT SENSOR UNIT
27
RADIAL DISPLACEMENT SENSOR UNIT
28
RADIAL DISPLACEMENT SENSOR UNIT
29
AXIAL MAGNETIC BEARING
6
RADIAL MAGNETIC BEARING
7
RADIAL MAGNETIC BEARING
8
ELECTRIC MOTOR
10
ROTATION SENSOR
11
SPINDLE UNIT
5

FIG. 4

FIG. 5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SENSOR CIRCUIT
ΔX
23
A/D
ΔX
19
35
40
INTEGRATION CONSTANT CHANGE
38
I
Ici
37
P
Icp
39
D
Icd
41
+
+
+
Ic
36
EXCITATION CURRENT GENERATION
Ia, Ib
25
D/A
Ia, Ib
17
MAGNETIC BEARING DRIVE CIRCUIT

FIG. 6A

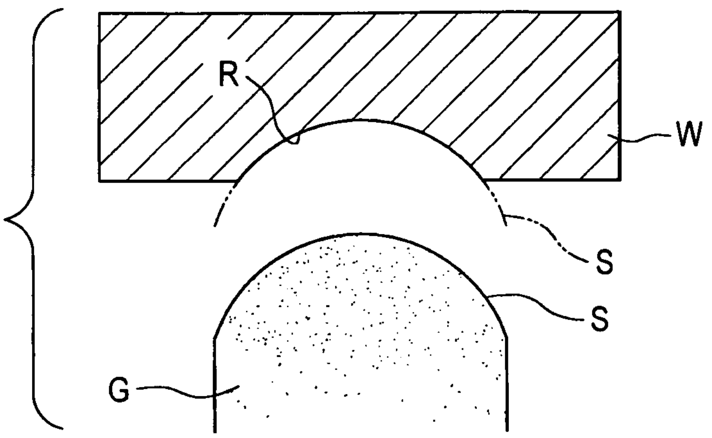


FIG. 6B

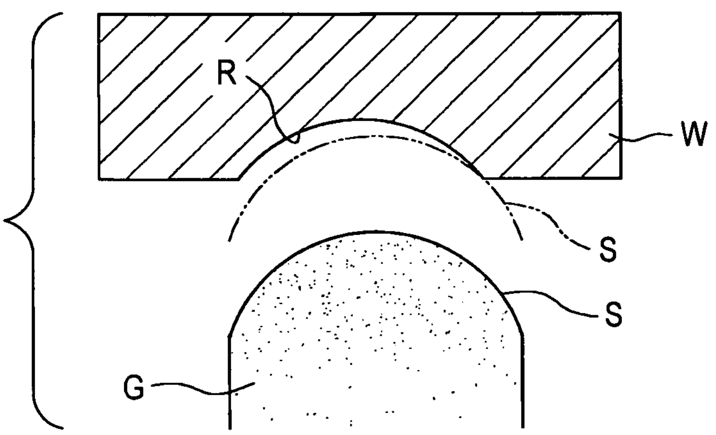
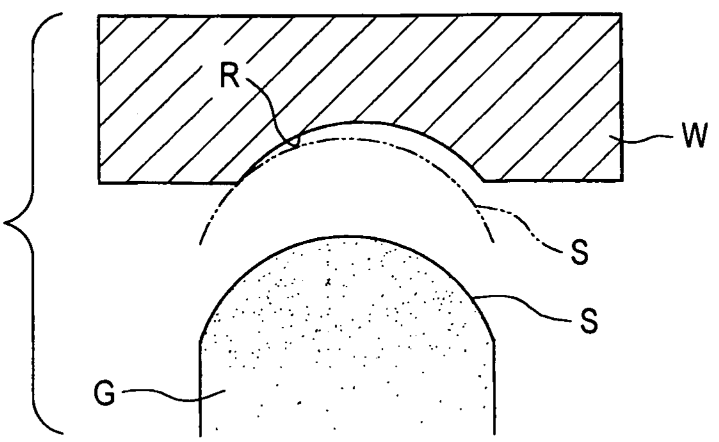


FIG. 6C



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- JP 57027660 A **[0004]**