

US Patent & Trademark Office

Patent Public Search | Text View

United States Patent	12392352
Kind Code	B2
Date of Patent	August 19, 2025
Inventor(s)	Ohtachi; Yoshinobu et al.

Vacuum exhaust apparatus and vacuum pump used therein

Abstract

A vacuum exhaust apparatus capable of accurately and rapidly adjusting the pressure in an exhaust chamber and a vacuum pump used therein are provided. A vacuum pump includes a rotor that rotates to exhaust an exhaust chamber and a casing having an inlet port. A valve is located between the inlet port of the vacuum pump and an outlet port of the exhaust chamber. A controller performs control such that the pressure in the exhaust chamber matches a target value. The controller adjusts the opening degree of the valve when the absolute value of the difference between the pressure in the exhaust chamber and the target value is greater than a predetermined value, and adjusts the rotational speed of the rotor of the vacuum pump when the absolute value of the difference between the pressure in the exhaust chamber and the target value is less than the predetermined value.

Inventors:	Ohtachi; Yoshinobu (Yachiyo, JP), Maejima; Yasushi (Yachiyo, JP), Takaada; Tsutomu (Yachiyo, JP)
Applicant:	Edwards Japan Limited (Yachiyo, JP)
Family ID:	1000008764481
Assignee:	Edwards Japan Limited (Yachiyo, JP)
Appl. No.:	17/779116
Filed (or PCT Filed):	November 27, 2020
PCT No.:	PCT/JP2020/044377
PCT Pub. No.:	WO2021/112021
PCT Pub. Date:	June 10, 2021

Prior Publication Data

Document Identifier	Publication Date
US 20220397122 A1	Dec. 15, 2022

Foreign Application Priority Data

JP	2019-220773	Dec. 05, 2019
JP	2019-221310	Dec. 06, 2019

Publication Classification

Int. Cl.: **F04D27/00** (20060101); **F04B49/06** (20060101); **F04B49/22** (20060101); **F04D19/04** (20060101)

U.S. Cl.:

CPC **F04D27/007** (20130101); **F04B49/06** (20130101); **F04B49/225** (20130101); **F04D19/04** (20130101);

Field of Classification Search

CPC: F04D (19/04); F04D (19/046); F04D (19/042); F04D (19/048); F04D (15/0022); F04D (15/0066); F04D (27/007); F04D (27/0207); F04D (27/0223)

USPC: 417/423.1; 417/423.4

References Cited

U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
5795328	12/1997	Barnitz	604/67	G05D 16/208
7993113	12/2010	Namiki	417/423.4	F04D 29/601
10443600	12/2018	Kozaki et al.	N/A	N/A
2019/0107110	12/2018	Kozaki et al.	N/A	N/A

FOREIGN PATENT DOCUMENTS

Patent No.	Application Date	Country	CPC
106014999	12/2015	CN	N/A
2018204448	12/2017	JP	N/A
201970924	12/2018	JP	N/A
2019070924	12/2018	JP	N/A

OTHER PUBLICATIONS

Extended Search Report from counterpart European Application No. 20896061.7 dated Nov. 27, 2023, 8 pp. cited by applicant

International Search Report and Written Opinion of International Application No. PCT/JP2020/044377, dated Feb. 9, 2021, 10 pp. cited by applicant

Primary Examiner: Stimpert; Philip E

Attorney, Agent or Firm: Shumaker & Sieffert, P.A.

Background/Summary

(1) This application is a U.S. national phase application under 35 U.S.C. § 371 of international application number PCT/JP2020/044377 filed on Nov. 27, 2020, which claims the benefit of JP application number 2019-220773 filed on Dec. 5, 2019 and JP application number 2019-221310 filed on Dec. 6, 2019. The entire contents of each of international application number PCT/JP2020/044377, JP application number 2019-220773 and JP application number 2019-221310 are incorporated herein by reference.

TECHNICAL FIELD

(2) The present disclosure relates to a vacuum exhaust apparatus for controlling the pressure in an exhaust chamber and a vacuum pump used therein.

BACKGROUND

(3) An apparatus that manufactures semiconductors, liquid crystals, solar cells, light emitting diodes (LEDs), and the like (hereinafter referred to as “semiconductors and the like”) has a vacuum chamber that is an exhaust chamber to be exhausted and into which process gas is introduced for processes, such as thin film formation and etching, on objects to be processed placed in the vacuum chamber.

(4) For example, Japanese Patent Application Publication No. 2014-148703 discloses a technique to perform control to set the pressure in such a vacuum chamber to a desired pressure by vacuum exhausting the vacuum chamber while changing the opening degree of a valve connected to the outlet port of the vacuum chamber and the rotational speed of the rotor of a turbomolecular pump, which is a vacuum pump connected to the downstream side of the valve.

SUMMARY

(5) However, with the above-mentioned vacuum exhaust technique, a change in the opening degree of the valve results in a relatively large change in the pressure in the vacuum chamber, whereas a change in the rotational speed of the rotor of the turbomolecular pump results in a relatively small change in the pressure in the vacuum chamber. Accordingly, it is difficult to set the pressure in the vacuum chamber to a desired pressure.

(6) In view of the above, it is an objective of the present disclosure to provide a vacuum exhaust apparatus capable of accurately and rapidly adjusting the pressure in an exhaust chamber and a vacuum pump used therein.

(7) In order to achieve the above objective, a vacuum exhaust apparatus according to the first aspect of the present disclosure includes: a vacuum pump including a rotor configured to rotate to exhaust an exhaust chamber, and a casing having an inlet port; a valve located between the inlet port of the vacuum pump and an outlet port of the exhaust chamber; and a controller configured to perform control such that a pressure in the exhaust chamber matches a target value, wherein the controller is configured to control the pressure by adjusting an opening degree of the valve when an absolute value of a difference between the target value and the pressure is greater than a predetermined value, and by adjusting a rotational speed of the rotor when the absolute value of the difference is less than the predetermined value.

(8) In the above vacuum exhaust apparatus, the controller may be configured to perform control such that the rotational speed of the rotor is constant when the absolute value of the difference is greater than the predetermined value, and that the opening degree of the valve is constant when the absolute value of the difference is less than the predetermined value.

(9) In the above vacuum exhaust apparatus, the controller may be configured to increase a gain of a transfer function $G_{sub.V}$ represented by equation (1):

$G_{sub.V} = O_{sub.V} / \delta_{sub.P}$ (1) when the absolute value of the difference is greater than the predetermined value, and increase a gain of a transfer function $G_{sub.M}$ represented by equation

(2):

$G_{sub.M} = \Omega_{sub.M} / \delta_{sub.P}$ (2) when the absolute value of the difference is less than the predetermined value, in equation (1), $O_{sub.V}$ is a Laplace transform where an initial value of the opening degree of the valve is 0, in equation (2), $\Omega_{sub.M}$ is a Laplace transform where an initial value of the rotational speed of the rotor is 0, and in equations (1) and (2), $\delta_{sub.P}$ is a Laplace transform where an initial value of the difference is 0.

(10) In the above vacuum exhaust apparatus, the controller may be configured to reduce the gain of the transfer function $G_{sub.M}$ when the absolute value of the difference is greater than the predetermined value, and reduce the gain of the transfer function $G_{sub.V}$ when the absolute value of the difference is less than the predetermined value.

(11) In the above vacuum exhaust apparatus, the vacuum pump may include a magnetic bearing configured to levitate and support the rotor, and the controller may be configured to change the opening degree of the valve when the rotational speed of the rotor matches a natural frequency of displacement of the rotor or an absolute value of a difference between the rotational speed and the natural frequency is less than or equal to a predetermined value while the pressure matches the target value, and control the rotational speed of the rotor such that the pressure matches the target value again.

(12) In the above vacuum exhaust apparatus, the predetermined value may be changed while the rotor is rotated according to at least one of the opening degree of the valve and a type and an amount of gas that is introduced into the exhaust chamber and exhausted by the vacuum pump.

(13) To achieve the above objective, a vacuum pump according to the second aspect of the present disclosure is a vacuum pump to be used in a vacuum exhaust apparatus including a valve and a controller configured to perform control such that a pressure in an exhaust chamber matches a target value, the vacuum pump including: a rotor configured to rotate to exhaust the exhaust chamber; and a casing having an inlet port that allows the valve to be located between the inlet port and an outlet port of the exhaust chamber, wherein the controller is configured to control the pressure by adjusting an opening degree of the valve when an absolute value of a difference between the target value and the pressure is greater than a predetermined value, and by adjusting a rotational speed of the rotor when the absolute value of the difference is less than the predetermined value.

(14) In the above vacuum pump, the controller may be configured to perform control such that the rotational speed of the rotor is constant when the absolute value of the difference is greater than the predetermined value, and that the opening degree of the valve is constant when the absolute value of the difference is less than the predetermined value.

(15) In the above vacuum pump, the controller may be configured to increase a gain of a transfer function $G_{sub.V}$ represented by equation (1):

$G_{sub.V} = O_{sub.V} / \delta_{sub.P}$ (1) when the absolute value of the difference is greater than the predetermined value, and increase a gain of a transfer function $G_{sub.M}$ represented by equation

(2):

$G_{sub.M} = \Omega_{sub.M} / \delta_{sub.P}$ (2) when the absolute value of the difference is less than the predetermined value, in equation (1), $O_{sub.V}$ is a Laplace transform where an initial value of the opening degree of the valve is 0, in equation (2), $\Omega_{sub.M}$ is a Laplace transform where an initial value of the rotational speed of the rotor is 0, and in equations (1) and (2), $\delta_{sub.P}$ is a Laplace transform where an initial value of the difference is 0.

(16) In the above vacuum pump, the controller may be configured to reduce the gain of the transfer function $G_{sub.V}$ when the absolute value of the difference is greater than the predetermined value, and reduce the gain of the transfer function $G_{sub.M}$ when the absolute value of the difference is less than the predetermined value.

(17) The above vacuum pump may further include a magnetic bearing configured to levitate and support the rotor.

- (18) The controller may be configured to change the opening degree of the valve when the rotational speed of the rotor matches a natural frequency of displacement of the rotor or an absolute value of a difference between the rotational speed and the natural frequency is less than or equal to a predetermined value while the pressure matches the target value, and control the rotational speed of the rotor such that the pressure matches the target value again.
- (19) In the above vacuum pump, the predetermined value may be changed while the rotor is rotated according to at least one of the opening degree of the valve and a type and an amount of gas that is introduced into the exhaust chamber and exhausted by the vacuum pump.
- (20) According to the present disclosure, a vacuum exhaust apparatus capable of accurately and rapidly adjusting the pressure in an exhaust chamber and a vacuum pump used therein are provided.
-

Description

BRIEF DESCRIPTION OF THE DRAWINGS

- (1) FIG. 1 is a schematic view showing the configuration of a vacuum apparatus including a vacuum exhaust apparatus according to an example of the present disclosure.
- (2) FIG. 2 is a vertical cross-sectional view showing the configuration of a vacuum pump of the vacuum exhaust apparatus of the example of the present disclosure.
- (3) FIG. 3 is a graph showing the relationship between the position of a rotating shaft and the position sensor detection value.
- (4) FIG. 4 is a graph showing the relationship between the value of current flowing through an electromagnet and the magnetic attraction force exerted by the electromagnet of a magnetic bearing on the rotating shaft.
- (5) FIG. 5 is a graph showing the relationship between the rotation frequency of the rotating shaft and the natural frequency of the rotor.
- (6) FIG. 6 is a schematic plan view showing the configuration of a valve of the vacuum exhaust apparatus according to the example of the present disclosure.
- (7) FIG. 7 is a block diagram showing a control system of a controller of the vacuum exhaust apparatus according to the example of the present disclosure.
- (8) FIG. 8A is a graph showing the relationship between the absolute value of the difference between the pressure target value and the pressure measurement value and the gain of the valve opening degree.
- (9) FIG. 8B is a graph showing the relationship between the absolute value of the difference between the pressure target value and the pressure measurement value and the gain of the rotational speed of the rotor.

DETAILED DESCRIPTION

- (10) A vacuum exhaust apparatus according to an example of the present disclosure is now described with reference to the drawings. As shown in FIG. 1, a vacuum exhaust apparatus **10** is an apparatus included in a vacuum apparatus D used for processes, such as thin film forming process and etching process, in a semiconductor manufacturing apparatus, for example. The vacuum exhaust apparatus **10** vacuum exhausts an exhaust chamber to be exhausted (vacuum chamber) **4**, in which objects to be processed are placed, so that the pressure in the exhaust chamber becomes a desired pressure.
- (11) The vacuum exhaust apparatus **10** includes a vacuum pump **1**, which exhausts the process gas introduced in the exhaust chamber **4**, a valve **2**, which is located between an outlet port (not shown) of the exhaust chamber **4** and an inlet port **11a** (FIG. 2) of the vacuum pump **1** to open and close the gas flow passage, and a controller **3** for performing control such that the pressure in the exhaust chamber **4** matches a target value.

(12) As shown in FIG. 2, the vacuum pump **1**, which is a turbomolecular pump, includes an outer cylinder portion **11**, a base portion **12** fixed to the outer cylinder portion **11**, and a rotor **20**, which is rotatably housed in a casing **13** formed by the outer cylinder portion **11** and the base portion **12**. The upper side as viewed in FIG. 2 of the outer cylinder portion **11** is opened to form a gas inlet port **11a**, and a gas outlet port **12a** is formed in the side surface of the base portion **12**. The outer cylinder portion **11** has a flange **11b** at the side including the inlet port **11a**, and the lower end surface of a valve main body **2a** (FIG. 6) of the valve **2** is fixed to this flange **11b**.

(13) The rotor **20** has a rotor main body **20a**, a rotating shaft **30**, and a washer **70**. The rotating shaft **30** is rotatably supported in the casing **13** to rotate the rotor **20**. A plurality of rotor blades **21** inclined at a predetermined angle is integrally formed on the outer circumferential surface of an upper part, as viewed in FIG. 2, of the rotor main body **20a**. The rotor blades **21** are arranged radially with respect to the axis of the rotating shaft **30** of the rotor **20** and in multiple stages in the axial direction of the rotating shaft **30** of the rotor **20**. Stator blades **40** are located between the stages of the rotor blades **21**. The rotor blades **21** and the stator blades **40** alternate in the axial direction of the rotating shaft **30** of the rotor **20**. The plurality of stator blades **40** is also inclined at a predetermined angle. The outer circumference ends of the stator blades **40** are held between multiple ring-shaped stator blade spacers **50** arranged in stages in the outer cylinder portion **11**, so that the stator blades **40** are arranged radially and in multiple stages between the rotor blades **21**.

(14) A threaded spacer **60** is provided between the base portion **12** and the stator blade spacer **50** that is the closest to the downstream side. The threaded spacer **60** is cylindrical and has a spiral thread groove **60a** in its inner circumference surface. A cylindrical portion **22** is formed under the rotor main body **20a** as viewed in FIG. 2 (on the downstream side in the gas flow direction) and about the axis of the rotating shaft **30**. The outer circumferential surface of the cylindrical portion **22** is adjacent to and faces the inner circumference surface including the thread groove **60a** of the threaded spacer **60**. The space defined by the outer circumferential surface of the cylindrical portion **22** and the thread groove **60a** of the threaded spacer **60** communicates with the outlet port **12a**.

(15) The disc-shaped washer **70** is formed about the axis of the rotating shaft **30**. Bolts **71** are fastened to the rotating shaft **30** through the rotor main body **20a** and the washer **70**, fixing the rotor main body **20a** and the washer **70** to the rotating shaft **30**.

(16) In the vacuum pump **1**, when the rotor **20** is rotated at high speed, the rotor blades **21** strike the gas molecules sucked through the inlet port **11a** toward the downstream side. The struck gas molecules collide against the stator blades **40**, which are alternately arranged, move downward, and are then struck by the rotor blades **21** of the next stage and thus moved to the downstream side. This action is sequentially repeated to the lowermost stages of the rotor blades **21** and the stator blades **40**. The gas thus sent to threaded spacer **60** is guided by the thread groove **60a** to the outlet port **12a** and exhausted from the outlet port **12a**. In this procedure, the pressure in the gas exhaust chamber **4** can be adjusted to a desired pressure by adjusting the rotational speed of the rotor **20**. As shown in FIG. 1, the vacuum pump **1** has a rotational speed detector **1a** for detecting the rotational speed of the rotor **20**. The detection value of the rotational speed of the rotor **20** detected by the rotational speed detector **1a** is output to the controller **3**.

(17) Protective bearings **31** are arranged near the upper side and the lower side as viewed in FIG. 2 (the upstream side and downstream side in the gas flow direction) of the rotating shaft **30**. The protective bearings **31** prevent damage of the vacuum pump **1**, which would otherwise occur if an abnormality renders radial magnetic bearings **33** or axial magnetic bearing **34**, which will be described below, uncontrollable, causing the vacuum pump **1** to be in contact with and support the rotating shaft **30**.

(18) The rotating shaft **30** is driven by a brushless DC pump motor **32** to rotate. Two radial magnetic bearings **33** support the rotating shaft **30** in the radial direction, and an axial magnetic bearing **34** supports the rotating shaft **30** in the axial direction. The two radial magnetic bearings **33**

are on opposite sides of the pump motor **32**. The rotating shaft **30** is levitated and supported by these radial magnetic bearings **33** and the axial magnetic bearing **34**.

(19) The two radial magnetic bearings **33** each have four electromagnets **33a**, which exert magnetic attraction force on the rotating shaft **30**. Two of the four electromagnets **33a** are located across the rotating shaft **30** on one of two coordinate axes that are perpendicular to the axis of the rotating shaft **30** and also perpendicular to each other. The other two electromagnets **33a** are located on the other coordinate axis. The two radial magnetic bearings **33** each have four position sensors **33b**, which may be inductance or eddy current sensors, for detecting the radial position of the rotating shaft **30**. Two of the four position sensors **33b** are located across the rotating shaft **30** on one of two coordinate axes that are perpendicular to the axis of the rotating shaft **30**, parallel to the above-mentioned coordinate axes, and perpendicular to each other. The other two position sensors **33b** are located on the other coordinate axis.

(20) The rotating shaft **30** has a magnetic disc (hereinafter referred to as “armature disc”) **80** located about the axis of the rotating shaft **30**. The axial magnetic bearing **34** has two electromagnets **34a** that exert magnetic attraction force on the armature disc **80**. The two electromagnets **34a** are on opposite sides of the armature disc **80**. The axial magnetic bearing **34** has a position sensor **34b**, which may be an inductance or eddy current sensor, for detecting the axial position of the rotating shaft **30**. The inductance or eddy current position sensors **33b** of the radial magnetic bearings **33** and the inductance or eddy current position sensor **34b** of the axial magnetic bearing **34** have the same structure as an electromagnet, and their cores, on which conductor coils are wound, face the rotating shaft **30**.

(21) A stator **90** extends upright from the base portion **12** to protect the radial magnetic bearings **33**, the axial magnetic bearing **34**, the pump motor **32**, and the like from the sucked gas.

(22) The vacuum pump **1** has a pump controller (not shown), which is integral with or connected via a cable to the vacuum pump **1**. The pump controller supplies power to the radial magnetic bearings **33**, the axial magnetic bearing **34**, and the pump motor **32** and transmits and receives signals to and from the position sensors **33b** and **34b**. The pump controller supplies a high-frequency alternating voltage having a predetermined amplitude to the conductor coils of the position sensors **33b** and **34b** of the radial magnetic bearings **33** and the axial magnetic bearing **34**. The inductance of the conductor coil wound around the core of each position sensor **33b**, **34b** varies according to the distance between the core and the rotating shaft **30**. This variation in the inductance results in variation in the amplitude of the voltage applied to the conductor coil. The pump controller detects this variation in the amplitude value, thereby detecting the position of the rotating shaft **30**. As shown in FIG. 3, this amplitude value (position sensor detection value E.sub.O) has nonlinearity and increases or decreases in a curve according to the variation in the position of the rotating shaft **30**. The sum E.sub.O1+E.sub.O2 (or the difference depending on how the positive and negative signs are set) of the amplitude values of the two position sensors **33b** facing each other across the rotating shaft **30** on each of the above-mentioned coordinate axes has quasi-linearity with respect to the variation in the position of the rotating shaft **30**. Thus, the pump controller calculates this sum (or difference) and uses the value as a detection signal of the position sensors **33b** in order to apply the linear control theory. This allows the position of the rotating shaft **30** to be controlled based on this theory. The pump controller places the rotating shaft **30** at the target position by performing feedback control that adjusts the values of current flowing through the electromagnets **33a** based on the sum (or difference) of the detection signals of the two position sensors **33b** on each coordinate axis.

(23) As shown in FIG. 4, the magnetic attraction force f exerted by each electromagnet **33a** of the radial magnetic bearings **33** on the rotating shaft **30** also has nonlinearity and increases or decreases in a curve according to the variation in the current flowing through the electromagnet **33a**. As such, when the rotating shaft **30** is deviated from the target position, one of the two electromagnets **33a** facing each other across the rotating shaft **30** on each coordinate axis that has a greater distance to

the rotating shaft **30** receives a current of a current value ($I_{\text{sub}.0} + i_{\text{sub}.1}$) obtained by adding a current value $i_{\text{sub}.1}$ to a predetermined DC current value $I_{\text{sub}.0}$ (hereinafter referred to as “bias current value”). The other of the two electromagnets **33a** that has a smaller distance to the rotating shaft **30** receives a current of a current value ($I_{\text{sub}.0} - i_{\text{sub}.1}$) obtained by subtracting the current value $i_{\text{sub}.1}$ from the bias current value $I_{\text{sub}.0}$. The current values are thus controlled. In this manner, the sum of the magnetic attraction forces $f_{\text{sub}.hx1} + (-f_{\text{sub}.hx2})$ exerted by two electromagnets **33a** is used as the magnetic attraction force acting on the rotating shaft **30**.

Accordingly, the magnetic attraction force has quasi-linearity with respect to the variation in the current value, allowing for the application of the above-mentioned linear control theory.

(24) The configuration of the axial magnetic bearing **34** is basically the same as the configuration of the radial magnetic bearings **33**. However, for purposes such as reducing the required space, instead of arranging two position sensors on opposite sides of the armature disc **80** in the axial direction of the rotating shaft **30**, only one position sensor **34b** may be placed, and the other position sensor may be replaced by a coil that is placed on a circuit substrate in the controller and has a predetermined inductance. In this case, the inductance of the coil provided on the circuit substrate is a predetermined value, and the amplitude value of the alternating voltage is a predetermined value. This lowers the accuracy of the linearization of the sum (or difference) of the two position sensors with respect to the variation in the position of the rotating shaft **30**.

Nevertheless, this technique is useful when the vacuum pump **1** operates normally.

(25) The bearing force for the rotor **20**, which is supported and levitated by the radial magnetic bearings **33** and axial magnetic bearing **34**, includes a component of force proportional to the variation in the position of the rotor **20**, that is, a component corresponding to elastic force. The rotor **20** therefore has a natural frequency according to its mass or moment of inertia. The levitated rotor **20** has six degrees of freedom in total, including three degrees of freedom in the directions of the coordinate axes of a three-dimensional rectangular coordinate system having one coordinate axis (hereinafter referred to as “z-axis”) aligned with the axis of the rotating shaft **30**, and three degrees of freedom about these axes. The angle of rotation of the degree of freedom about the z-axis is controlled by the pump motor **32**. The other five degrees of freedom are affected by the bearing forces of the radial magnetic bearings **33** and the axial magnetic bearing **34** and thus have natural frequencies according to the bearing forces of the radial magnetic bearings **33** and the axial magnetic bearing **34**. In particular, each of the equations of motion of the rotor **20** of the two degrees of freedom about the two axes perpendicular to the z-axis and perpendicular to each other (hereinafter referred to as “x-axis” and “y-axis”) includes a term that is proportional to the rotational speed about the axis of the other of these degrees of freedom (hereinafter referred to as an “interaction term”), as shown in equation (3) of the equation of motion about the x-axis and equation (4) of the equation of motion about the y-axis below. The magnitudes of these interaction terms are proportional to the rotational speed of the rotating shaft **30** rotated by the pump motor **32**.

[Math. 1]

$$D_{\text{sub}.x} - J \ddot{\theta}_{\text{sub}.x} - C \dot{\theta}_{\text{sub}.x} - G_{\text{sub}.x} \theta_{\text{sub}.x} - J_{\text{sub}.z} \ddot{\theta}_{\text{sub}.z} = 0 \quad (3)$$

$$D_{\text{sub}.y} - J \ddot{\theta}_{\text{sub}.y} - C \dot{\theta}_{\text{sub}.y} - G_{\text{sub}.y} \theta_{\text{sub}.y} + J_{\text{sub}.z} \ddot{\theta}_{\text{sub}.z} = 0 \quad (4)$$

(26) In equations (3) and (4), J is the moment of inertia about the x-axis or y-axis of the rotor **20**, $J_{\text{sub}.z}$ is the moment of inertia about the z-axis of the rotor **20**, C is the viscous resistance coefficient about the x-axis or y-axis, $\theta_{\text{sub}.x}$ is the angle of rotation of the rotor **20** about the x-axis, $\theta_{\text{sub}.y}$ is the angle of rotation of the rotor **20** about the y-axis, and $\theta_{\text{sub}.z}$ is the angle of rotation of the rotor **20** about the z-axis. In equation (3), $D_{\text{sub}.x}$ is the disturbance moment acting about the x-axis, and $G_{\text{sub}.x}$ is the spring constant of the moment about the x-axis produced by the bearing force of the radial magnetic bearings **33**. In equation (4), $D_{\text{sub}.y}$ is the disturbance moment acting about the y-axis, and $G_{\text{sub}.y}$ is the spring constant of the moment about the y-axis produced by the

bearing force of the radial magnetic bearings **33**. D.sub.x and D.sub.y are caused by factors such as the imbalance of the rotor **20** and the exhaust load of the vacuum pump **1**. G.sub.x and G.sub.y actually have frequency characteristics according to the control design of the radial magnetic bearings **33**. Specifically, since the rotor **20** has the rotor main body **20a**, the rotating shaft **30**, and the washer **70** as described above, the moment of inertia J.sub.z and the moment of inertia J are the sum of the moments of inertia of the rotor main body **20a**, the rotating shaft **30**, and the washer **70**. (27) Normally, an equation for obtaining the natural frequency of each degree of freedom can be derived from the equation of motion of the degree of freedom. However, as for the degrees of freedom about the x-axis and y-axis of the radial magnetic bearings **33**, it is difficult to derive the equations for obtaining the natural frequencies for reasons such as the presence of the interaction terms in the equations of motion of these degrees of freedom as described above. For this reason, a conventional technique designs a specific magnetic bearing and relies on trial experiments or computer simulation using the finite element method or the like to obtain values of the natural frequencies of the specific magnetic bearing.

(28) However, even though this technique can determine the natural frequency for each specific magnetic bearing, qualitative analyses of natural frequency, such as an analysis on how the natural frequency changes when the design value is changed, cannot be conducted. The natural frequency of a specific magnetic bearing is obtained after its design is completed, and if the design is changed for some reason, the natural frequency is obtained again after completing the design change. The design needs to be changed again in case of any problem. As a result, a significant amount of time is required to design a magnetic bearing and a turbomolecular pump.

(29) In the present disclosure, in light of the fact that the radial magnetic bearings **33** of the vacuum pump **1**, which is a turbomolecular pump, are used in a vacuum, the viscous resistance coefficient C is taken as 0, and equations (5) and (6) that give two natural frequencies $\omega_{\text{sub.1}}$ and $\omega_{\text{sub.2}}$ of the rotor **20** that are present about each of the x-axis and the y-axis are derived from equations (3) and (4) above. Two natural frequencies given by equations (5) and (6) are present for each of the degrees of freedom about the x-axis and y-axis.

[Math. 2]

$$(30) \quad \omega_{\text{sub.1}} = \frac{\sqrt{J(G_x + G_y) + J_z^2 \cdot \omega_z^2} - \sqrt{2J(G_x + G_y)J_z^2 \cdot \omega_z^2 + J_z^4 \cdot \omega_z^4}}{2J^2} \quad (5)$$

$$\omega_{\text{sub.2}} = \frac{\sqrt{J(G_x + G_y) + J_z^2 \cdot \omega_z^2} + \sqrt{2J(G_x + G_y)J_z^2 \cdot \omega_z^2 + J_z^4 \cdot \omega_z^4}}{2J^2} \quad (6)$$

(31) As shown in FIG. 5, as the

ROTATION FREQUENCY $\Omega_{\text{sub.z}} (= \{\dot{\theta}\}_{\text{sub.z}})$

increases after the rotating shaft **30** starts to rotate, the natural frequency $\omega_{\text{sub.1}}$ of the rotor **20** decreases while the natural frequency $\omega_{\text{sub.2}}$ increases. As the rotation frequency $\Omega_{\text{sub.z}}$ increases, the natural frequency $\omega_{\text{sub.2}}$ approaches the rotation frequency $\Omega_{\text{sub.z}}$, matches the rotation frequency $\Omega_{\text{sub.z}}$, and then departs from the rotation frequency $\Omega_{\text{sub.z}}$.

(32) When the natural frequencies $\omega_{\text{sub.1}}$ and $\omega_{\text{sub.2}}$ are equal or close to the rotation frequency $\Omega_{\text{sub.z}}$ of the rotating shaft **30**, resonance of the rotor **20** is induced, making it difficult for the radial magnetic bearings **33** and the axial magnetic bearing **34** to levitate and support the rotor **20** and also causing fatigue failure due to the continuous vibration of the rotor blades **21** and the repeated stress fluctuation. As such, the controller **3** changes the opening degree of the valve **2** when the rotational speed (rotation frequency $\Omega_{\text{sub.z}}$) of the rotor **20** matches the natural frequency $\omega_{\text{sub.1}}$, $\omega_{\text{sub.2}}$ of displacement, or when the absolute value of the difference between the rotational speed of the rotor **20** and the natural frequency $\omega_{\text{sub.1}}$, $\omega_{\text{sub.2}}$ is less than or equal to a predetermined value while the pressure in the exhaust chamber **4** matches the target value, and controls the rotational speed of the rotor **20** such that the pressure in the exhaust chamber **4** matches the target value again.

(33) As shown in FIG. 6, the valve 2 includes a valve main body 2a, a valve body 2c fixed to a shaft 2b, a valve motor 2d that drives and rotates the shaft 2b to pivot the valve body 2c, and an opening 2e, which is opened and closed by the valve body 2c. The valve 2 is provided between the outlet port (not shown) of the exhaust chamber 4 and the inlet port 11a of the vacuum pump 1. The opening 2e of the valve 2 is connected to and communicates with the outlet port of the exhaust chamber 4 and the inlet port 11a of the vacuum pump 1.

(34) The valve 2 uses the valve motor 2d to pivot the valve body 2c to place it at a desired position overlapping the opening 2e. The opening area of the opening 2e is thus adjusted to adjust the opening degree. By adjusting the opening degree of the valve 2, the pressure in the exhaust chamber 4 can be adjusted to a desired pressure. As shown in FIG. 1, the valve 2 has an opening degree detector 2f, such as an encoder, that detects the opening degree. The detection value of the opening degree of the valve 2 detected by the opening degree detector 2f is output to the controller 3.

(35) The controller 3 performs control such that the pressure in the exhaust chamber 4 matches a target value by adjusting the opening degree of the valve 2 or the rotational speed of the rotor 20 of the vacuum pump 1 under predetermined conditions. The controller 3 has portions including a control portion, which may include a central processing unit (CPU) (not shown), and a storage portion, which may include a random-access memory (RAM), read-only memory (ROM), and flash memory. The storage portion stores various data such as programs to be executed by the control portion, fixed data, and detection data. The storage portion also functions as working memory for the control portion. The control portion controls the pressure in the exhaust chamber 4 by executing a program stored in the storage portion.

(36) When the opening degree of the valve 2 is changed, a change in the opening degree results in a relatively large change in the pressure in the exhaust chamber 4. For example, when the pressure in the exhaust chamber 4 needs to be increased only minimally, even a minimal decrease in the opening degree of the valve 2 increases the pressure significantly. When the pressure needs to be lowered only minimally, even a minimal increase in the opening degree of the valve 2 reduces the pressure significantly. Furthermore, factors such as the backlash of the gear that transmits the rotation of the valve motor 2d to the valve body 2c or the elastic slippage or movement slippage of the belt may cause an error in the position of the valve body 2c moved by a rotation of the valve motor 2d. This may prevent the accurate setting of the desired opening degree. An attempt to achieve accurate control by increasing the gain of a change in the opening degree of the valve 2 with respect to a change in pressure and reducing the steady-state deviation of the pressure with respect to the desired pressure would cause, in the worst case, the oscillatory phenomenon of the opening degree of valve 2. As such, the desired pressure cannot be achieved accurately.

(37) In contrast, when the rotational speed of the rotor 20 of the vacuum pump 1 is changed, a change in the rotational speed results in a relatively small change in the pressure in the exhaust chamber 4. Thus, when the pressure in the exhaust chamber 4 needs to be changed significantly, a significant change is required in the rotational speed of the rotor 20. However, when the vacuum pump 1 is a turbomolecular pump, the rotor 20 needs to be rotated at high speed to provide a desired exhaust performance and is thus made of a high-strength metal, such as an aluminum alloy, that resists damage when receiving a large centrifugal force. Accordingly, the rotor 20 has a large moment of inertia. It is therefore difficult to significantly change the rotational speed of the rotor 20 within a short time, or rapidly.

(38) It may also be contemplated to use a motor capable of generating high torque as the pump motor 32 for rotating the rotor 20 to increase the acceleration/deceleration torque. However, when a brushless DC motor, which is relatively inexpensive to manufacture, is used, a greater torque constant increases the induced voltage constant. This in turn increases the counter-electromotive force during high-speed operation, which may prevent a current from flowing sufficiently to generate acceleration/deceleration torque. As a result, a significant rapid change in the rotational

speed cannot be achieved. Inability to achieve a significant rapid change in the rotational speed of the rotor **20** lengthens the time required for a semiconductor manufacturing apparatus to treat wafer surfaces, for example, hindering an increase in the quantity of manufactured semiconductors.

(39) The controller **3** solves the above problem by adjusting the opening degree of the valve **2** when the absolute value of the difference between the pressure in the exhaust chamber **4** and the target value is greater than a predetermined value, and adjusting the rotational speed of the rotor **20** of the vacuum pump **1** when the absolute value of the difference between the pressure in the exhaust chamber **4** and the target value is less than the predetermined value.

(40) A method is now described that vacuum exhausts the exhaust chamber **4** using the controller **3** so that the pressure in the exhaust chamber **4** becomes a desired pressure. As shown in FIG. **1**, a pressure gauge **5** is provided in the exhaust chamber **4**, into which process gas flows, and the pressure gauge **5** measures the pressure in the exhaust chamber **4**. The pressure measurement value measured by the pressure gauge **5** is output to the controller **3** and is compared with the pressure target value by the controller **3**.

(41) When the absolute value of the difference between the pressure target value and the pressure measurement value is greater than a predetermined value, the controller **3** transmits a drive signal having a value corresponding to the value of difference to the valve motor **2d** of the valve **2** to adjust the opening degree of the valve **2**. At this time, the controller **3** may use the control system shown in FIG. **7** to increase the gain $|G_{\text{sub.V}}|$ of a transfer function $G_{\text{sub.V}}$ represented by equation (1) below as shown in FIG. **8A**. Alternatively, the controller **3** may use the control system in FIG. **7** to reduce the gain $|G_{\text{sub.M}}|$ of a transfer function $G_{\text{sub.M}}$ represented by equation (2) below as shown in FIG. **8B**. Additionally, the controller **3** may perform control to maintain the rotational speed of the rotor **20** detected by the rotational speed detector **1a** constant.

$$G_{\text{sub.V}} = O_{\text{sub.V}} / \delta_{\text{sub.P}} \quad (1)$$

$$G_{\text{sub.M}} = \Omega_{\text{sub.M}} / \delta_{\text{sub.P}} \quad (2)$$

(42) In equation (1), $O_{\text{sub.V}}$ is a Laplace transform where the initial value of the opening degree of the valve **2** is 0. In equation (2), $\Omega_{\text{sub.M}}$ is a Laplace transform where the initial value of the rotational speed of the rotor **20** is 0. In equations (1) and (2), $\delta_{\text{sub.P}}$ is a Laplace transform where the initial value of the difference between the pressure target value and the pressure measurement value is 0.

(43) Here, increasing the gain refers to increasing the gain by 3 dB or more with respect to the gain when the frequency is 0, that is, the direct current gain. Reducing the gain refers to reducing the gain by 3 dB or more with respect to the gain when the frequency is 0, that is, the direct current. Alternatively, increasing or reducing the gain refers to setting the average value of gains for the range of absolute values between the pressure target value and pressure measurement values that is less than a predetermined value to be greater than or less than the average value of gains for the range that is greater than the predetermined value. Alternatively, increasing or reducing the gain refers to setting the average value of gains for the range of absolute values between the pressure target value and pressure measurement values that is greater than the predetermined value to be greater than or less than the average value of gains for the range that is less than the predetermined value.

(44) When the absolute value of the difference between the pressure target value and the pressure measurement value is smaller than the predetermined value, the controller **3** transmits a drive signal having a value corresponding to the value of difference to the pump motor **32** of the vacuum pump **1** to adjust the rotational speed of the rotor **20**. In this case, the controller **3** may increase the gain $|G_{\text{sub.M}}|$ of the rotational speed of the rotor **20** with respect to the absolute value of the difference between the pressure target value and the pressure measurement value. Conversely, the controller **3** may reduce the gain $|G_{\text{sub.V}}|$ of the opening degree of the valve **2** with respect to the absolute value of the difference between the pressure target value and the pressure measurement value. Additionally, the controller **3** may perform control to maintain the opening degree of the valve **2**

detected by the opening degree detector **2f** constant. Accordingly, the pressure in the exhaust chamber **4** can be adjusted more accurately and rapidly.

(45) A method is now described that solves the problem of induced resonance of the rotor **20** of the vacuum pump **1** described above and in which the controller **3** controls to vacuum exhaust the exhaust chamber **4** so that the pressure in the exhaust chamber **4** becomes a desired pressure. The controller **3** compares the rotational speed of the rotor **20** detected by the rotational speed detector **1a** with the natural frequencies $\omega_{\text{sub.1}}$ and $\omega_{\text{sub.2}}$ of the rotor **20**. When the rotational speed of the rotor **20** matches the natural frequency $\omega_{\text{sub.1}}$, $\omega_{\text{sub.2}}$ or the absolute value of the difference between the rotational speed and the natural frequency is less than or equal to a predetermined value while the pressure measurement value measured by the pressure gauge **5** matches the pressure target value, the controller **3** sends an opening degree change command signal to the valve motor **2d** to change the opening degree of the valve **2** by a specific amount. Then, a drive signal having a value corresponding to the difference between the pressure target value and the pressure measurement value measured by the pressure gauge **5** is transmitted to the pump motor **32** to adjust the rotational speed of the rotor **20** so that the pressure measurement value matches the pressure target value.

(46) According to the example, the controller **3** adjusts the opening degree of the valve **2** when the absolute value of the difference between the pressure in the exhaust chamber **4** and the target value is greater than a predetermined value, and adjusts the rotational speed of the rotor **20** of the vacuum pump **1** when the absolute value of the difference between the pressure in the exhaust chamber **4** and the target value is less than the predetermined value. As a result, the problem caused by changing the opening degree of the valve **2** and the problem caused by changing the rotational speed of the rotor **20** are avoided, and the pressure in the exhaust chamber **4** can be accurately adjusted to a desired pressure in a short time, or rapidly.

(47) The present disclosure is described above with reference to examples, but the present disclosure is not limited to the above examples and can be modified in various manners. For example, the above examples are examples in which the valve motor **2d** pivots the valve body **2c** to place it at a desired position overlapping the opening **2e**, thereby adjusting the opening area of the opening **2e** to adjust the opening degree. However, the mechanism of the valve is not limited to this, and the valve may have any mechanism as long as it can open and close the gas flow passage. For example, the valve **2** may be a butterfly valve or a flap valve. Also, instead of the valve motor **2d**, gears, belts, or the like, a valve may be used that drives the valve body **2c** by means of the pressurized air generated by a compressor or the like.

(48) According to the present disclosure, the method for controlling the pressure in the exhaust chamber **4** is changed depending on whether the absolute value of the difference between the pressure target value and the pressure measurement value is greater or less than the predetermined value. This predetermined value is appropriately selected according to factors including the type of the vacuum apparatus **D**, such as a semiconductor manufacturing apparatus, an electronic microscope, a surface analyzer, or a micromachining apparatus, that uses the vacuum exhaust apparatus **10**, the condition and situation in which the vacuum exhaust apparatus **10** is used, and the mechanisms and types of the vacuum pump **1** and the valve **2**.

(49) Furthermore, this predetermined value may be appropriately changed while the rotor **20** is rotated according to the opening degree of the valve **2**, the type and amount of process gas introduced into the exhaust chamber **4** and exhausted by the vacuum pump **1**, and the like. In this case, the storage portion of the controller **3** may store a plurality of predetermined values, and the predetermined value may be appropriately changed to a value selected or calculated from these values.

Claims

1. A vacuum exhaust apparatus comprising: a vacuum pump including a rotor configured to rotate to exhaust an exhaust chamber, and a casing having an inlet port; a valve located between the inlet port of the vacuum pump and an outlet port of the exhaust chamber; and a controller configured to perform control such that a pressure in the exhaust chamber matches a target value, wherein the controller is configured to control the pressure by: adjusting, responsive to a first determination that an absolute value of a difference between the target value and the pressure is greater than a predetermined value, an opening degree of the valve based on a function of the difference between the target value and the pressure, and adjusting, responsive to a second determination that the absolute value of the difference between the target value and the pressure is less than the predetermined value, a rotational speed of the rotor based on a function of the difference between the target value and the pressure.

2. A vacuum exhaust apparatus comprising: a vacuum pump including a rotor configured to rotate to exhaust an exhaust chamber, and a casing having an inlet port; a valve located between the inlet port of the vacuum pump and an outlet port of the exhaust chamber; and a controller configured to perform control such that a pressure in the exhaust chamber matches a target value, wherein the controller is configured to control the pressure by increasing a gain of a transfer function $G_{sub.v}$ represented by equation (1) and adjusting an opening degree of the valve:

$G_{sub.V} = O_{sub.V} / \delta_{sub.P}$ (1) when an absolute value of a difference between the target value and the pressure is greater than a predetermined value, and increasing a gain of a transfer function $G_{sub.M}$ represented by equation (2) and adjusting a rotational speed of the rotor:

$G_{sub.M} = \Omega_{sub.M} / \delta_{sub.P}$ (2) when the absolute value of the difference is less than the predetermined value, in equation (1), $O_{sub.v}$ is a Laplace transform of the opening degree of the valve in which an initial value of the opening degree of the valve is set to 0, in equation (2), $\Omega_{sub.M}$ is a Laplace transform of the rotational speed of the rotor in which an initial value of the rotational speed of the rotor is set to 0, and in equations (1) and (2), $\delta_{sub.p}$ is a Laplace transform of the difference in which an initial value of the difference is set to 0.

3. The vacuum exhaust apparatus according to claim 2, wherein the controller is configured to reduce the gain of the transfer function $G_{sub.M}$ when the absolute value of the difference is greater than the predetermined value, and reduce the gain of the transfer function $G_{sub.v}$ when the absolute value of the difference is less than the predetermined value.

4. The vacuum exhaust apparatus according to claim 1, wherein the vacuum pump includes a magnetic bearing configured to levitate and support the rotor, and the controller is configured to change the opening degree of the valve when the rotational speed of the rotor matches a natural frequency of displacement of the rotor or an absolute value of a difference between the rotational speed and the natural frequency is less than or equal to a predetermined value while the pressure matches the target value, and control the rotational speed of the rotor such that the pressure matches the target value again.

5. The vacuum exhaust apparatus according to claim 1, wherein the predetermined value is changed while the rotor is rotated according to at least one of the opening degree of the valve and a type and an amount of gas that is introduced into the exhaust chamber and exhausted by the vacuum pump.

6. A vacuum pump comprising: a controller configured to perform control such that a pressure in an exhaust chamber matches a target value; a rotor configured to rotate to exhaust the exhaust chamber; and a casing having an inlet port that allows a valve to be located between the inlet port and an outlet port of the exhaust chamber, wherein the controller is configured to control the pressure by: adjusting, responsive to a first determination that an absolute value of a difference between the target value and the pressure is greater than a predetermined value, an opening degree of the valve based on a function of the difference between the target value and the pressure, and adjusting, responsive to a second determination that the absolute value of the difference between the target value and the pressure is less than the predetermined value, a rotational speed of the rotor

based on a function of the difference between the target value and the pressure.

7. A vacuum pump comprising: a controller configured to perform control such that a pressure in an exhaust chamber matches a target value; a rotor configured to rotate to exhaust the exhaust chamber; a casing having an inlet port; and a valve located between the inlet port and an outlet port of the exhaust chamber, wherein the controller is configured to control the pressure by increasing a gain of a transfer function $G_{sub.v}$ represented by equation (1) and adjusting an opening degree of the valve:

$G_{sub.V} = O_{sub.V} / \delta_{sub.P}$ (1) when an absolute value of a difference between the target value and the pressure is greater than a predetermined value, and increasing a gain of a transfer function $G_{sub.M}$ represented by equation (2) and adjusting a rotational speed of the rotor:

$G_{sub.M} = \Omega_{sub.M} / \delta_{sub.P}$ (2) when the absolute value of the difference is less than the predetermined value, in equation (1), $O_{sub.v}$ is a Laplace transform of the opening degree of the valve in which an initial value of the opening degree of the valve is set to 0, in equation (2), $\Omega_{sub.M}$ is a Laplace transform of the rotational speed of the rotor in which an initial value of the rotational speed of the rotor is set to 0, and in equations (1) and (2), $\delta_{sub.p}$ is a Laplace transform of the difference in which an initial value of the difference is set to 0.

8. The vacuum pump according to claim 7, wherein the controller is configured to reduce the gain of the transfer function $G_{sub.M}$ when the absolute value of the difference is greater than the predetermined value, and reduce the gain of the transfer function $G_{sub.v}$ when the absolute value of the difference is less than the predetermined value.

9. The vacuum pump according to claim 7, further comprising: a magnetic bearing configured to levitate and support the rotor, wherein the controller is configured to change the opening degree of the valve when the rotational speed of the rotor matches a natural frequency of displacement of the rotor or an absolute value of a difference between the rotational speed and the natural frequency is less than or equal to a predetermined value while the pressure matches the target value, and control the rotational speed of the rotor such that the pressure matches the target value again.

10. The vacuum pump according to claim 6, wherein the predetermined value is changed while the rotor is rotated according to at least one of the opening degree of the valve and a type and an amount of gas that is introduced into the exhaust chamber and exhausted by the vacuum pump.
