



(51) International Patent Classification:

F04D 19/04 (2006.01) *F04D 29/059* (2006.01)
F04D 29/051 (2006.01)

(21) International Application Number:

PCT/GB2020/050298

(22) International Filing Date:

10 February 2020 (10.02.2020)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

1901814.2 11 February 2019 (11.02.2019) GB

(71) Applicants: **EDWARDS LIMITED** [GB/GB]; Innovation Drive, Burgess Hill, Sussex RH15 9TW (GB). **LEYBOLD GMBH** [DE/DE]; Bonner Str. 498, 50968 Cologne (DE).

(72) Inventors: **MILES, Christopher**; Edwards Limited, Innovation Drive, Burgess Hill, Sussex RH15 9TW (GB). **GRANT, Nicolas Jonathan**; Edwards Limited, Innovation Drive, Burgess Hill, Sussex RH15 9TW (GB). **PATEY,**

Alexander James; Edwards Limited, Innovation Drive, Burgess Hill, Sussex RH15 9TW (GB). **LUCCHETTA, Emiliano**; Edwards Limited, Innovation Drive, Burgess Hill, Sussex RH15 9TW (GB). **SMITH, Paul David**; Edwards Limited, Innovation Drive, Burgess Hill, Sussex RH15 9TW (GB). **BERGER, Christian**; Leybold GmbH, Bonner Str. 498, 50968 Cologne (DE).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ,

(54) Title: VACUUM PUMP

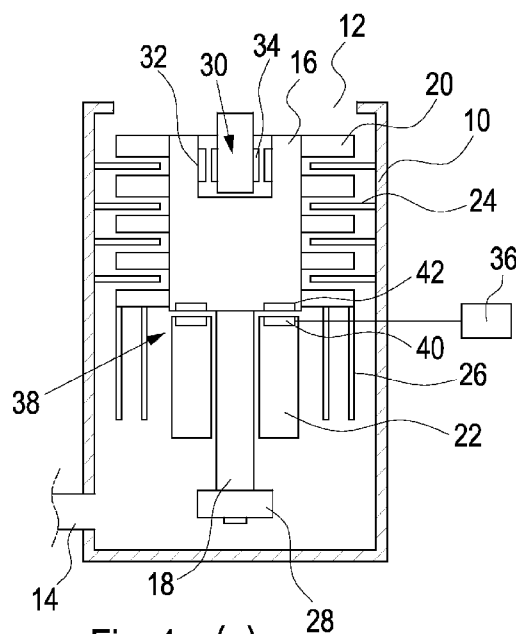


Fig. 1 (a)

(57) Abstract: Vacuum pump, in particular turbomolecular pump comprising rotor assembly rotatable supported by a first bearing and a second bearing, wherein at least one bearing is a ball bearing. Further, the vacuum pump comprises a preload force compensator unit, wherein the preload force compensator unit is built to generate a force to adjust the preload force on the at least one ball bearing. A control unit is connected to at least one sensor detect a pumping parameter, then further connected to the preload force compensator unit to generate a force dependent on the detected pump parameter.



UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

- 1 -

Vacuum pump

The present invention relates to a vacuum pump and in particular to a turbomolecular vacuum pump.

5

Known vacuum pumps comprise a housing with an inlet and an outlet. A rotor assembly is disposed in the housing. The rotor assembly comprises a rotor shaft rotated by an electric motor and at least one rotor element. The rotor element is interacting with a stator connected to the housing in order to convey
10 a gaseous medium from the inlet to the outlet. Thereby, the rotor shaft is supported by bearings.

The majority of turbomolecular pumps with oil fed or grease bearings use at least one ball bearing. During assembly, the preload force to the ball bearing
15 is adjusted to the intended use of the vacuum pump by either a spring applying an axial force to the rotor assembly or for a magnetic bearing by slight misalignment between the rotated part and the static part of that bearing, both in a passive way. Thereby the magnetic forces are axially shifted in order to generate an axial force. The amount of preload force can be adjusted by the
20 amount of axial shift between the rotated part and the static part of the respective magnetic bearing. In common vacuum pumps after assembly the introduced preload force cannot be changed while the pump is being operated. However, additional forces that may cause additional misalignment of at least one of the bearings may lead to additional forces being added to the bearing
25 preload force. Additional negative or positive preload forces that are outside the normal limits can cause conditions such as ball skidding or fatigue of the main bearing. Such conditions can greatly reduce the service life of the product caused by the operating life of the main bearing.

30 It is an object of the present invention to provide a vacuum pump with an improved service life.

- 2 -

The vacuum pump in accordance to the present invention which is in particular a turbomolecular vacuum pump comprises a rotor assembly rotatably supported by a first bearing and a second bearing, wherein at least the first bearing is a ball bearing. The rotor assembly is disposed in a housing of the vacuum pump and comprises at least one rotor element. Therein, the rotor assembly may comprise a plurality of pump elements built as vanes, if the vacuum pump is a turbomolecular vacuum pump. The at least one rotor element is interacting with a stator of the vacuum pump wherein the stator is connected to the housing of the vacuum pump. Due to the interaction of the rotor element of the rotor assembly with the stator of the vacuum pump, a gaseous medium is conveyed from an inlet to an outlet due to rotating of the rotor assembly by an electric motor. Further, the vacuum pump comprises a preload force compensator unit, wherein the preload force compensator unit is built to generate a force to adjust the preload force of the at least one ball bearing. Further, the vacuum pump comprises a control unit connected to at least one sensor to detect a pump parameter. Further, the control unit is connected to the preload force compensator unit to generate a compensating force dependent on the detected pump parameter.

The vacuum pump in accordance to the present invention may provide the beneficial technical effect that due to the preload force compensator unit any additional forces to the at least one ball bearing are compensated. Thus, if during start up of the vacuum pump or operation of the vacuum pump a condition may arise in which the preload force to the at least one ball bearing is outside the normal limits, a force is generated by the preload force compensator unit to compensate for this undesired preload force such that the preload force is transferred back to within the normal limits which are for example set during the assembly process of the vacuum pump. Thus, ball skidding or fatigue of the main bearing is prevented and service life of the product is prolonged.

Preferably, the preload force compensator unit comprises at least one electromagnet and an armature wherein in particular the armature is connected to the rotor assembly. This may provide the beneficial effect that

- 3 -

with the electromagnet a force can be applied to the armature in order to compensate the undesirable preload force to the at least one ball bearing. Thereby, the electromagnetic force can be controlled to compensate for the undesired preload force. Thereby, the force of the electromagnet to the armature can be tailored to maintain under all operation conditions of the vacuum pump an optimal preload force to the at least one ball bearing.

Preferably, the electromagnet is placed in axial direction relative to the armature. Alternatively, the electromagnet is placed radially to the armature.

10

Preferably, the electromagnet is connected to an electric motor of the vacuum pump. More preferably the electromagnet is an integral part of the motor stator. Thus, the electromagnet can be arranged in close proximity within the stator potted stator assembly or can be built as a modified motor unit that in addition to the driving torque can also exert an axial force on the shaft via the armature.

15

Alternatively, the armature is built from a permanent magnet. Thus, it is possible to apply positive as well as negative forces to the armature by the electromagnet, simply by switching polarity of the supply current. Preferably, the armature is built from a material that can be magnetized by the electromagnet in order to generate an attractive force.

20

Additionally or alternatively to the electromagnet, the preload force compensator unit preferably comprises a smart material element to adjust the preload force of the ball bearing. Therein, a smart material is any reactive material which properties can be changed by exposure to stimuli such as electromagnetic fields, stress, moisture and temperature, e. g. a material which can be made to expand or contract by applying a voltage. Examples for a smart material are electro active polymers (EAP). This may provide the advantage that the smart material element can be implemented easily and fine-controlled to adapt the preload force to the at least one ball bearing. Further, with implementing a smart material the number of magnetic coils

25

30

- 4 -

might be reduced to enhance the electromagnetic compatibility of the vacuum pump.

5 Additionally or alternatively to the electromagnet, the preload force compensator unit preferably comprises a piezo element to adjust the preload force of the ball bearing. This may provide the advantage that the piezo element can be implemented easily and fine-controlled to adapt the preload force to the at least one ball bearing. Further, piezo-electric materials of the piezo element are long-life materials which provide a reliable effect to maintain
10 the optimal preload force to the at least one ball bearing. Further, with implementing a piezo element the number of magnetic coils might be reduced to enhance the electromagnetic compatibility of the vacuum pump.

15 Preferably, the smart material element and/or the piezo element is connected to the outer race of the at least one ball bearing in order to adjust the position of the ball bearing and thereby adjust also the preload force of the ball bearing. This may provide the advantage that the position of the outer race of the ball bearing can be adjusted in order to maintain the optimal preload force to the at least one ball bearing. Therein, the smart material element or the piezo
20 element can be implemented alone to compensate for the preload force. Alternatively, the smart material element and the piezo element can act together in order to compensate the preload force.

25 Preferably, more than one smart material element or piezo element are implemented, wherein more preferably each smart material element or piezo element is configured to compensate substantially the mass of the rotor. This may provide the advantage that, if the vacuum pump is constructed to be operated in an upright orientation than upon rotation of the vacuum pump in a horizontal orientation, the preload to the bearing is compensated by a first
30 smart material element or piezo element. If the vacuum pump is operated upside down, the preload can be further compensated by a second smart material element or piezo element.

- 5 -

Preferably, the second bearing is built as permanent magnetic bearing. Wherein, more preferably, the second bearing is placed towards the direction of the inlet of the vacuum pump, i.e. towards the region of lower pressures. Since the permanent magnetic bearing can be operated contactless, no grease or lubricant is necessary in the regions of low pressures, i. e. high vacuums. Consequently, the first bearing which is built as ball bearing is disposed towards the outlet of the vacuum pump, towards the regions of high pressures, i.e. low vacuum.

10 Preferably, the permanent magnetic bearing comprises a first magnetic element connected to the rotor assembly and preferably connected to the rotor shaft, and a static second magnetic element connected to the stator or housing of the vacuum pump and interacting with the first magnetic element to support the rotor assembly. Thereby, the position of the second magnetic element is
15 adjusted by the smart material element or the piezo element in order to adjust the preload force to the first bearing, i.e. the ball bearing. Therein, the smart material element or the piezo element can be implemented alone to compensate for the preload force. Alternatively, the smart material element and the piezo element can act together in order to compensate the preload
20 force.

Preferably, the detected pump parameter includes but is not limited to at least one or more of the following parameters: the temperature in particular the temperature of the rotor assembly, the temperature difference between the
25 rotor assembly and the stator, orientation of the vacuum pump, rotational speed of the rotor assembly, pressure at the inlet and/or the outlet, pressure change over time, power consumption of the electric motor, force to the ball bearing such as strain, position of the rotor assembly or impedance value of the at least one ball bearing. This might have the following advantages:

- 30 • due to the temperature difference between the rotor assembly and the stator, the rotor assembly may undergo a larger thermal expansion than the stator leading to an increase of the preload force to the at least one ball bearing. Thus, upon measuring the temperature or the temperature difference between the rotor assembly and the stator, the preload force

- 6 -

introduced by this pump parameter can be compensated by the preload force compensator unit.

- Further, the orientation of the vacuum pump may lead to additional forces to the rotor assembly of the vacuum pump. Thus, if the preload force is set with the vacuum pump in the vertical position, and for example then operated in the horizontal or inverted position, the changed gravitational force acting on the rotor assembly will apply an addition force to the at least one ball bearing as preload force. Thus, upon detecting the orientation of the vacuum pump undesired preload force to the at least one ball bearing can be compensated by the preload force compensator unit.
- Further, in dependence on the rotational speed of the rotor assembly due to the Poisson-effect, the preload force might be reduced with increasing rotational speed. Thus, upon detecting the rotational speed of the rotor assembly, the preload force to the at least one ball bearing can be compensated by the preload force compensator unit.
- Further, a change of rotational speed or deceleration rate might be used for detection of venting that might cause an additional preload force to the at least one ball bearing that is compensated by the preload force compensator unit.
- Further, upon detecting pressure or pressure change and more preferably the inlet pressure and the outlet pressure, preload force to the at least one ball bearing can be compensated. In particular, during harsh venting axial forces to the rotor may occur which lead to an increase of the preload force to the at least one ball bearing which can be compensated by the preload force compensator unit.
- Further, power consumption of the electric motor can be detected by the sensor. The power consumption depends on the load of the vacuum pump, i.e. current volume flow, and might give also a hint to the inlet pressure. During high volume flow or at the beginning of a pump cycle at high pressures at the inlet or low vacuum, an increased preload force can be occurring to the at least one ball bearing which can be compensated by the preload force compensator unit.

- 7 -

- Further, the sensor can be built as strain sensor in order to directly measure the preload force to the at least one ball bearing such that the preload force compensator unit can compensate the preload force to the at least one ball bearing in dependence on the measured force to the at least one ball bearing preload force.
5
- Further, the sensor can be built as position sensor in order to detect the axial position of the rotor assembly. The axial position of the rotor assembly might depend on an axial force applied to the rotor assembly resulting in additional preload forces. Thus, by detecting the axial position of the rotor assembly excessive or additional preload force to the at least one ball bearing can be compensated by the preload force compensator unit. Preferably, the position of the positioning sensor might be in the vicinity of or next to the at least one ball bearing. This might have the advantage that deviations for example due to thermal expansion are minimized and a direct connection between the axial position and the preload force can be established.
10
- Further, the sensor can be built in order to measure the impedance of the at least one ball bearing. By measuring the impedance of the ball bearing load of the bearing can be determined. In particular, together with temperature and rotational speed a preload force to the at least one ball bearing can be detected. The preload force compensator unit can compensate the preload force to the at least one ball bearing in dependence on the measured impedance to the at least one ball bearing.
15
- 20
- 25 Preferably, more than one pump parameter is considered by the control unit in order to control the preload force compensator unit to generate a force to compensate for any additional forces and maintain an optimal preload to the at least one ball bearing. In particular, counteracting effects or the direction of the effective forces are considered. If one effect leads to an increase of the preload force and another effect leads to a decrease of the preload force, only
30 the difference of preload forces between these two effects are compensated for.

Preferably, the control unit comprises a look-up table to determine the required force exerted by the preload force compensator unit from the detected pump parameter or pump parameters. Additionally or alternatively, the control unit comprises a mapping function between the detected pump parameter and the force required to maintain the optimal preload force to the at least one ball bearing. Additionally or alternatively, the control unit comprises a machine learning unit which has been trained to connect the detected pump parameter to the preload force on the at least one ball bearing. Thus, for training the vacuum pump may comprise a sensor to detect a pump parameter other than the force or strain sensor to the ball bearing and additionally strain sensor to detect the force or strain to the ball bearing directly. Then, the machine learning unit connects the detected parameter directly to the strain exerted on the ball bearing. If the machine learning algorithm is sufficiently trained, the machine learning unit can be transferred to same or similar vacuum pumps. This may have the advantage that costly and complex strain sensors to directly detect the strain on the ball bearing can be avoided. Temperature, pressure, rotational speed and the orientation of the vacuum pump may be detected for other reasons as well and can be also used for the preload force adjustment by the control unit and the preload force compensator unit.

The following is a detailed description of the invention with reference to preferred embodiments and to the accompanied drawings.

The figures:

Figures 1a to 1e: the vacuum pump in accordance to the present invention with different configurations of the preload force compensator unit as electromagnet,

Figure 2a and 2b: a vacuum pump in accordance with the present invention with different configurations of the preload force compensator unit, and

Figure 3: a block diagram in accordance with an embodiment of the present invention.

Figure 1a shows a vacuum pump in accordance to the present invention with a housing 10. The housing 10 defines an inlet 12 and an outlet 14. In the housing is disposed a rotor assembly 16. The rotor assembly 16 comprises a rotor shaft 18 and numerous rotor elements 20. The rotor assembly 16 is rotated by an electric motor 22. Thereby, the rotor elements 20 are interacting with stator elements 24 which are connected to the housing 10 of the vacuum pump. By rotating of the rotor assembly 16 a gaseous medium is conveyed from the inlet 12 to the outlet 14. In the present embodiment, the vacuum is built as turbomolecular pump with an additional molecule drag stage 26.

For rotation of the rotor assembly 16, the rotor assembly 16 is supported by a first bearing 28 and a second bearing 30. The first bearing 28 is built as ball bearing and arranged towards the outlet 14 of the vacuum pump. The second bearing 30 is built as permanent magnetic bearing and arranged toward the inlet 12 of the vacuum pump in the range of low pressures, i.e. high vacuums. The permanent magnetic bearing 30 comprises a first magnetic element 32 which is connected to the rotor assembly 16 and rotated together with the rotor assembly 16 during operation. Further, the permanent magnetic bearing 30 comprises a static second magnetic element 34 connected to an element of the housing 10 and arranged to interact with the first magnetic element 32 to contactless support the rotor assembly 16. Therein the second magnetic element 34 might be slightly displaced during assembly of the vacuum pump relative to the first magnetic element in order to generate an axial force towards the ball bearing. By this axial force a passive and determined preload force is applied to the ball bearing necessary for proper operation of the ball bearing.

The vacuum pump comprises a control unit 36 which is connected with a preload force compensator unit 38. The preload force compensator unit 38 comprises an electromagnet 40 in the example of figure 1a integrated into to the electric motor 22. The electromagnet 40 is controlled by the control unit 36 in order to exert a force to an armature 42, wherein the armature 42 is connected to the rotor assembly 16 of the vacuum pump. Thus, by the

- 10 -

electromagnet 40 an attracting force to the armature 42 can be applied, thereby controlling the preload force on the first bearing 28 which is built as ball bearing. This may have advantage that by controlling the preload force on the ball bearing, actively the preload force to the ball bearing can be maintained in narrow limits around an optimum of the ball bearing. Thus, life time or service life of the ball bearing 28 can be enhanced.

In the following figures, the same or similar elements are indicated by identical reference signs.

10

In figure 1b, the armature 42 is connected to the rotor shaft 18. The electromagnets 40 are placed axially relative to the armature 42 in order to generate an electromagnetic force on the rotor assembly 16 to control the preload force on the first bearing 28. Thereby, the armature 42 can be built as permanent magnet in order to generate by the electromagnets 40 positive or negative forces on the rotor assembly 16. Alternatively, as indicated in figure 1b, the preload force compensator unit 38 comprises a second electromagnetic coil 44 in order to generate a positive as well as a negative force on the rotor assembly 16.

20

In figure 1c, the armature 42 is connected to the rotor shaft 18 while the electromagnet 40 of the preload force compensator unit 38 is connected to the coils of the electric motor 22.

25 In figure 1d, the armature 42 is integrated into the shaft 18 of the rotor assembly 16. The electromagnet 40 of the preload force compensator unit 38 is integrated in the electric motor 22 and arranged radially to the armature 42. Therein the electromagnet 40 can be arranged in close proximity within the stator potted stator assembly or can be built as a modified motor unit that in addition to the driving torque can also exert an axial force on the shaft via the armature. Thus, by controlling the electromagnets 40 of the preload force compensator unit 38 a force can be generated on the rotor assembly 16 to compensate undesired preload force on the first bearing 28.

- 11 -

In figure 1e, the armature 42 is connected to the rotor shaft 18, wherein the electromagnets 40 of the preload force compensator unit 38 are arranged radially and apart from the coil of the electric motor 22.

- 5 In figure 2a, the preload force compensator unit 38 comprises a smart material element 46 which is connected to the control unit 36. By the smart material element 46, the position of the second magnetic element 34 can be adapted in order to exert a force on the rotor assembly 16. Thereby, the preload force on the first bearing 28 can be controlled. In an alternative embodiment, instead
10 of the shown smart material element 46, a piezo element is used to adjust the preload force.

Figure 2b shows that the smart material element 46 is connected to the outer race of the first bearing 28. Thus, by the smart material element 46 the position
15 of the outer rays can be adapted and therefore additional force on the rotor assembly compensated to maintain the preload force on the first bearing 28 within the optimal limits.

Figure 3 shows a block diagram of the control unit 36, wherein the control unit
20 36 is connected to the preload force compensator unit 38 in order to control the preload force on the at least one ball bearing 28.

With the control unit 36, numerous sensors 48 are connected. The first sensor
25 50 may detect the temperature or temperature difference between the rotor assembly 16 and the stator 24 or housing 10. Due to the thermal expansion of the rotor assembly 16, the first bearing 28 may experience undesired preload force. This might occur during start-up of the vacuum pump, if the rotor assembly 16 has not yet its operation temperature. Thus, thermal expansion of the rotor assembly 16 might not be sufficient to ensure the optimal preload
30 force to the first bearing 28. Alternatively, if the temperature of the rotor assembly is too high, for example due to an increased temperature of the conveyed gaseous medium, the thermal expansion might exceed the optimal value causing increased preload force to the first bearing 28. In both cases,

- 12 -

the preload force compensator unit 38 is controlled by the control unit 36 to compensate for the undesired preload force.

5 A second sensor 52 may detect the orientation of the vacuum pump. Due to different orientations of the vacuum pump, the rotor assembly 16 may experience different forces due to the gravitational force. Thus, different orientations of the vacuum pump lead to different preload forces on the first bearing 28 which may be compensated by the preload force compensation unit 38.

10

A third sensor 54 may detect the rotational speed of the rotator assembly which also influences the preload force on the first bearing 28 due to the Poisson-effect. Thus, this effect can be also considered by the preload force compensation unit 38 while compensating the preload force on the first bearing 15 28. Further, by the third sensor detecting the rotational speed, change of rotational speed or deceleration rate of the rotor can be detected caused by venting of the vacuum pump which causes additional preload force to the at least one ball bearing.

20 A fourth sensor 56 may detect the pressure at the inlet 12 and the pressure change at the inlet 12 over time. Alternatively, or additionally, the energy consumption of the electric motor 22 is detected which can be connected to the pressure at the inlet. However, pressure and in particular pressure during harsh venting can lead to an additional force on the rotor assembly 16 which 25 might be compensated by the preload force compensation unit 38.

While in the above the first to fourth sensor are described as individual entities, they can be integrated into one or more sensors or the detection can be provided by different elements of the vacuum pump, i.e. the control unit 30 controlling operation of the vacuum pump, which then are considered as sensors in the meaning of the present invention.

While the first to fourth sensor 50-56 describe an open loop detection and compensating system, it is also possible to have a fifth sensor 58 which directly

- 13 -

measures the preload force or strain on the first bearing 28 to build a closed loop detection circuit. Thus, the strain on the first bearing 28 can be directly measured and compensated if necessary. Additionally or alternatively a sensor can be used to measure the axial position of the rotor assembly 16. The axial position of the rotor assembly 16 might depend on an axial force applied resulting in additional preload forces. Thus, by detecting the axial position of the rotor assembly 16 excessive or additional preload force to the at least one ball bearing can be compensated by the preload force compensator unit 38 preferably in a closed loop detection circuit. Preferably, the position of the sensor for detecting the axial position of the rotor assembly 16 might be in the vicinity of or next to the at least one ball bearing. Additionally or alternatively a sensor can be used to measure the impedance of the at least one ball bearing. By measuring the impedance of the ball bearing the load of the bearing can be determined. In particular, together with temperature and rotational speed a preload force to the at least one ball bearing can be detected. The preload force compensator unit 38 can compensate the preload force to the at least one ball bearing in dependence on the measured impedance to the at least one ball bearing. Therein the sensor for measuring the impedance of the at least one ball bearing can be implemented in a closed loop detection circuit directly compensating any excessive preload force to the at least one ball bearing.

It is clear that the present invention is not limited to the specific combination of sensors as described above. One, more than one or all described pump parameter can be used to determine the necessary compensation of the preload force. Additionally, other pump parameters can be detected if these pump parameters can be directly or indirectly connected to the preload force on the bearings of the vacuum pump. The above given list of possible pump parameters is not intended to be exhaustive or limiting.

For example, another sensor could be implemented detecting the power consumption of the electric motor 22 which is directly related to the pumping condition such as inlet pressure or volume flow through the vacuum pump. Increased inlet pressure or increased volume flow might cause additional

- 14 -

preload forces to the at least one ball bearing which can be properly compensated by the preload force compensation unit 38.

Further, the control unit 36 comprises a correlation unit 60 which might be built as look-up table. Then, the control unit 36 connects the required force for compensating the preload force to the detected pump parameters by the look-up table.

Alternatively, a mapping function between the detected pump parameters and the required force is stored in the correlation unit, whereby the control unit 36 uses this mapping function to determine the required force for compensating undesired preload force and maintain an optimal preload force on the at least one ball bearing. For example, a model can be applied describing the influence of the detected pump parameter to the resulting preload force such that a mathematical function is given receiving the respective pump parameter and outputting the required force.

Additionally or alternatively, the correlation unit 16 comprises a machine learning unit which is trained properly, wherein preferably during training at least one open loop detection circuit with one of the first sensors to fourth sensors are correlated to the measurements of the closed loop detection circuit detecting the strain or force on the first bearing 28 directly. If the correlation unit 60 is properly trained, the correlation unit can be transferred to same or similar vacuum pumps. Then no direct detection circuit is necessary and a sensor for directly measuring the strain or preload force on the first bearing might be omitted.

Reference numbers:

	10	housing
	12	inlet
	14	outlet
5	16	rotor assembly
	18	rotor shaft
	20	rotor elements
	22	electric motor
	24	stator elements
10	26	molecule drag stage
	28	first bearing
	30	second
	32	first magnetic element
	34	second magnetic element
15	36	control unit
	38	preload force compensator unit
	40	electromagnet
	42	armature
	44	second electromagnetic coil
20	46	smart material element
	48	sensors
	50	first sensor
	52	second sensor
	54	third sensor
25	56	fourth sensor
	58	fifth sensor
	60	correlation unit

CLAIMS

1. Vacuum pump, in particular a turbomolecular pump, comprising
 - 5 a rotor assembly rotatably supported by a first bearing and a second bearing, wherein at least one bearing is a ball bearing, and
a preload force compensator unit, wherein the preload force compensator unit is built to generate a force to control the preload force on the at least
10 one ball bearing,
a control unit connected to at least one sensor to detect a pump parameter and further connected to the preload force compensator unit to generate a force dependent on the detected pump parameter.
- 15 2. Vacuum pump according to claim 1, characterized in that the preload force compensator unit comprises at least one electromagnet and an armature.
3. Vacuum pump according to claim 2, characterized in that the armature is
20 connected to the rotor assembly.
4. Vacuum pump according to claim 2 or 3, characterized in that the electromagnet is placed in an axial direction relative to the armature or placed radially.
- 25 5. Vacuum pump according to any of claims 2 to 4, characterized in that the electromagnet is connected to an electric motor of the vacuum pump.
6. Vacuum pump according to any of claims 1 to 5, characterized in that the
30 preload force compensator unit comprises at least one smart material element to adjust the preload force to the ball bearing.

- 17 -

7. Vacuum pump according to any of claims 1 to 6, characterized in that the preload force compensator unit comprises at least one piezo element to adjust the preload force to the ball bearing.
- 5 8. Vacuum pump according to claim 6 or 7, characterized in that the position of an outer race of the ball bearing is adjusted by the smart material element and/or the piezo element in order to adjust the preload force.
9. Vacuum pump according to any of claims 1 to 8, characterized in that the
10 second bearing is a permanent magnetic bearing.
10. Vacuum pump according to claim 9, characterized in that the permanent magnetic bearing comprises a first magnetic element connected to the rotor assembly and a static second magnetic element, wherein the
15 position of the second magnetic element is adjusted by the smart material element or piezo element in order to adjust the preload force to the ball bearing.
11. Vacuum pump according to any of claims 1 to 10, characterized in that
20 the pump parameter comprises at least one of the following parameters: Temperature, temperature difference between the rotor and a stator, orientation of the vacuum pump, rotational speed, pressure, pressure change, power consumption of the electric motor, strain on the ball bearing, position of the rotor, impedance of the at least one ball bearing.
- 25 12. Vacuum pump according to claim 11, characterized in that more than one pump parameter is considered by the control unit.
13. Vacuum pump according to any of claims 1 to 12, wherein the control unit
30 comprises a look-up table or a functional relationship, or a machine learning unit to determine the required force exerted by the preload force compensator unit in dependence on the detected pump parameter.

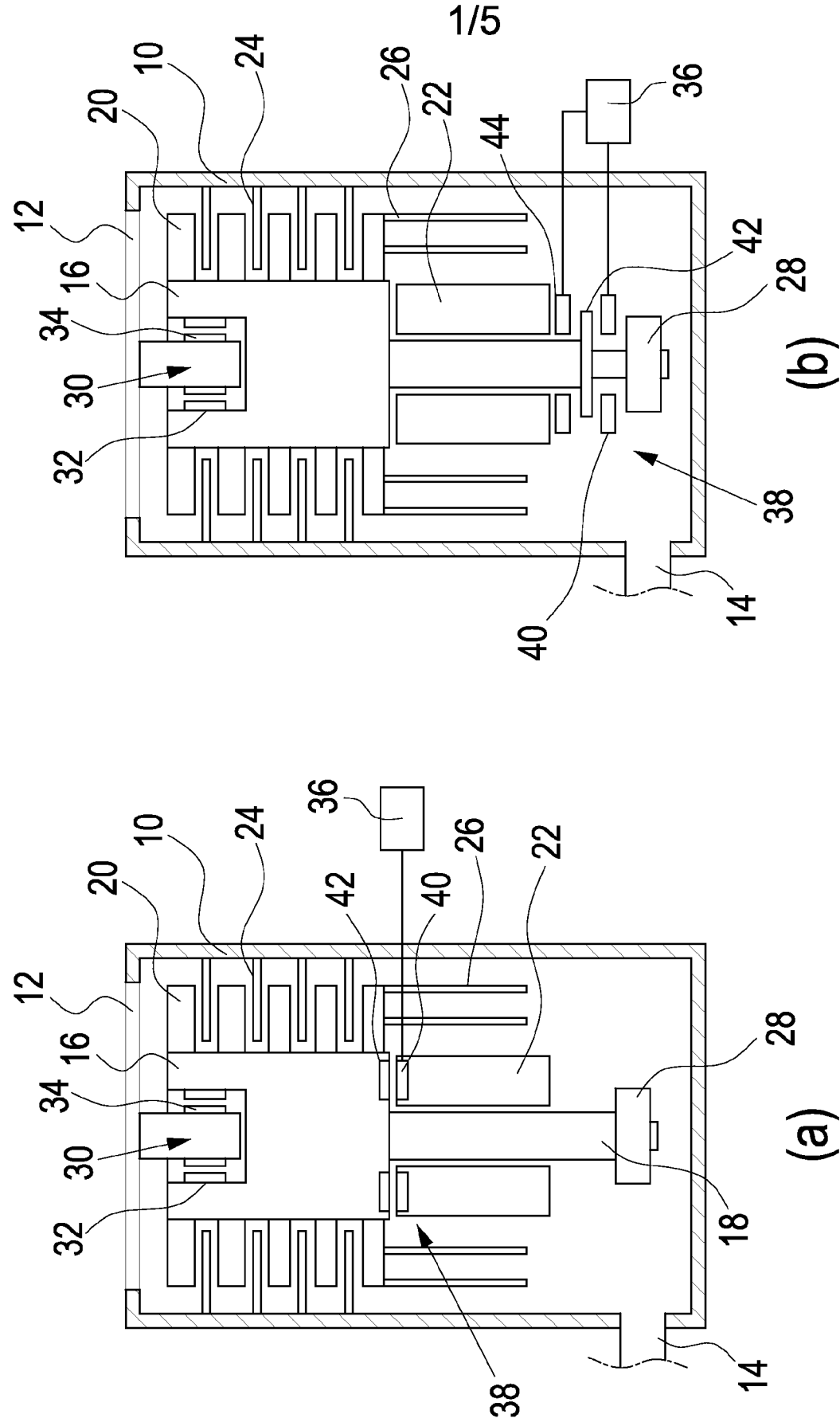


Fig. 1

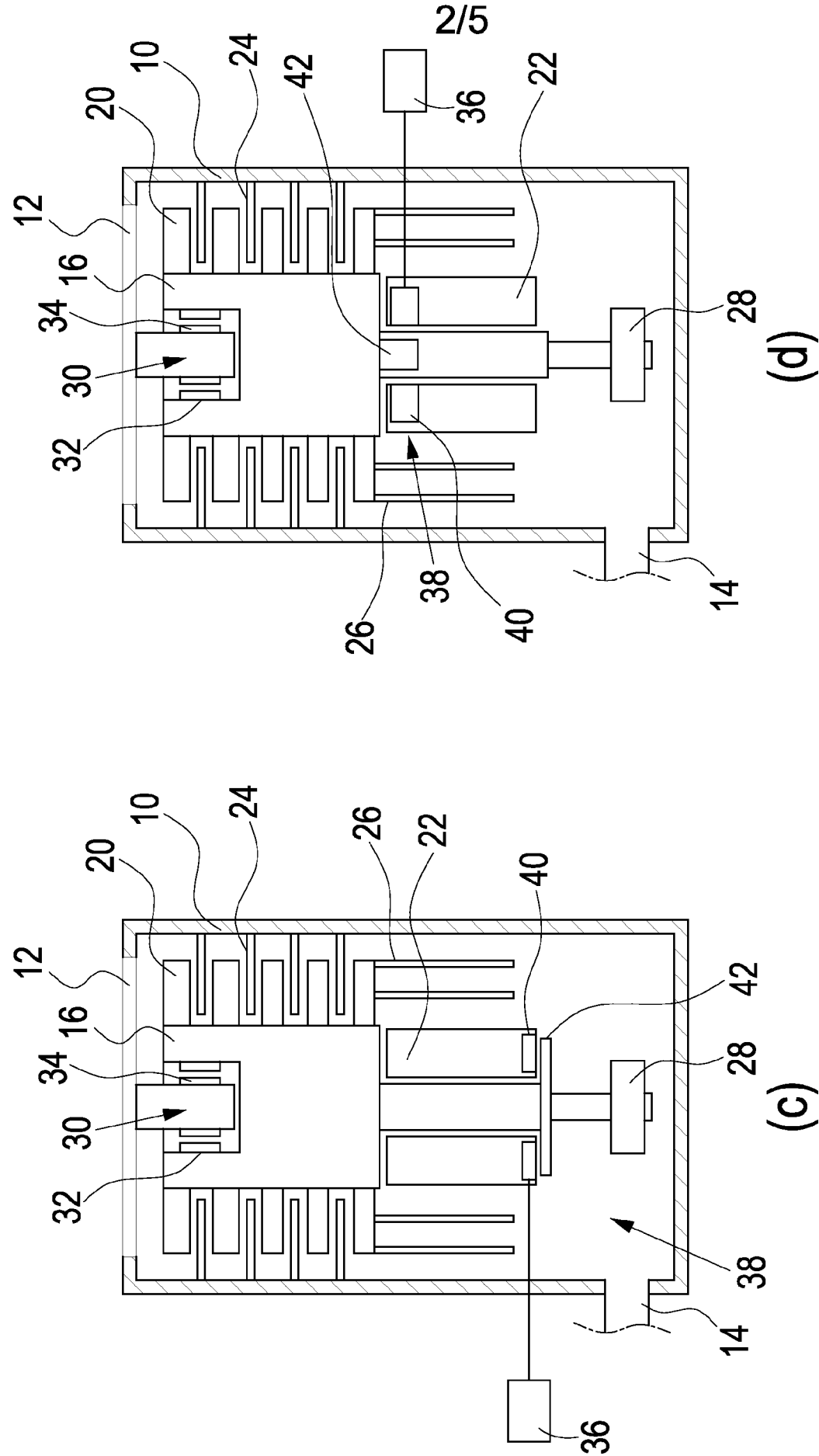


Fig. 1

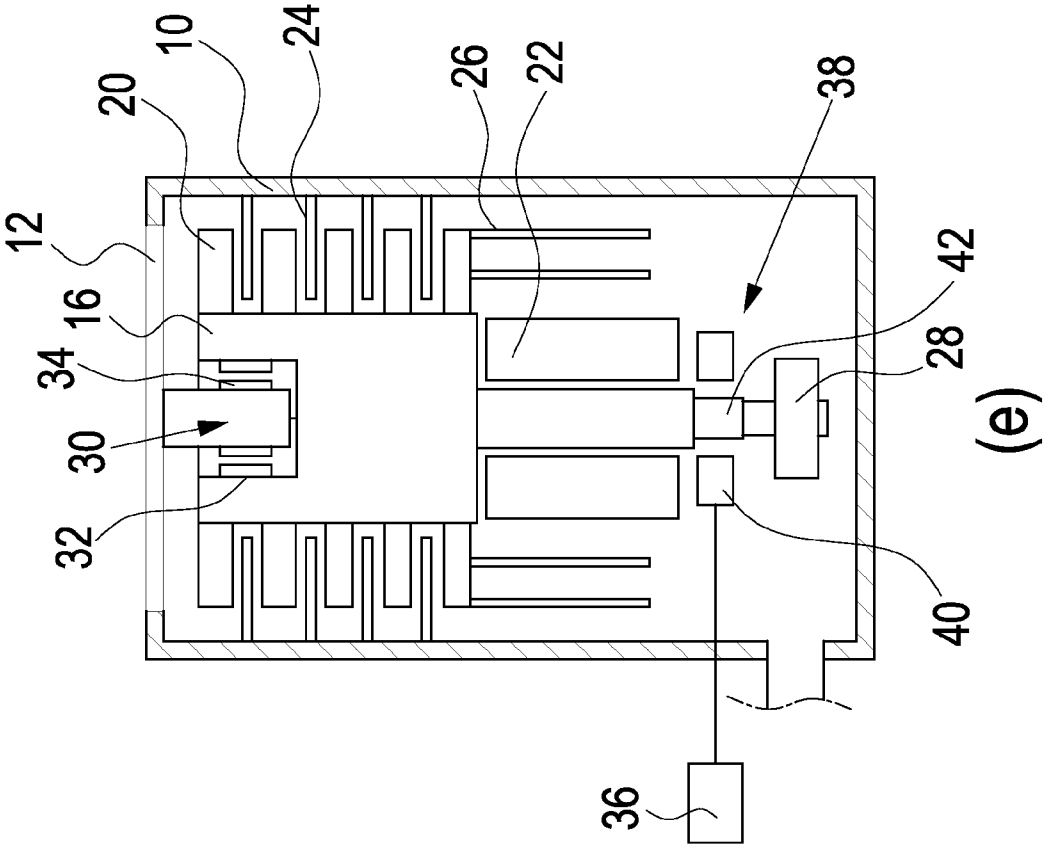


Fig. 1

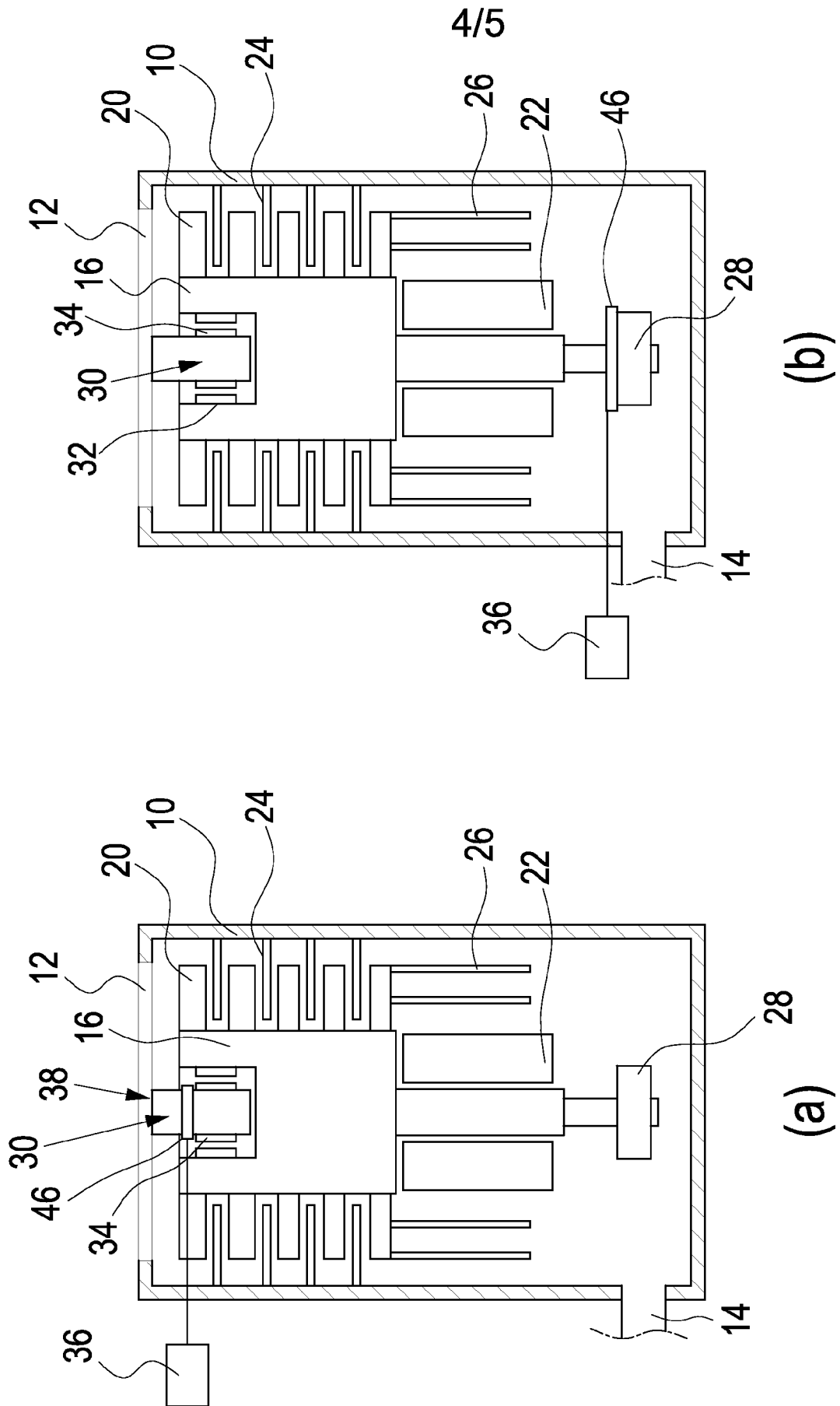


Fig. 2

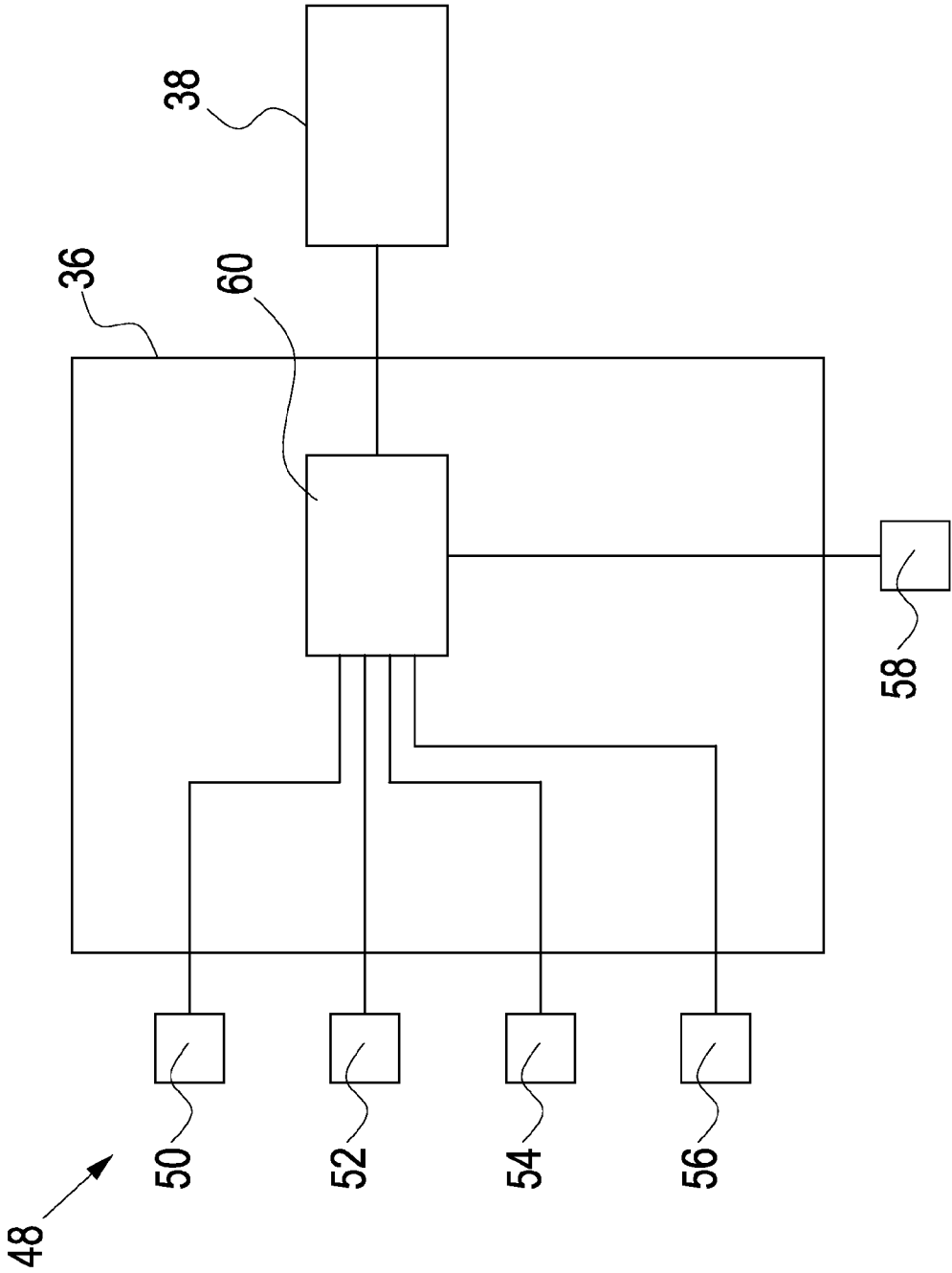


Fig. 3

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2020/050298

A. CLASSIFICATION OF SUBJECT MATTER
INV. F04D19/04 F04D29/051 F04D29/059
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F04D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 2 431 614 A2 (PFEIFFER VACUUM GMBH [DE]) 21 March 2012 (2012-03-21)	1-7,9-13
Y	abstract paragraph [0017] - paragraph [0048] figures	8
X	WO 02/18794 A1 (LEYBOLD VAKUUM GMBH [DE]; BEYER CHRISTIAN [DE] ET AL.) 7 March 2002 (2002-03-07)	1-5,9, 11-13
A	abstract page 6, paragraph 1 - page 12, paragraph 1 figures	6-8,10
Y	DE 103 20 851 A1 (LEYBOLD VAKUUM GMBH [DE]) 25 November 2004 (2004-11-25)	8
A	abstract paragraph [0004] - paragraph [0024] figures	1-7,9-13
	----- -/-	



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

21 April 2020

Date of mailing of the international search report

04/05/2020

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Kolby, Lars

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2020/050298

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	DE 20 2009 013629 U1 (OERLIKON LEYBOLD VACUUM GMBH [DE]) 24 February 2011 (2011-02-24)	8
A	abstract paragraph [0001] - paragraph [0024] figures -----	1-7,9-13
A	DE 10 2009 024337 A1 (OERLIKON LEYBOLD VACUUM GMBH [DE]) 16 December 2010 (2010-12-16) abstract paragraph [0002] - paragraph [0035] figures -----	1-13

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2020/050298

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
EP 2431614	A2	21-03-2012	DE 102010045716 A1	22-03-2012
			EP 2431614 A2	21-03-2012

WO 0218794	A1	07-03-2002	DE 10043235 A1	14-03-2002
			EP 1313951 A1	28-05-2003
			JP 2004513277 A	30-04-2004
			US 2003180162 A1	25-09-2003
			WO 0218794 A1	07-03-2002

DE 10320851	A1	25-11-2004	DE 10320851 A1	25-11-2004
			TW 200506222 A	16-02-2005
			WO 2004099622 A1	18-11-2004

DE 202009013629 U1		24-02-2011	DE 202009013629 U1	24-02-2011
			EP 2376798 A1	19-10-2011
			JP 2013507558 A	04-03-2013
			TW 201118270 A	01-06-2011
			WO 2011042452 A1	14-04-2011

DE 102009024337 A1		16-12-2010	DE 102009024337 A1	16-12-2010
			EP 2440789 A1	18-04-2012
			JP 2012529591 A	22-11-2012
			TW 201105864 A	16-02-2011
			WO 2010142633 A1	16-12-2010
