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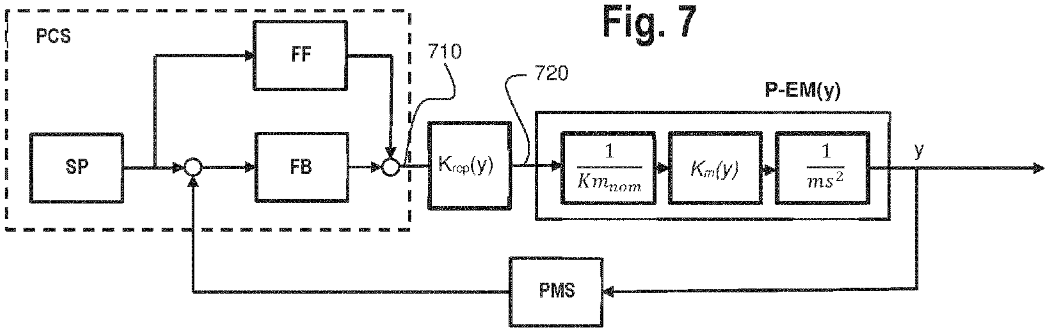
(54) **Title:** ELECTROMAGNETIC MOTOR AND METHOD OF DETERMINING A POSITION DEPENDENT MOTOR CONSTANT FOR AN ELECTROMAGNETIC MOTOR

Fig. 7




(57) **Abstract:** The invention provides a method of determining a position dependent motor constant of an electromagnetic motor, the electromagnetic motor comprising a magnet assembly and a coil assembly that are configured to displace relative to each other in a direction of movement, the method comprising: - causing a displacement of the magnet assembly relative to the coil assembly along a predetermined trajectory of interest in the direction of movement, at a substantially constant velocity; - applying a disturbance having a predetermined frequency to the electromagnetic motor, during the displacement of the magnet assembly relative to the coil assembly; - determining a position error of the magnet assembly relative to the coil assembly and an electromagnetic motor force, along the predetermined trajectory of interest; - determining a position dependent motor constant of the electromagnetic motor along the predetermined trajectory of interest, based on the determined position error and the electromagnetic motor force.

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# ELECTROMAGNETIC MOTOR AND METHOD OF DETERMINING A POSITION DEPENDENT MOTOR CONSTANT FOR AN ELECTROMAGNETIC MOTOR

## CROSS-REFERENCE TO RELATED APPLICATIONS

**[0001]** This application claims priority of EP application 23166250.3 which was filed on 31. March 2023, and which is incorporated herein in its entirety by reference.

## FIELD

**[0002]** The present invention relates to an electromagnetic motor, in particular an electromagnetic motor as can be applied in a lithographic apparatus, e.g. to displace or position a patterning device or a substrate.

## BACKGROUND

**[0003]** A lithographic apparatus is a machine constructed to apply a desired pattern onto a substrate. A lithographic apparatus can be used, for example, in the manufacture of integrated circuits (ICs). A lithographic apparatus may, for example, project a pattern (also often referred to as “design layout” or “design”) of a patterning device (e.g., a mask) onto a layer of radiation-sensitive material (resist) provided on a substrate (e.g., a wafer).

**[0004]** As semiconductor manufacturing processes continue to advance, the dimensions of circuit elements have continually been reduced while the amount of functional elements, such as transistors, per device has been steadily increasing over decades, following a trend commonly referred to as ‘Moore’s law’. To keep up with Moore’s law the semiconductor industry is chasing technologies that enable to create increasingly smaller features. To project a pattern on a substrate a lithographic apparatus may use electromagnetic radiation. The wavelength of this radiation determines the minimum size of features which are patterned on the substrate. Typical wavelengths currently in use are 365 nm (i-line), 248 nm, 193 nm and 13.5 nm. A lithographic apparatus, which uses extreme ultraviolet (EUV) radiation, having a wavelength within a range of 4 nm to 20 nm, for example 6.7 nm or 13.5 nm, may be used to form smaller features on a substrate than a lithographic apparatus which uses, for example, radiation with a wavelength of 193 nm.

**[0005]** In order to pattern the pattern of the patterning device onto the substrate, typically a scanning process is applied whereby both the patterning device and the substrate are displaced relative to the radiation beam as applied. Typically, electromagnetic motors and actuators are applied to enable this displacement. To ensure an accurate positioning of the pattern of the patterning device on the substrate, it is important to have an accurate control of the motors and actuators involved in the positioning. In general, due to various causes, the response of known actuators or motors to a particular control signal, may be unknown to a certain degree. In particular, it is known that the motor constant, which indicates the generated force per unit current, is not constant over the displacement range of the motor or actuator. In order to anticipate on this, methods have been developed to determine said motor constant, in order to improve the positioning of the motors or actuators. Known methods to determine the motor constant have been found to be rather time-consuming or to have an insufficient resolution.

SUMMARY

**[0006]** It is an objective of the present invention to provide a method of determining a position dependent motor constant of an electromagnetic motor which at least mitigates the aforementioned issues of known methods.

**[0007]** According to an aspect of the invention, there is provided an electromagnetic motor comprising:

- a magnet assembly configured to generate a magnetic field;
- a coil assembly comprising at least one coil; the coil assembly being configured to co-operate with the magnet assembly so as to cause a movement of the magnet assembly relative to the coil assembly in a direction of movement;
- a power supply configured to, during use, power the coil assembly;
- a control unit configured to:
    - control the power supply to supply the coil assembly with an electric current so as to cause a displacement of the magnet assembly relative to the coil assembly along a predetermined trajectory of interest in the direction of movement, at a substantially constant velocity;
    - apply a disturbance having a predetermined frequency to the electromagnetic motor, during the displacement of the magnet assembly relative to the coil assembly;
    - determine a position of the magnet assembly relative to the coil assembly and an electromagnetic motor force, along the predetermined trajectory of interest;
    - determine a position dependent motor constant of the electromagnetic motor along the predetermined trajectory of interest, based on the determined position and the electromagnetic motor force.

**[0008]** According to another aspect, there is provided a stage apparatus for use in a lithographic apparatus, the stage comprising an electromagnetic motor according to the invention. The stage apparatus may e.g. be configured to hold a patterning device or a substrate.

**[0009]** According to yet another aspect, there is provided a lithographic apparatus comprising the stage apparatus according to the invention.

**[00010]** According to yet another aspect of the invention, there is provided a method of determining a position dependent motor constant of an electromagnetic motor, the electromagnetic motor comprising a magnet assembly and a coil assembly that are configured to displace relative to each other in a direction of movement, the method comprising:

- causing a displacement of the magnet assembly relative to the coil assembly along a predetermined trajectory of interest in the direction of movement, at a substantially constant velocity;
- applying a disturbance having a predetermined frequency to the electromagnetic motor, during the displacement of the magnet assembly relative to the coil assembly;
- determining a position error of the magnet assembly relative to the coil assembly and an electromagnetic motor force, along the predetermined trajectory of interest;
- determining a position dependent motor constant of the electromagnetic motor along the predetermined trajectory of interest, based on the determined position error and the electromagnetic motor force.

BRIEF DESCRIPTION OF THE DRAWINGS

**[00011]** Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings, in which:

- Figure 1 depicts a schematic overview of a lithographic apparatus;
- Figure 2 depicts a detailed view of a part of the lithographic apparatus of Figure 1;
- Figure 3 schematically depicts a position control system;
- Figure 4 depicts a first electromagnetic motor according to the invention;
- Figure 5 depicts a second electromagnetic motor according to the invention;
- Figure 6 schematically illustrates the variation of the motor constant along a trajectory Y1 – Y2;
- Figure 7 schematically depicts a position control system as can be applied in the present invention;
- Figure 8 schematically depicts a flowchart of the method according to the invention;
- Figure 9 schematically depicts a position control system as can be applied in the present invention, including possible locations to insert a disturbance;
- Figure 10 schematically illustrates various ways to determine an amplitude of an alternating signal.

DETAILED DESCRIPTION

**[00012]** In the present document, the terms “radiation” and “beam” are used to encompass all types of electromagnetic radiation, including ultraviolet radiation (e.g. with a wavelength of 365, 248, 193, 157 or 126 nm) and EUV (extreme ultra-violet radiation, e.g. having a wavelength in the range of about 5-100 nm).

**[00013]** The term “reticle”, “mask” or “patterning device” as employed in this text may be broadly interpreted as referring to a generic patterning device that can be used to endow an incoming radiation beam with a patterned cross-section, corresponding to a pattern that is to be created in a target portion of the substrate. The term “light valve” can also be used in this context. Besides the classic mask (transmissive or reflective, binary, phase-shifting, hybrid, etc.), examples of other such patterning devices include a programmable mirror array and a programmable LCD array.

**[00014]** Figure 1 schematically depicts a lithographic apparatus LA. The lithographic apparatus LA includes an illumination system (also referred to as illuminator) IL configured to condition a radiation beam B (e.g., UV radiation, DUV radiation or EUV radiation), a mask support (e.g., a mask table) MT constructed to support a patterning device (e.g., a mask) MA and connected to a first positioner PM configured to accurately position the patterning device MA in accordance with certain parameters, a substrate support (e.g., a wafer table) WT constructed to hold a substrate (e.g., a resist coated wafer) W and connected to a second positioner PW configured to accurately position the substrate support in accordance with certain parameters, and a projection system (e.g., a refractive projection lens system) PS configured to project a pattern imparted to the radiation beam B by patterning device MA onto a target portion C (e.g., comprising one or more dies) of the substrate W.

**[00015]** In operation, the illumination system IL receives a radiation beam from a radiation source SO, e.g. via a beam delivery system BD. The illumination system IL may include various types of optical components, such as refractive, reflective, magnetic, electromagnetic, electrostatic, and/or other types of optical components, or any combination thereof, for directing, shaping, and/or controlling radiation. The illuminator IL may be used to condition the radiation beam B to have a desired spatial and angular intensity distribution in its cross section at a plane of the patterning device MA.

**[00016]** The term “projection system” PS used herein should be broadly interpreted as encompassing various types of projection system, including refractive, reflective, catadioptric, anamorphic, magnetic, electromagnetic and/or electrostatic optical systems, or any combination thereof, as appropriate for the exposure radiation being used, and/or for other factors such as the use of an immersion liquid or the use of a vacuum. Any use of the term “projection lens” herein may be considered as synonymous with the more general term “projection system” PS.

**[00017]** The lithographic apparatus LA may be of a type wherein at least a portion of the substrate may be covered by a liquid having a relatively high refractive index, e.g., water, so as to fill a space between the projection system PS and the substrate W – which is also referred to as immersion lithography. More information on immersion techniques is given in US6952253, which is incorporated herein by reference.

**[00018]** The lithographic apparatus LA may also be of a type having two or more substrate supports WT (also named “dual stage”). In such “multiple stage” machine, the substrate supports WT may be used in parallel, and/or steps in preparation of a subsequent exposure of the substrate W may be carried out on the substrate W located on one of the substrate support WT while another substrate W on the other substrate support WT is being used for exposing a pattern on the other substrate W.

**[00019]** In addition to the substrate support WT, the lithographic apparatus LA may comprise a measurement stage. The measurement stage is arranged to hold a sensor and/or a cleaning device. The sensor may be arranged to measure a property of the projection system PS or a property of the radiation beam B. The measurement stage may hold multiple sensors. The cleaning device may be arranged to clean part of the lithographic apparatus, for example a part of the projection system PS or a part of a system that provides the immersion liquid. The measurement stage may move beneath the projection system PS when the substrate support WT is away from the projection system PS.

**[00020]** In operation, the radiation beam B is incident on the patterning device, e.g. mask, MA which is held on the mask support MT, and is patterned by the pattern (design layout) present on patterning device MA. Having traversed the patterning device MA, the radiation beam B passes through the projection system PS, which focuses the beam onto a target portion C of the substrate W. With the aid of the second positioner PW and a position measurement system IF, the substrate support WT can be moved accurately, e.g., so as to position different target portions C in the path of the radiation beam B at a focused and aligned position. Similarly, the first positioner PM and possibly another position sensor (which is not explicitly depicted in Figure 1) may be used to accurately position the patterning device MA with respect to the path of the radiation beam B. Patterning device MA and substrate W may be aligned using mask alignment marks M1, M2 and substrate alignment marks P1, P2. Although the substrate alignment marks P1, P2 as illustrated occupy dedicated target portions, they may be located in spaces between target portions. Substrate alignment marks P1, P2 are known as scribe-lane alignment marks when these are located between the target portions C.

**[00021]** To clarify the invention, a Cartesian coordinate system is used. The Cartesian coordinate system has three axis, i.e., an x-axis, a y-axis and a z-axis. Each of the three axis is orthogonal to the other two axis. A rotation around the x-axis is referred to as an Rx-rotation. A rotation around the y-axis is referred to as an Ry-rotation. A rotation around about the z-axis is referred to as an Rz-rotation. The x-axis and the y-axis define a horizontal plane, whereas the z-axis is in a vertical direction. The Cartesian coordinate system is not limiting the invention and is used for clarification only. Instead, another coordinate system, such as a cylindrical coordinate system, may be used to clarify the invention. The orientation of the Cartesian coordinate system may be different, for example, such that the z-axis has a component along the horizontal plane.

**[00022]** Figure 2 shows a more detailed view of a part of the lithographic apparatus LA of Figure 1. The lithographic apparatus LA may be provided with a base frame BF, a balance mass BM, a metrology frame MF and a vibration isolation system IS. The metrology frame MF supports the projection system PS. Additionally, the metrology frame MF may support a part of the position measurement system PMS of Figure 1. The metrology frame MF is supported by the base frame BF via the vibration isolation system IS. The vibration isolation system IS is arranged to prevent or reduce vibrations from propagating from the base frame BF to the metrology frame MF.

[00023] The second positioner PW is arranged to accelerate the substrate support WT by providing a driving force between the substrate support WT and the balance mass BM. The driving force accelerates the substrate support WT in a desired direction. Due to the conservation of momentum, the driving force is also applied to the balance mass BM with equal magnitude, but at a direction opposite to the desired direction. Typically, the mass of the balance mass BM is significantly larger than the masses of the moving part of the second positioner PW and the substrate support WT.

[00024] In an embodiment, the second positioner PW is supported by the balance mass BM. For example, wherein the second positioner PW comprises a planar motor to levitate the substrate support WT above the balance mass BM. In another embodiment, the second positioner PW is supported by the base frame BF. For example, wherein the second positioner PW comprises a linear motor and wherein the second positioner PW comprises a bearing, like a gas bearing, to levitate the substrate support WT above the base frame BF.

[00025] The position measurement system PMS may comprise any type of sensor that is suitable to determine a position of the substrate support WT. The position measurement system PMS may comprise any type of sensor that is suitable to determine a position of the mask support MT. The sensor may be an optical sensor such as an interferometer or an encoder. The position measurement system PMS may comprise a combined system of an interferometer and an encoder. The sensor may be another type of sensor, such as a magnetic sensor. a capacitive sensor or an inductive sensor. The position measurement system PMS may determine the position relative to a reference, for example the metrology frame MF or the projection system PS. The position measurement system PMS may determine the position of the substrate table WT and/or the mask support MT by measuring the position or by measuring a time derivative of the position, such as velocity or acceleration.

[00026] The position measurement system PMS may comprise an encoder system. An encoder system is known from for example, United States patent application US2007/0058173A1, filed on September 7, 2006, hereby incorporated by reference. The encoder system comprises an encoder head, a grating and a sensor. The encoder system may receive a primary radiation beam and a secondary radiation beam. Both the primary radiation beam as well as the secondary radiation beam originate from the same radiation beam, i.e., the original radiation beam. At least one of the primary radiation beam and the secondary radiation beam is created by diffracting the original radiation beam with the grating. If both the primary radiation beam and the secondary radiation beam are created by diffracting the original radiation beam with the grating, the primary radiation beam needs to have a different diffraction order than the secondary radiation beam. Different diffraction orders are, for example,+1$^{st}$ order, -1$^{st}$ order, +2$^{nd}$ order and -2$^{nd}$ order. The encoder system optically combines the primary radiation beam and the secondary radiation beam into a combined radiation beam. A sensor in the encoder head determines a phase or phase difference of the combined radiation beam. The sensor generates a signal based on the

phase or phase difference. The signal is representative of a position of the encoder head relative to the grating. One of the encoder head and the grating may be arranged on the substrate structure WT. The other of the encoder head and the grating may be arranged on the metrology frame MF or the base frame BF. For example, a plurality of encoder heads are arranged on the metrology frame MF, whereas a grating is arranged on a top surface of the substrate support WT. In another example, a grating is arranged on a bottom surface of the substrate support WT, and an encoder head is arranged below the substrate support WT.

**[00027]** The position measurement system PMS may comprise an interferometer system. An interferometer system is known from, for example, United States patent US6,020,964, filed on July 13, 1998, hereby incorporated by reference. The interferometer system may comprise a beam splitter, a mirror, a reference mirror and a sensor. A beam of radiation is split by the beam splitter into a reference beam and a measurement beam. The measurement beam propagates to the mirror and is reflected by the mirror back to the beam splitter. The reference beam propagates to the reference mirror and is reflected by the reference mirror back to the beam splitter. At the beam splitter, the measurement beam and the reference beam are combined into a combined radiation beam. The combined radiation beam is incident on the sensor. The sensor determines a phase or a frequency of the combined radiation beam. The sensor generates a signal based on the phase or the frequency. The signal is representative of a displacement of the mirror. In an embodiment, the mirror is connected to the substrate support WT. The reference mirror may be connected to the metrology frame MF. In an embodiment, the measurement beam and the reference beam are combined into a combined radiation beam by an additional optical component instead of the beam splitter.

**[00028]** The first positioner PM may comprise a long-stroke module and a short-stroke module. The short-stroke module is arranged to move the mask support MT relative to the long-stroke module with a high accuracy over a small range of movement. The long-stroke module is arranged to move the short-stroke module relative to the projection system PS with a relatively low accuracy over a large range of movement. With the combination of the long-stroke module and the short-stroke module, the first positioner PM is able to move the mask support MT relative to the projection system PS with a high accuracy over a large range of movement. Similarly, the second positioner PW may comprise a long-stroke module and a short-stroke module. The short-stroke module is arranged to move the substrate support WT relative to the long-stroke module with a high accuracy over a small range of movement. The long-stroke module is arranged to move the short-stroke module relative to the projection system PS with a relatively low accuracy over a large range of movement. With the combination of the long-stroke module and the short-stroke module, the second positioner PW is able to move the substrate support WT relative to the projection system PS with a high accuracy over a large range of movement.

**[00029]** The first positioner PM and the second positioner PW each are provided with an electromagnetic motor to move respectively the mask support MT and the substrate support WT. The electromagnetic motor may be a linear motor to provide a driving force along a single axis, for example the y-axis. Multiple linear motors may be applied to provide driving forces along multiple axis. The motor may be a planar motor to provide a driving force along multiple axis. For example, the planar motor may be arranged to move the substrate support WT in 6 degrees of freedom. The electromagnetic motor may be an electromagnetic actuator comprising at least one coil and at least one magnet. The actuator is arranged to move the at least one coil relative to the at least one magnet by applying an electrical current to the at least one coil. The actuator may be a moving-magnet type actuator, which has the at least one magnet coupled to the substrate support WT respectively to the mask support MT. The actuator may be a moving-coil type actuator which has the at least one coil coupled to the substrate support WT respectively to the mask support MT. The electromagnetic actuator may be a voice-coil actuator, a reluctance actuator, a Lorentz-actuator or a piezo-actuator, or any other suitable actuator.

**[00030]** The lithographic apparatus LA comprises a position control system PCS as schematically depicted in Figure 3. The position control system PCS comprises a setpoint generator SP, a feedforward controller FF and a feedback controller FB. The position control system PCS provides a drive signal to the plant / motor combination P-EM / P. The plant / motor combination comprises an electromagnetic motor EM, which may be the motor of the first positioner PM or the second positioner PW. The motor EM of the plant / motor combination P-EM drives the plant P, which may comprise the substrate support WT or the mask support MT. The plant P may also be referred to as the load that is driven by the motor. An output of the plant / motor combination P-EM is a position quantity such as position or velocity or acceleration of the plant. The position quantity is measured with the position measurement system PMS. The position measurement system PMS generates a signal, which is a position signal representative of the position quantity of the plant P. The setpoint generator SP generates a signal, which is a reference signal representative of a desired position quantity of the plant P. For example, the reference signal represents a desired trajectory of the substrate support WT. A difference between the reference signal and the position signal forms an input for the feedback controller FB. Based on the input, the feedback controller FB provides at least part of the drive signal for the electromagnetic motor EM of the plant / motor combination P-EM. The reference signal may form an input for the feedforward controller FF. Based on the input, the feedforward controller FF provides at least part of the drive signal for the motor EM of the plant / motor combination. The feedforward FF may make use of information about dynamical characteristics of the plant P, such as mass, stiffness, resonance modes and eigenfrequencies.

**[00031]** The present invention aims to improve the performance of the electromagnetic motors or actuators that are applied in a lithographic apparatus, e.g. the motors as applied in the above mentioned long-stroke or short-stroke modules.

**[00032]** Figure 4 schematically shows a first example of an electromagnetic motor 400 according to the present invention. In the embodiment as shown, the electromagnetic motor 400 comprises a magnet assembly 410 and a coil assembly 420. The magnet assembly 410 as shown comprises two magnetic yokes 410.1 which are provided with permanent magnets 410.2. The coil assembly 420 as shown comprises a single coil which can carry an electric current in a direction perpendicular to the plane of the drawing. When supplied with such a current, a force will be generated between the magnet assembly 410 and the coil assembly 420, the force acting in the indicated X-direction. Said force can cause a movement of the coil assembly 410 relative to the magnet assembly 420 in said direction, which is therefore also referred to as the direction of movement of the electromagnetic actuator 400. In general, the coil assembly 420 may also have multiple coils.

**[00033]** In accordance with the present invention, the electromagnetic motor 400 further comprises a power supply 430 for powering the coil assembly. The power supply 430 can e.g. be configured to supply a current, indicated by the dotted line 430.1, to the coil or coils of the coil assembly 410 of the electromagnetic motor 400. The electromagnetic motor 400 further comprises a control unit 440 that is configured to control the power supply 430 of the electromagnetic motor 400. In particular, in accordance with the present invention, the control unit is configured to control the electromagnetic motor in a particular manner, in order to determine a position dependent motor constant of the electromagnetic motor along a trajectory of interest in the direction of movement. The trajectory of interest can e.g. correspond to a certain stroke of the electromagnetic motor as shown.

**[00034]** In an embodiment, the control unit of the electromagnetic motor according to the present invention can include a position control system as illustrated in Figure 3. In general, the control unit 440 of the electromagnetic motor according to the present invention may be configured to receive one or more input signals such as position measurement signals or setpoint signals and may be configured to output one or more control signals to control the electromagnetic motor. In order to determine the position dependent motor constant, the control unit 440 of the electromagnetic motor according to the present invention is configured to perform the following actions.

**[00035]** In a first step, the control unit 440 of the electromagnetic motor 400 is configured to control the power supply 430, indicated by control signal 440.1, to supply the coil assembly 410 with an electric current so as to cause a displacement of the magnet assembly relative to the coil assembly along a predetermined trajectory of interest in the direction of movement, at a substantially constant velocity. In order to do so, the control unit 440 may be configured to generate a required position set point to achieve the displacement. As such, the control unit 440 may include a setpoint generator similar to setpoint generator SP as described above. Alternatively, the control unit 440 may receive a setpoint signal 440.2 from an external setpoint generator.

**[00036]** In a second step, the control unit 440 is configured to apply a disturbance having a predetermined frequency to the electromagnetic motor 400, during the displacement of the magnet assembly relative to the coil assembly. As will be explained in more detail below, there are various manners to apply a disturbance to the electromagnetic motor, e.g. by injecting a disturbance force in the control scheme applied by the control unit, or by applying an actual disturbance force to the electromagnetic actuator.

**[00037]** In a third step, the control unit 440 is configured to determine a position of the magnet assembly relative to the coil assembly and an electromagnetic motor force, along the trajectory of interest. In an embodiment, the control unit 440 may be connected to a position measurement system such as the system PMS shown in Figure 3, which can be configured to measure a position of the coil assembly 420 and/or the magnet assembly 410, so as to obtain a position measurement signal of the coil assembly and/or the magnet assembly.

**[00038]** In a fourth step, the control unit is configured to determine the position dependent motor constant of the electromagnetic motor along the predetermined trajectory of interest, based on the determined position and the electromagnetic motor force.

**[00039]** As a result, the motor constant of the electromagnetic motor is obtained, along the predetermined trajectory of interest. When subsequently this position dependent motor constant is implemented in the control unit of the electromagnetic motor, a more accurate position control of the load that is driven by the motor can be obtained.

**[00040]** The exemplary electromagnetic motor 400 shown in Figure 4 may also be referred to as an electromagnetic actuator or a linear actuator or Lorentz actuator. Such an electromagnetic motor or actuator typically has a comparatively small stroke. In case a load, or plant, is to be displaced over a comparative long distance, use can e.g. be made of electromagnetic motors having coil assemblies with an array of coils and magnet assemblies with an array of magnets.

**[00041]** Figure 5 schematically shows an electromagnetic motor 500 according to the present invention which is capable of a comparatively large displacement of the coil assembly relative to the magnet assembly. Figure 5 (a) schematically shows a cross-section of the motor 500 showing a magnet assembly 510 comprising an array of magnets 510.1, e.g. permanent magnets, arranged on a magnetic yoke 510.2, e.g. a ferromagnetic yoke or the like. The motor 500 further comprises a coil assembly 520, comprising an array of coils 520.2 arranged in the indicated Y-direction and mounted to a holder 520.1. In the arrangement as shown, the array of magnets 510.1 is configured to generate, during use, a spatially alternating magnetic field along the indicated Y-direction, which can also be referred to as the direction of movement since, during use, a movement of the coil assembly 520 relative to the magnet assembly 510 in the direction of movement can be established, when a suitable set of electric currents is supplied to the array of coils 520.2 of the coil assembly 520. Note that, in a similar manner as discussed with respect to Figure 4, the electromagnetic motor 500 further includes a power supply and a control unit for powering and controlling the coil assembly 520 of the electromagnetic motor 500. These components are not shown in Figure 5. Figures 5 (b) and 5 (c) schematically show the electromagnetic motor 500 for two different positions of the coil assembly 520 relative to the magnet assembly 510 of the motor. In Figure 5 (b), the coil assembly 520 is at a left most position, relative to the magnet assembly 510 along the direction of movement, whereas, in Figure 5 (c), the coil assembly 520 is at a right most position, relative to the magnet assembly 510 along the direction of movement. As such, the range or stroke Y1 – Y2 can be considered to be the useful operating range of the motor, or the trajectory of interest in the direction of movement. Note that a positioning of the coil assembly relative to the magnet assembly beyond the range Y1 – Y2, would result in a reduced interaction between the coil assembly and the magnet assembly, which would result in a substantial reduction of the motor constant, i.e. the amount of force generated per unit of current supplied to the coil assembly.

**[00042]** Merely as an illustration, Figure 6 schematically indicates a motor constant K as a function of the relative position (Y) between a coil assembly and a magnet assembly of a motor such as electromagnetic motor 500. Note that the motor constant K(y) may vary between a value Kmin and a value Kmax along the range Y1 – Y2 which may be a range similar to the range as indicated in Figure 5. In general, the motor constant variation as perceived may have different causes such as manufacturing tolerances of the magnet assembly, the applied magnets, the coils of the array of coils and the coil assembly. The motor constant variation as perceived will typically also comprise periodic components which may e.g. be associated with a magnetic pitch of the array of magnets of the magnet assembly of the motor.

**[00043]** The method to obtain the position dependent motor constant according to the present invention will be explained in more detail, with reference to Figures 7-8.

**[00044]** Figure 7 schematically shows a more detailed position control scheme as can be applied to control an electromagnetic motor according to the invention, e.g. to control a stage apparatus in a lithographic apparatus. The control scheme, in particular the position control scheme PCS can e.g. be implemented in a control unit of an electromagnetic motor according to the invention. The control scheme as shown in Figure 7 is similar to the control scheme of Figure 3, apart from the following. In the control scheme of Figure 7, the plant motor combination P-EM(y) has been further detailed, to illustrate that the electromagnetic motor as applied in the plant motor combination may have a position dependent motor constant, i.e. a motor constant depending on the y-position of the plant motor combination. From a control point of view, the plant motor combination can be considered to be a system or component which converts a force into an acceleration which then causes a displacement along the direction of movement. In such case, the plant motor combination may be characterised by a nominal motor constant $Km_{nom}$, which is a singular value. Due to the aforementioned effects, the actual motor constant will not be constant but will be a function of the position y in the direction of movement. This is indicated in the detailed plant / motor combination P-EM of Figure 7 as Km(y). The output of block Km(y) in Figure 7 thus represents the actual force as generated by the motor, which is used to accelerate the load, which is represented by a mass m. The output of the P-EM(y) block thus corresponds to the displacement y of the plant or load that is driven.

**[00045]** The output of the position control system PCS corresponds to, as mentioned above, a drive signal for the P-EM(y) combination. In the shown PCS system, the drive signal is the combination of the outputs of the feedforward controller FF and the feedback controller FB. Typically, the drive signal, indicated by reference number 710, would be considered the desired driving force or desired motor force for driving the plant to the desired position indicated by the setpoint generator. In view of the position dependent motor constant $K_m(y)$, this drive signal would not result in the desired acceleration or displacement of the plant. In case the position dependent motor constant Km(y) would be known in advance, a correction could be applied to the drive signal, in such manner that the desired control of the plant is obtained. In Figure 7, said correction is indicated as $K_{rcp}(y)$, which is thus a position dependent correction or adjustment which can be applied to the generated drive signal 710. As a result of the correction or adjustment, an adjusted drive signal 720 can thus be obtained, which takes account of the position dependent motor constant Km(y). In the present invention, a method is disclosed which enables to determine the position dependent motor constant $K_m(y)$, and thus the required correction or adjustment $K_{rcp}(y)$ to take the position dependency into account. This method of determining a position dependent motor constant, which can also be considered a type of calibration method of the electromagnetic motor, is schematically illustrated in the flowchart of Figure 8.

**[00046]** The method of determining a position dependent motor constant according to the present invention as illustrated in Figure 8 comprises a first step 810 of causing a displacement of the magnet assembly of the electromagnetic motor relative to the coil assembly of the electromagnetic motor along a predetermined trajectory of interest in the direction of movement, at a substantially constant velocity. In an embodiment said first step can e.g. be implemented in practice by means of a control unit of the electromagnetic motor, the control unit being configured to control a power supply of the electromagnetic motor, as e.g. described above with reference to Figure 4. The trajectory of interest can e.g. be a range of motion of the electromagnetic motor, e.g. the range Y1 – Y2 illustrated in Figures 5 and 6.

**[00047]** The method of determining a position dependent motor constant according to the present invention further comprises a second step 820 of applying a disturbance having a predetermined frequency, that exposes the plant's mass behavior, to the electromagnetic motor, during the displacement of the magnet assembly relative to the coil assembly. Phrased differently, the frequency of the disturbance should be within the range where the plant or load shows mass behavior, i.e. $1/ms^2$, having a -2 slope in magnitude. The various manners to implement such a disturbance will be detailed out below.

**[00048]** The method of determining a position dependent motor constant according to the present invention further comprises a third step 830 of determining a position of the magnet assembly relative to the coil assembly and an electromagnetic motor force, along the predetermined trajectory of interest. Referring to the control scheme of e.g. Figure 7, the position of the magnet assembly relative to the coil assembly may e.g. be determined using a position measurement system such as the indicated PMS system.

**[00049]** The method of determining a position dependent motor constant according to the present invention further comprises a fourth step 840 determining a position dependent motor constant of the electromagnetic motor along the predetermined trajectory of interest, based on the determined position error and the electromagnetic motor force. Referring to the control scheme of Figure 7, the electromagnetic motor force may, in an embodiment of the present invention, be equated to the drive signal 710 as generated by the position control system PCS.

**[00050]** With respect to the implementation of step 820 of the method according to the present invention, the following methods can be applied.

**[00051]** In a first embodiment, the disturbance as mentioned in step 820 of the method of determining a position dependent motor constant according to the present invention can be implemented in the position control system or control unit as applied to control the electromagnetic motor which motor constant is to be determined. This is illustrated in Figure 9. Figure 9 schematically illustrates a position control scheme similar to the scheme of Figure 7, apart from the position dependent correction or adjustment $K_{rcp}(y)$, which is to be determined.

**[00052]** As a first example, the disturbance of step 820 of the method according to the invention can be injected or superimposed to the drive signal as generated by the position control system PCS. In Figure 9, this is indicated by the arrow 910. In the embodiment as shown, the drive signal, i.e. the combination of the outputs of the feedforward controller FF and the feedback controller FB which represent a desired drive force or desired motor force is combined with a disturbance indicated by the arrow 910. In this example, the disturbance can thus be considered a disturbance force or force component that is added to the drive signal outputted by the PCS. Such a disturbance force is further on referred as disturbance force F_dist(y).

**[00053]** As a second example, the disturbance of step 820 of the method according to the invention can be injected or superimposed to the setpoint that is used by the PCS. In Figure 9, the setpoint generator SP may be configured to generate a setpoint to perform the displacement along the predetermined trajectory of interest that is mentioned in step 810 of the method according to the invention. A disturbance, indicated by the arrow 920 may thus be added to said setpoint. In this example, the disturbance can thus be considered a positional disturbance that is added to the setpoint.

**[00054]** As a third example, the disturbance of step 820 of the method according to the invention can be injected or superimposed to the position error determined by the PCS. In Figure 9, the position error is obtained by the difference between the setpoint of the setpoint generator SP and the y-position as determined by the position measurement system PMS. Said position error is inputted in the feedback controller FB. A disturbance, indicated by the arrow 930, may be injected or superimposed to said position error. In this example, the disturbance can thus be considered a positional disturbance that is added to the position error. The position error is further on referred to as e(y).

**[00055]** In a second embodiment, the disturbance of step 820 of the method according to the invention may be implemented as an actual disturbance force that is applied to the electromagnetic motor that is calibrated. This can e.g. be done by applying a disturbance force to either the stator or the mover of the electromagnetic motor in case both are displaceable. In case the stator is mounted to a rigid construction, the disturbance force may be applied to the mover. In the context of a lithographic apparatus, electromagnetic motors such as the motor shown in Figure 5 may be applied in a long-stroke module, as e.g. discussed above. Such a long-stroke module may also comprise a short-stroke module e.g. comprising one or more actuators configured to position an object table. In an embodiment, one or more of said actuators of a short-stroke module may be used to cause a disturbance force on the electromagnetic motor of the long-stroke module.

**[00056]** In an embodiment of the present invention, the disturbance as applied is a substantially sinusoidal disturbance having a predetermined frequency.

**[00057]** The method of determining a position dependent motor constant according to the present invention, in particular the step 840 of the method can be implemented as follows.

**[00058]** As illustrated in Figure 9, an electromagnetic motor used for driving a plant or object such as an object table will have a position dependent motor constant which can be described by $K_m(y)$. Alternatively, Km(y) may be expressed as:

$$K_m(y) = Km_{avg}[1 + k(y)] \qquad (1)$$

**[00059]** In order to compensate the position dependent effect of the motor constant, the correction Krcp(y) should be such that:

$$K_{rcp}(y) \cdot [1 + k(y)] = c \qquad (2)$$

whereby c is a constant.

As such, when [1+k(y)] or $K_m(y)$ is known, $K_{rcp}(y)$ can easily be derived. Apart from a constant gain, the position dependent motor constant, and thus also the compensation, can be determined by determining the transfer function P-EM(y) shown in Figures 7 and 9.

**[00060]** In accordance with the method of the present invention, this is done as follows: In order to determine the position dependent motor constant, along a predetermined trajectory of interest, the electromagnet motor is displaced along the trajectory at a substantially constant velocity. During said displacement, a disturbance having a predetermined frequency, e.g. a sinusoidally varying disturbance, is applied to the motor. During said displacement, various characteristics can be traced. In particular the position of the magnet assembly relative to the coil assembly and the electromagnetic motor force F_act(y) are to be traced, as a function of the displacement, i.e. along the trajectory of interest. Other variables that can be traced during the displacement along the trajectory of interest are the position error e and the applied disturbance, e.g. the disturbance force F_dist(y). Due to the nature of the applied disturbance, the electromagnetic motor force and the error e, as well as the disturbance force are alternating signals or traces. In order to determine the transfer function P-EM(y), only the amplitudes of said traced variables are required.

**[00061]** Using this traced data, the transfer function P-EM(y) can be determined as follows: the transfer function P-EM(y) be determined based on the process sensitivity PS(y) and the sensitivity S(y) of the process. In particular:

$$\mathrm{PS}(y) = \frac{\bar{e}(y)}{\bar{F}\_\mathrm{dist}(y)}, \quad \mathrm{S}(y) = \frac{\bar{F}\_\mathrm{act}(y)}{\bar{F}\_\mathrm{dist}(y)} \qquad (3)$$

Wherein:

$\bar{e}(y)$ is the amplitude of the position error e along the predetermined trajectory,

$\bar{F}\_\mathrm{dist}(y)$ is the amplitude of the disturbance force as applied during the displacement along the predetermined trajectory, and

$\bar{F}\_\mathrm{act}(y)$ is the amplitude of the actuator force as applied during the displacement along the predetermined trajectory.

$$\mathrm{P} - \mathrm{EM}(y) = \mathrm{PS}(y) * \mathrm{S}(y)^{-1} \qquad (4)$$

$$\mathrm{P} - \mathrm{EM}(y) = \frac{\bar{e}(y)}{\bar{F}\_\mathrm{act}(y)} \qquad (5)$$

In view of equation (5), the transfer function P-EM(y), and thus the position dependent motor constant as e.g. given by equation (1) can be derived from the position error e and from the actuator force $\bar{F}\_\mathrm{act}(y)$.

**[00062]** Note that position error e can easily be obtained as the difference between the actual position y, as e.g. measured by the PMS system shown in Figures 7 and 9 and the setpoint obtained from the setpoint generator SP.

**[00063]** It can further be noted that, as mentioned above, that the electromagnetic motor force $\bar{F}\_\mathrm{act}(y)$ can be equated to the drive signal 710 as generated by the position control system PCS shown in Figures 7 and 9.

**[00064]** As indicated above, the position error, the disturbance force and the electromagnetic motor force are typically alternating signals. The amplitude of such signals can e.g. be determined using a fitting algorithm or similar methods. Such methods are schematically explained with reference to Figure 10.

**[00065]** Figure 10 schematically shows a signal S, which can e.g. correspond to the actual position y as measured, the position error e, the disturbance force or the electromagnetic motor force along the trajectory of interest. Note that it is assumed that the displacement along the trajectory of interest is a displacement at a substantially constant speed, the indicated signal S also corresponds to the signal as obtained over time, i.e. during the constant speed displacement.

**[00066]** A first method to derive the amplitude of the signal S is to perform a fitting of the signal with a sinusoidal signal spanning one or more periods of the signal S. Note that the period of the signal S is known since it will correspond to the period of the disturbance force, which has a predetermined frequency. In Figure 10, window 1000 spans 3 periods of the signal S. In order to determine the amplitude of the signal S over said window, the signal S can be fitted to a sinusoidal signal M(y) spanning the same period as the window 1000.

**[00067]** The signal M(y) can be considered a sinusoidal signal with unknown amplitude and phase, optionally with an unknown offset and an unknown slope. A general expression of M(y) would thus be:

$$M(y) = A_1 * \sin(2\pi * y + A_2) + A_3 * y + A_4 \qquad (6)$$

**[00068]** Using known fitting techniques, e.g. least-squares fitting, the parameters $A_1 - A_4$ can be obtained, whereby A1 can then be considered to correspond to the amplitude of the signal S over the window 1000. This process can then be repeated for an adjacent window until the amplitude of the signal S is obtained across the desired trajectory of interest. Note that by the first method as illustrated one would obtain one value for the amplitude of the signal S over the window 1000. In order to obtain a more dense or detailed dataset for the amplitude of the signal S, the window 1000 can be made more narrow, e.g. spanning only one period. Alternatively or in addition, the sequency of windows that is applied can be overlapping.

**[00069]** A second method to obtain the amplitude of the signal S would be to determine the maxima and minima of the signal S. For a portion of the signal S, these maxima and minima are indicated by resp. MAX and MIN in Figure 10. In order to obtain the amplitude of the signal S, one could then consider a polynomial, or the like, fitting through the maxima and the minima, resulting in polynomials Pmax and Pmin. Subtracting Pmin from Pmax would then result in the amplitude of the signal S.

**[00070]** A third method to obtain the amplitude of the signal S, which can be considered a simplified version of the second method, is illustrated on the right of Figure 10. In order to obtain an amplitude value for the signal S, a line L is constructed between two adjacent maxima of the signal. The amplitude of the signal S at the minimum between the two adjacent maxima can then be construed as the distance D between said minimum and the line.

**[00071]** Irrespective of the method as applied, it can be pointed out that it is preferred to select the frequency of the disturbance sufficiently high, and/or the substantially constant velocity of the displacement sufficiently low to ensure that the available amplitude data is sufficient to accurately assess the motor constant variation of the electromagnetic motor. In this respect, it is advisable to ensure that at least 5 data points are available within a magnetic pitch of the electromagnetic motor.

**[00072]** Once the amplitudes of the required signals are obtained, the transfer function P-EM(y) can be determined, as well as the correction $K_{rcp}(y)$. When the correction $K_{rcp}(y)$ is subsequently implemented in a position control system or control unit of an electromagnetic motor, a more accurate positioning or displacement of the load or plant that is driven by the motor can be obtained.

**[00073]** As mentioned, the electromagnetic motor according to the invention may advantageously be applied to drive a stage of a lithographic apparatus. As will be understood by the skilled person, the electromagnetic motor according to the invention may also be applied to drive other components in a lithographic apparatus as well, such as e.g. a reticle masking device. Advantageously, the electromagnetic motor according to the invention may also be applied outside the field of lithography.

**[00074]** Although specific reference may be made in this text to the use of a lithographic apparatus in the manufacture of ICs, it should be understood that the lithographic apparatus described herein may have other applications. Possible other applications include the manufacture of integrated optical systems, guidance and detection patterns for magnetic domain memories, flat-panel displays, liquid-crystal displays (LCDs), thin-film magnetic heads, etc.

**[00075]** Although specific reference may be made in this text to embodiments of the invention in the context of a lithographic apparatus, embodiments of the invention may be used in other apparatus. Embodiments of the invention may form part of a mask inspection apparatus, a metrology apparatus, or any apparatus that measures or processes an object such as a wafer (or other substrate) or mask (or other patterning device). These apparatus may be generally referred to as lithographic tools. Such a lithographic tool may use vacuum conditions or ambient (non-vacuum) conditions.

**[00076]** Although specific reference may have been made above to the use of embodiments of the invention in the context of optical lithography, it will be appreciated that the invention, where the context allows, is not limited to optical lithography and may be used in other applications, for example imprint lithography.

**[00077]** Where the context allows, embodiments of the invention may be implemented in hardware, firmware, software, or any combination thereof. Embodiments of the invention may also be implemented as instructions stored on a machine-readable medium, which may be read and executed by one or more processors. A machine-readable medium may include any mechanism for storing or transmitting information in a form readable by a machine (e.g., a computing device). For example, a machine-readable medium may include read only memory (ROM); random access memory (RAM); magnetic storage media; optical storage media; flash memory devices; electrical, optical, acoustical or other forms of propagated signals (e.g. carrier waves, infrared signals, digital signals, etc.), and others. Further, firmware, software, routines, instructions may be described herein as performing certain actions. However, it should be appreciated that such descriptions are merely for convenience and that such actions in fact result from computing devices, processors, controllers, or other devices executing the firmware, software, routines, instructions, etc. and in doing that may cause actuators or other devices to interact with the physical world.

**[00078]** While specific embodiments of the invention have been described above, it will be appreciated that the invention may be practiced otherwise than as described. The descriptions above are intended to be illustrative, not limiting. Thus it will be apparent to one skilled in the art that modifications may be made to the invention as described without departing from the scope of the claims set out below. Other aspects of the invention are set-out as in the following numbered clauses.

1. An electromagnetic motor comprising:
   - a magnet assembly configured to generate a magnetic field;

- a coil assembly comprising at least one coil; the coil assembly being configured to co-operate with the magnet assembly so as to cause a movement of the magnet assembly relative to the coil assembly in a direction of movement;
- a power supply configured to, during use, power the coil assembly;
- a control unit configured to:
    - o control the power supply to supply the coil assembly with an electric current so as to cause a displacement of the magnet assembly relative to the coil assembly along a predetermined trajectory of interest in the direction of movement, at a substantially constant velocity;
    - o apply a disturbance having a predetermined frequency to the electromagnetic motor, during the displacement of the magnet assembly relative to the coil assembly;
    - o determine a position of the magnet assembly relative to the coil assembly and an electromagnetic motor force, along the predetermined trajectory of interest;
    - o determine a position dependent motor constant of the electromagnetic motor along the predetermined trajectory of interest, based on the determined position and the electromagnetic motor force.

2. The electromagnetic motor according to clause 1, wherein the magnet assembly comprises an array of magnets to generate, during use, a spatially alternating magnetic field in the direction of movement, and wherein the coil assembly comprises an array of coils arranged in the direction of movement.
3. The electromagnetic motor according to clause 1 or 2, wherein the disturbance is a substantially sinusoidal disturbance.
4. The electromagnetic motor according to any of the preceding clauses, wherein the control unit is configured to receive or generate a position setpoint for the electromagnetic motor to cause the displacement, and receive a position signal representing a position of the electromagnetic motor.
5. The electromagnetic motor according to clause 4, wherein the control unit is configured to determine a position error along the trajectory of interest based on the position signal and the position setpoint and to determine the position dependent motor constant of the electromagnetic motor along the predetermined trajectory of interest, based on the determined position error and the electromagnetic motor force.
6. The electromagnetic motor according to clause 4 or 5, wherein the control unit is configured to determine a desired motor force during the displacement, based on the position setpoint and the position signal.

7. The electromagnetic motor according to clause 6, wherein the disturbance is a disturbance force and wherein the control unit is configured to superimpose the disturbance force to the desired motor force.
8. The electromagnetic motor according to any of the clauses 4 to 7, wherein the disturbance is a positional disturbance and wherein the control unit is configured to superimpose the positional disturbance to the position setpoint or to the difference between the position setpoint and the position signal.
9. The electromagnetic motor according to any of the clauses 4 to 7, wherein the electromagnetic motor further comprises an actuator and wherein the control unit is configured to control an operation of the actuator so as to cause the disturbance.
10. The electromagnetic motor according to any of the preceding clauses, wherein determining the position of the magnet assembly relative to the coil assembly and the electromagnetic motor force comprises determining an amplitude of the position and the electromagnetic motor force along the predetermined trajectory of interest.
11. The electromagnetic motor according to any of the preceding clauses referring to clause 2, wherein the predetermined frequency and substantially constant speed are selected to have multiple periods of the disturbance during a displacement of the magnet assembly relative to the coil assembly spanning a magnet pitch of the array of magnets.
12. A stage apparatus for use in a lithographic apparatus, the stage comprising an electromagnetic motor according to any of the preceding clauses.
13. The stage apparatus according to clause 12, wherein the stage is configured to hold a patterning device or a substrate.
14. A lithographic apparatus comprising a stage apparatus according to clause 12 or 13.
15. A method of determining a position dependent motor constant of an electromagnetic motor, the electromagnetic motor comprising a magnet assembly and a coil assembly that are configured to displace relative to each other in a direction of movement, the method comprising:
    - causing a displacement of the magnet assembly relative to the coil assembly along a predetermined trajectory of interest in the direction of movement, at a substantially constant velocity;
    - applying a disturbance having a predetermined frequency to the electromagnetic motor, during the displacement of the magnet assembly relative to the coil assembly;
    - determining a position error of the magnet assembly relative to the coil assembly and an electromagnetic motor force, along the predetermined trajectory of interest;
    - determining a position dependent motor constant of the electromagnetic motor along the predetermined trajectory of interest, based on the determined position error and the electromagnetic motor force.
16. The method according to clause 15, further comprising:

- receiving or generating a position setpoint for the electromagnetic motor to cause the displacement, and receiving a position signal representing a position of the electromagnetic motor.

17. The method according to clause 16, further comprising:
    - determining a desired motor force during the displacement, based on the position setpoint and the position signal.
18. The method according to clause 17, wherein the disturbance is a disturbance force and wherein applying the disturbance comprises superimposing the disturbance force to the desired motor force.

CLAIMS

1. An electromagnetic motor comprising:
   - a magnet assembly configured to generate a magnetic field;
   - a coil assembly comprising at least one coil; the coil assembly being configured to co-operate with the magnet assembly so as to cause a movement of the magnet assembly relative to the coil assembly in a direction of movement;
   - a power supply configured to, during use, power the coil assembly;
   - a control unit configured to:
     - control the power supply to supply the coil assembly with an electric current so as to cause a displacement of the magnet assembly relative to the coil assembly along a predetermined trajectory of interest in the direction of movement, at a substantially constant velocity;
     - apply a disturbance having a predetermined frequency to the electromagnetic motor, during the displacement of the magnet assembly relative to the coil assembly;
     - determine a position of the magnet assembly relative to the coil assembly and an electromagnetic motor force, along the predetermined trajectory of interest;
     - determine a position dependent motor constant of the electromagnetic motor along the predetermined trajectory of interest, based on the determined position and the electromagnetic motor force.

2. The electromagnetic motor according to claim 1, wherein the magnet assembly comprises an array of magnets to generate, during use, a spatially alternating magnetic field in the direction of movement, and wherein the coil assembly comprises an array of coils arranged in the direction of movement.

3. The electromagnetic motor according to claim 1 or 2, wherein the disturbance is a substantially sinusoidal disturbance.

4. The electromagnetic motor according to any of the preceding claims, wherein the control unit is configured to receive or generate a position setpoint for the electromagnetic motor to cause the displacement, and receive a position signal representing a position of the electromagnetic motor.

5. The electromagnetic motor according to claim 4, wherein the control unit is configured to determine a position error along the trajectory of interest based on the position signal and the

position setpoint and to determine the position dependent motor constant of the electromagnetic motor along the predetermined trajectory of interest, based on the determined position error and the electromagnetic motor force.

6. The electromagnetic motor according to claim 4 or 5, wherein the control unit is configured to determine a desired motor force during the displacement, based on the position setpoint and the position signal.

7. The electromagnetic motor according to any of the claims 4 to 6, wherein the disturbance is a positional disturbance and wherein the control unit is configured to superimpose the positional disturbance to the position setpoint or to the difference between the position setpoint and the position signal.

8. The electromagnetic motor according to any of the claims 4 to 6, wherein the electromagnetic motor further comprises an actuator and wherein the control unit is configured to control an operation of the actuator so as to cause the disturbance.

9. The electromagnetic motor according to any of the preceding claims, wherein determining the position of the magnet assembly relative to the coil assembly and the electromagnetic motor force comprises determining an amplitude of the position and the electromagnetic motor force along the predetermined trajectory of interest.

10. The electromagnetic motor according to any of the preceding claims referring to claim 2, wherein the predetermined frequency and substantially constant speed are selected to have multiple periods of the disturbance during a displacement of the magnet assembly relative to the coil assembly spanning a magnet pitch of the array of magnets.

11. A stage apparatus for use in a lithographic apparatus, the stage comprising an electromagnetic motor according to any of the preceding claims.

12. The stage apparatus according to claim 11, wherein the stage is configured to hold a patterning device or a substrate.

13. A lithographic apparatus comprising a stage apparatus according to claim 11 or 12.

14. A method of determining a position dependent motor constant of an electromagnetic motor, the electromagnetic motor comprising a magnet assembly and a coil assembly that are configured to displace relative to each other in a direction of movement, the method comprising:
    - causing a displacement of the magnet assembly relative to the coil assembly along a predetermined trajectory of interest in the direction of movement, at a substantially constant velocity;
    - applying a disturbance having a predetermined frequency to the electromagnetic motor, during the displacement of the magnet assembly relative to the coil assembly;
    - determining a position error of the magnet assembly relative to the coil assembly and an electromagnetic motor force, along the predetermined trajectory of interest;
    - determining a position dependent motor constant of the electromagnetic motor along the predetermined trajectory of interest, based on the determined position error and the electromagnetic motor force.

15. The method according to claim 14, further comprising:
    - receiving or generating a position setpoint for the electromagnetic motor to cause the displacement, and receiving a position signal representing a position of the electromagnetic motor.

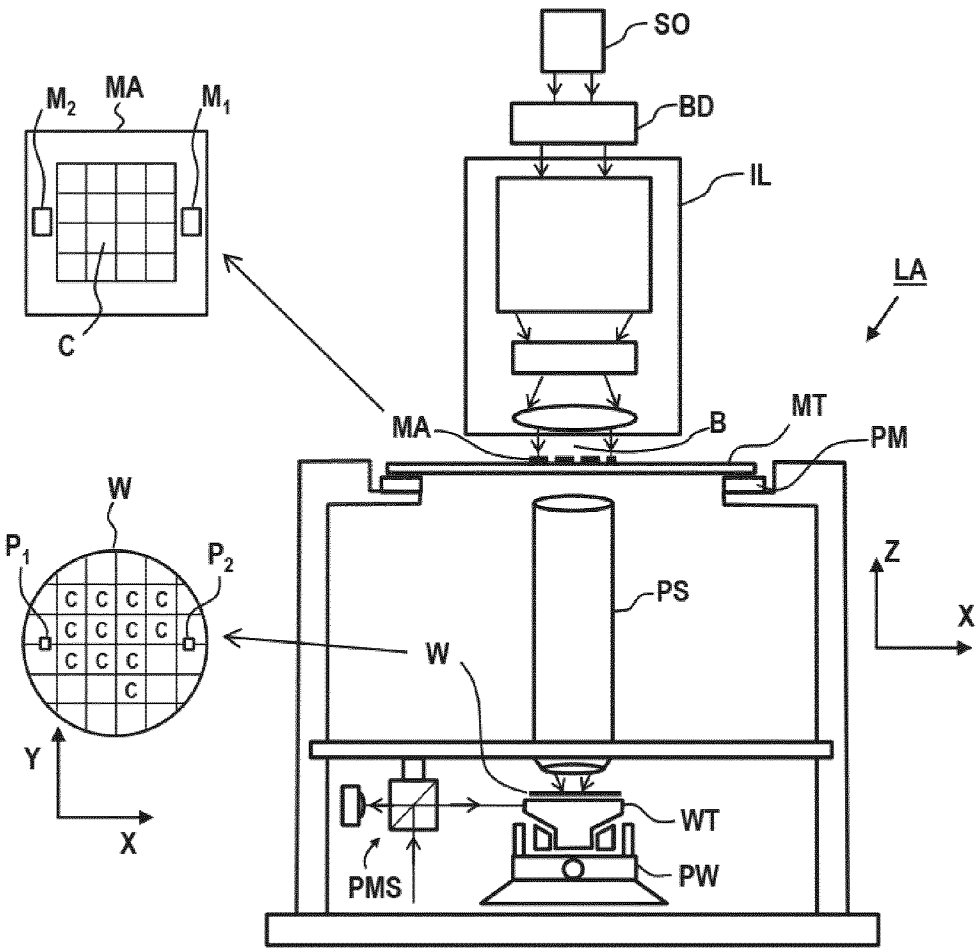
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Fig. 1

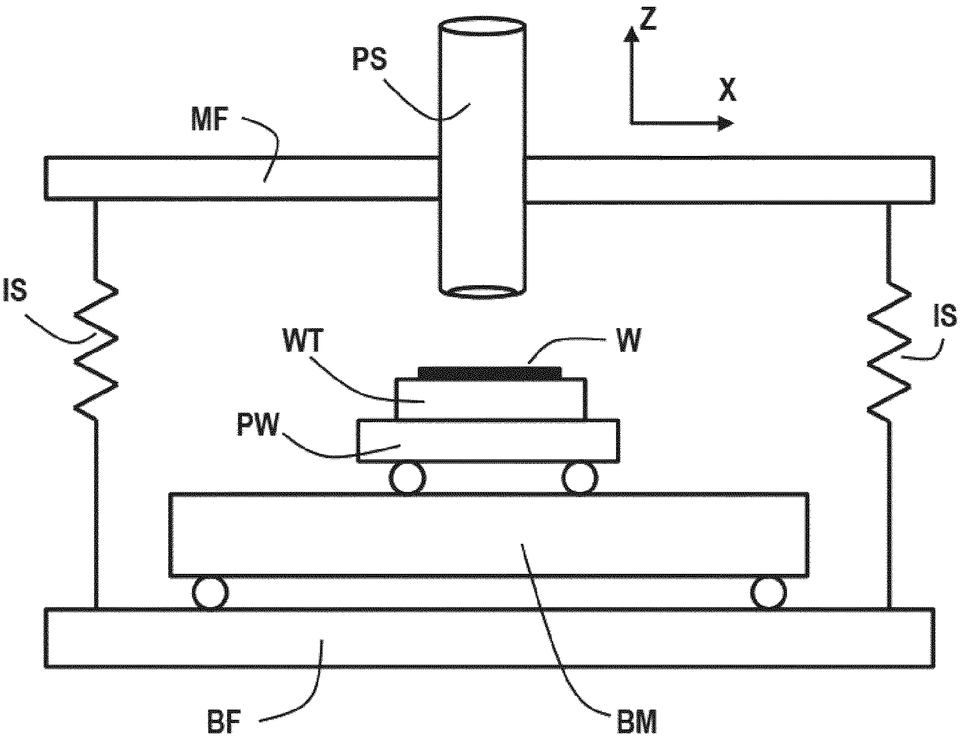
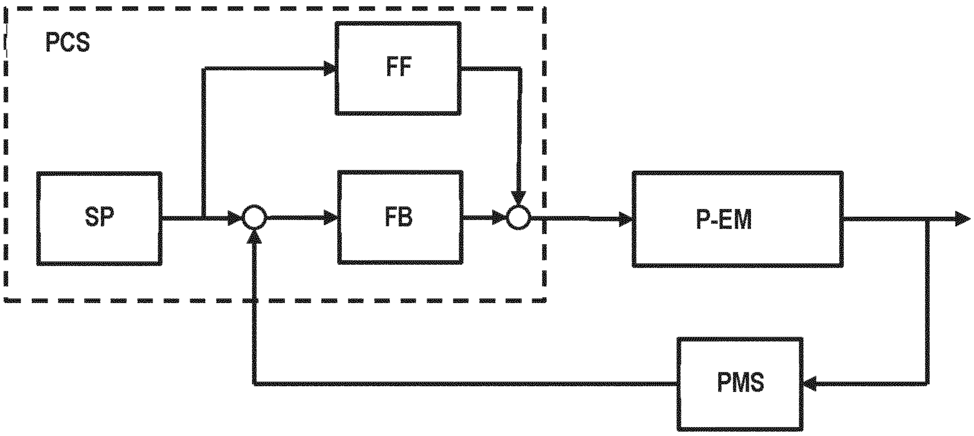



Fig. 2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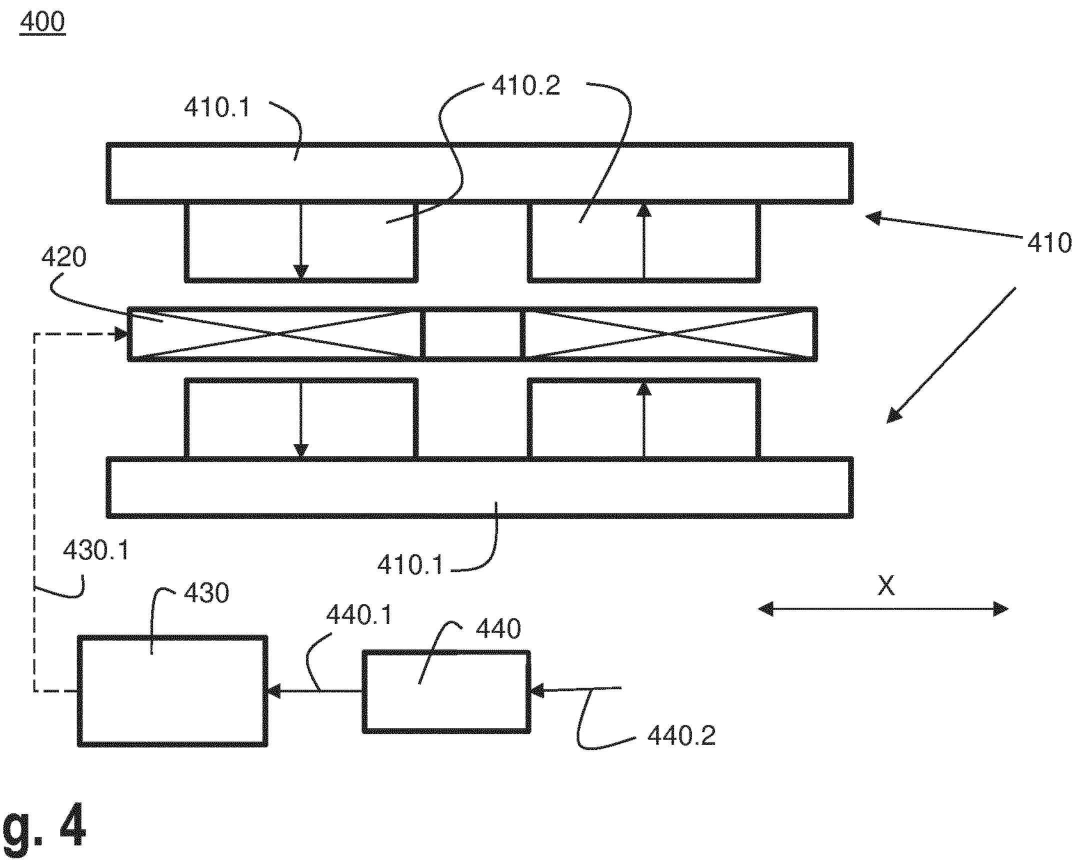
P-EM
PMS

Fig. 3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440
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440.2

Fig. 4

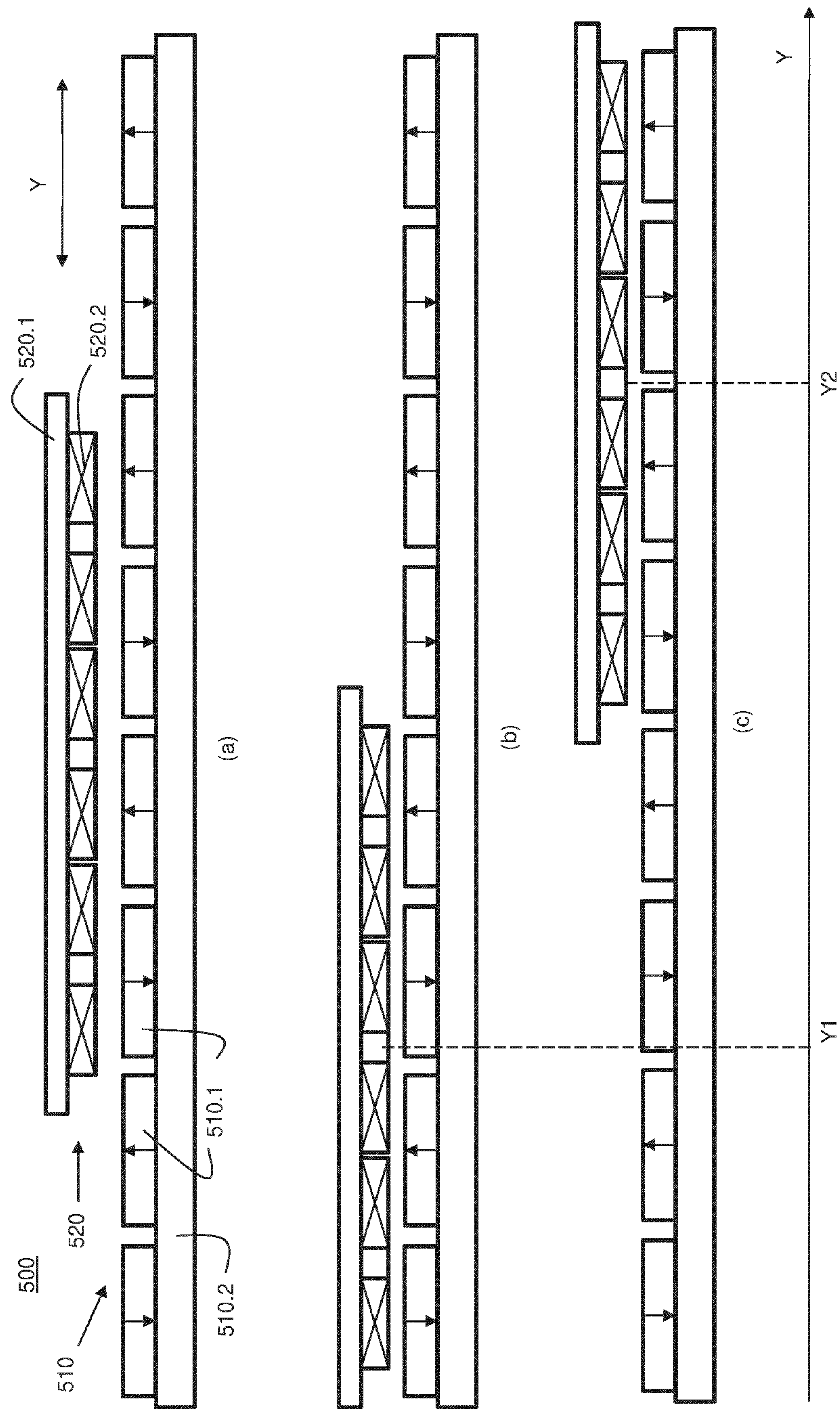


Fig. 5

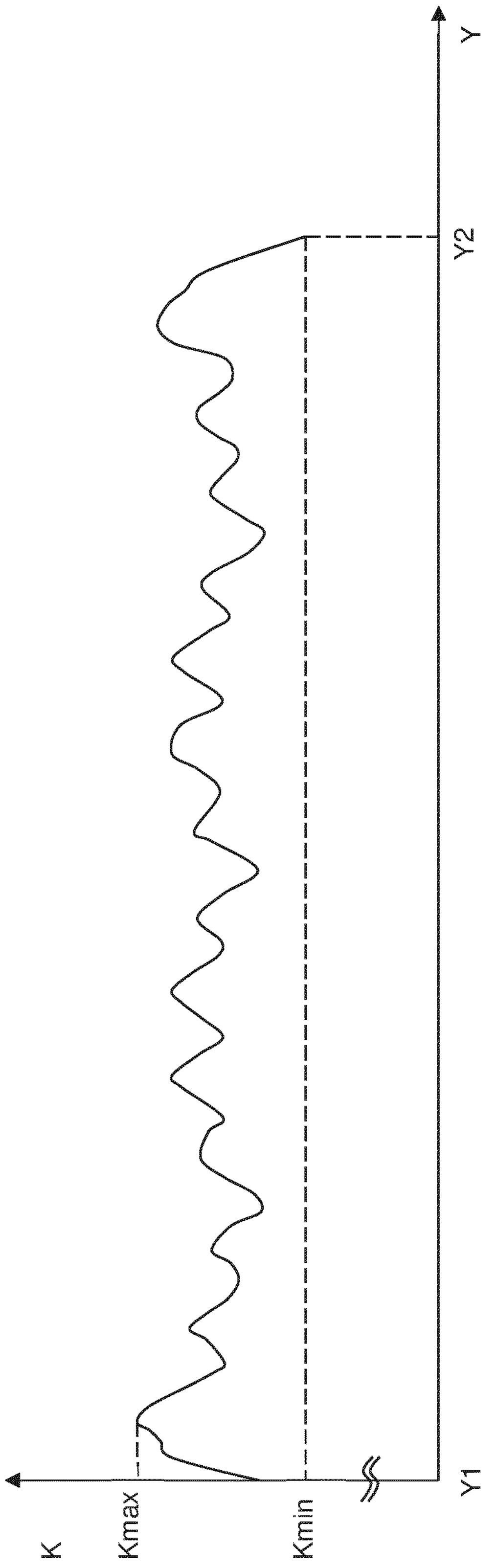


Fig. 6

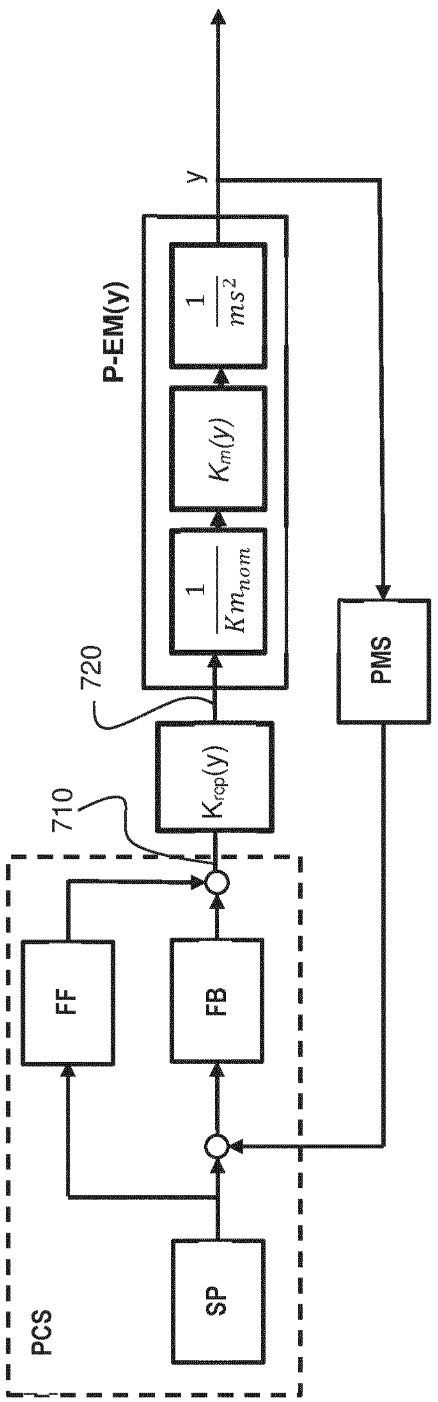


Fig. 7

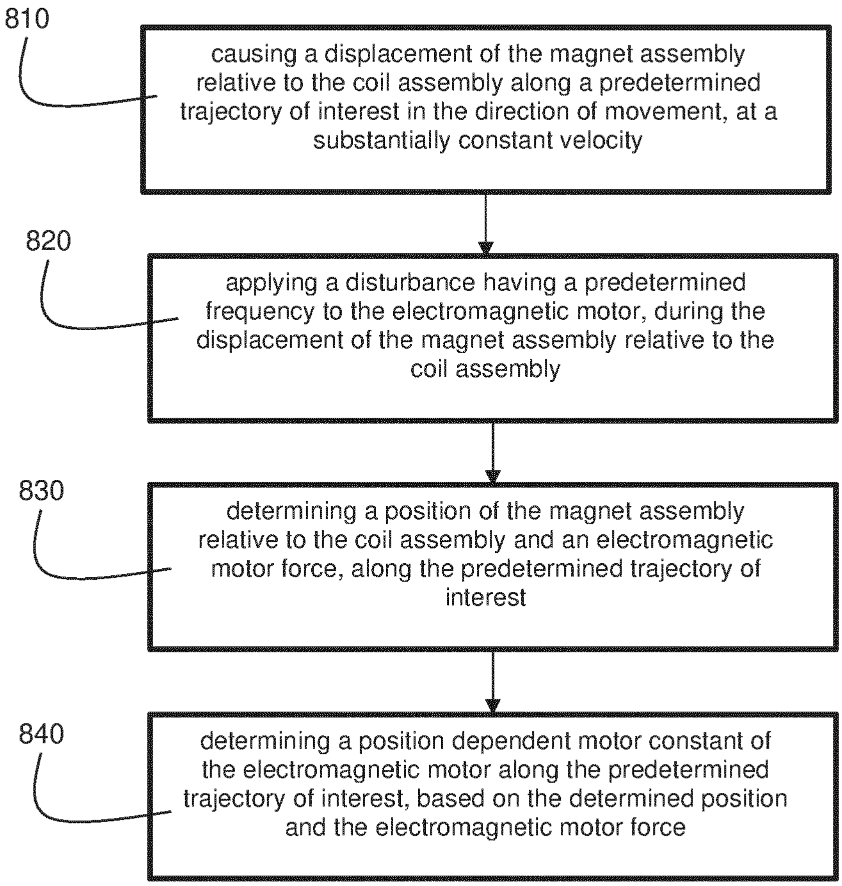
810
causing a displacement of the magnet assembly relative to the coil assembly along a predetermined trajectory of interest in the direction of movement, at a substantially constant velocity
820
applying a disturbance having a predetermined frequency to the electromagnetic motor, during the displacement of the magnet assembly relative to the coil assembly
830
determining a position of the magnet assembly relative to the coil assembly and an electromagnetic motor force, along the predetermined trajectory of interest
840
determining a position dependent motor constant of the electromagnetic motor along the predetermined trajectory of interest, based on the determined position and the electromagnetic motor force

Fig. 8

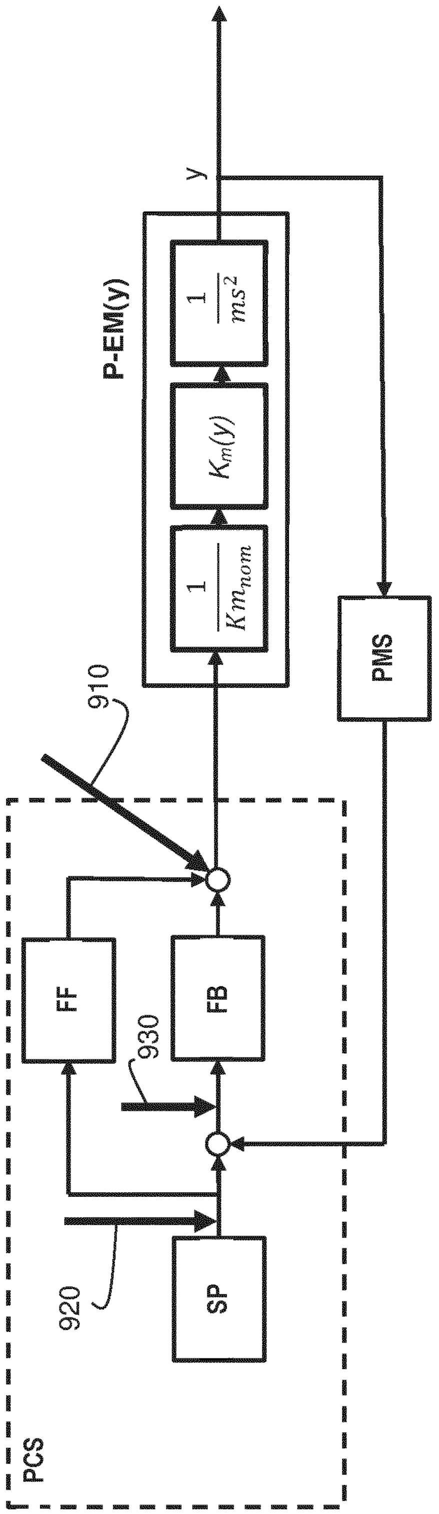


Fig. 9

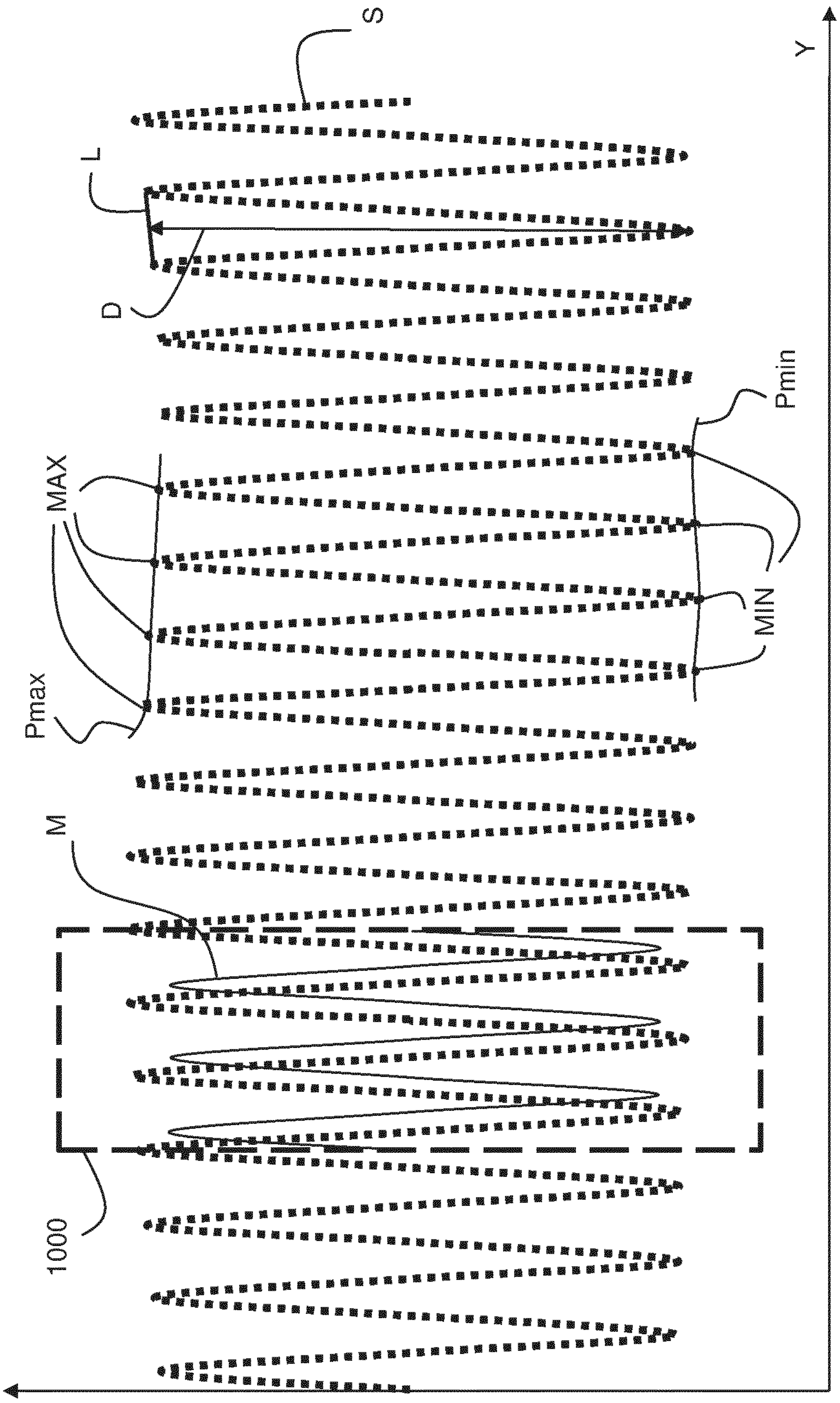


Fig. 10

# INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2024/055645

**A. CLASSIFICATION OF SUBJECT MATTER**
INV. H02P6/00 H02P23/14 H02P25/06
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)
H02P H02K G03F

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, WPI Data

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | JP 2009 159741 A (YASKAWA ELECTRIC CORP) 16 July 2009 (2009-07-16) | 1,2,4,6, 9,10,14, 15 |
| Y | paragraphs [0010] - [0013], [0014]; figures 1,2<br>paragraphs [0018], [0019]; figure 3 | 3,8, 11-13 |
| Y | US 2019/089283 A1 (HAMM CARSTEN [DE] ET AL) 21 March 2019 (2019-03-21)<br>paragraph [0020] | 3,8 |
| Y | US 2022/200385 A1 (KIMMAN MAARTEN HARTGER [NL] ET AL) 23 June 2022 (2022-06-23)<br>paragraph [0002]; figure 2 | 11-13 |

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 23 May 2024 | 04/06/2024 |

| Name and mailing address of the ISA/ | Authorized officer |
|---|---|
| European Patent Office, P.B. 5818 Patentlaan 2<br>NL - 2280 HV Rijswijk<br>Tel. (+31-70) 340-2040,<br>Fax: (+31-70) 340-3016 | Schürle, Patrick |

# INTERNATIONAL SEARCH REPORT

**Information on patent family members**

International application No

PCT/EP2024/055645

| Patent document cited in search report | | Publication date | Patent family member(s) | | | Publication date |
|---|---|---|---|---|---|---|
| JP 2009159741 | A | 16-07-2009 | NONE | | | |
| US 2019089283 | A1 | 21-03-2019 | CA | 3017305 | A1 | 15-03-2019 |
| | | | CN | 109510406 | A | 22-03-2019 |
| | | | EP | 3457558 | A1 | 20-03-2019 |
| | | | ES | 2901490 | T3 | 22-03-2022 |
| | | | US | 2019089283 | A1 | 21-03-2019 |
| US 2022200385 | A1 | 23-06-2022 | CN | 108604853 | A | 28-09-2018 |
| | | | JP | 6697564 | B2 | 20-05-2020 |
| | | | JP | 2019508001 | A | 22-03-2019 |
| | | | US | 2022200385 | A1 | 23-06-2022 |
| | | | WO | 2017137181 | A1 | 17-08-2017 |