

POSITIONING DEVICE, METHOD OF APPLYING A PLURALITY OF
FORCES, METHOD OF POSITIONING, LITHOGRAPHIC APPARATUS
AND DEVICE MANUFACTURING METHOD

5 **[0001]** CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority of EP application 14185498.4, which was filed on 19 September 2014 and which is incorporated herein in its entirety by reference.

FIELD

10 **[0002]** The present invention relates to a positioning device, a method of applying a plurality of forces, a method of positioning, a lithographic apparatus, and a device manufacturing method.

BACKGROUND

15 **[0003]** A lithographic apparatus is a machine that applies a desired pattern onto a substrate, usually onto a target portion of the substrate. A lithographic apparatus can be used, for example, in the manufacture of integrated circuits (ICs).

[0004] In a lithographic apparatus many physical components are present on which an external force is applied. The external force may vary in magnitude and/or the position at
20 which it acts on the physical component may vary. The magnitude and/or position may be unknown. The application of such an external force can cause difficulties in controlling the position of the physical component. One way of controlling the physical component is by way of feedback. For example, the position of the physical component is measured and positioning forces are applied to the physical component. The positioning forces reduce the
25 difference between a desired position of the physical component and the measured position of the physical component. Forces are applied to the physical component to counteract the external force as well as the force on the physical component due to gravity. Thus, force equilibrium and moment equilibrium of the physical component is achieved.

[0005] It is desirable to improve control of the position of a target portion on a
30 physical component. In particular it is desirable to improve control of application of a plurality of forces to a physical component in response to an external force being applied to the physical component.

SUMMARY

[0006] According to an aspect of the invention, there is provided a method of applying a plurality of forces to a physical component in response to an external force being applied to the physical component, wherein: each respective one of the plurality of forces is being applied at a respective one of a plurality of predetermined different locations at the physical component; the plurality of forces are higher in number than a minimum number needed to counteract a displacement of the physical component as a result of the external force and to counteract a change of orientation of the physical component as a result of the external force; the method comprises applying the plurality of forces by: (i) controlling the plurality of forces so as to counteract the external force and achieve force equilibrium and moment equilibrium of the physical component; and (ii) controlling the plurality of forces so as to control an elastic deformation of the physical component at a region-of-interest at the physical component, the plurality of forces being controlled dependent on at least one of: a further location on the physical component at which the external force is being applied to the physical component, a magnitude of the external force, a direction of the external force and an estimated elastic deformation of the physical component at the region-of-interest, the elastic deformation occurring as a result of the plurality of forces and of the external force being applied.

[0007] According to an aspect of the invention, there is provided a method of positioning a target portion on a physical component, the method comprising: applying a respective one of a plurality of forces at a respective one of a plurality of predetermined different locations at the physical component so as to counteract an external force being applied to the physical component and achieve force equilibrium and moment equilibrium on the physical component; determining a measured position of the physical component using a sensor component on the physical component; applying at least one positioning force to the physical component at at least one of the plurality of predetermined different locations at the physical component, the at least one positioning force being controlled according to a difference between the measured position and a desired position of the physical component as measured using the sensor component; determining an estimated magnitude of the external force applied to the physical component from the measured position and the plurality of forces and/or any positioning forces for displacing or re-orientating the physical component applied at the plurality of predetermined different locations at the physical component; determining an estimated position on the physical component at which the external force is applied; and using the estimated magnitude and estimated position to: (i) to control an elastic

deformation of the physical component at a region-of-interest at the physical component, the plurality of forces being controlled dependent on at least one of: a further location on the physical component at which the external force is being applied to the physical component, a magnitude of the external force, a direction of the external force and an estimated elastic deformation of the physical component at the region-of-interest, the elastic deformation occurring as a result of the plurality of forces and of the external force being applied; and/or (ii) control the at least one positioning force to compensate for a change in relative position between the target portion and the sensor component due to any remaining elastic deformation of the physical component, the remaining elastic deformation occurring as a result of the plurality of forces and of the external force being applied.

[0008] According to an aspect of the invention, there is provided a positioning device comprising: a physical component; a plurality of predetermined different locations at which a respective one of a plurality of forces may be applied to the physical component, the plurality of predetermined different locations being higher in number than a minimum number needed to enable counteraction against a displacement of the physical component as a result of an external force being applied to the physical component and counteraction against a change of orientation of the physical component as a result of the external force; and a controller adapted to: control the plurality of forces so as to counteract the external force and achieve force equilibrium and moment equilibrium on the physical component; and control the plurality of forces so as to control an elastic deformation of the physical component at a region-of-interest of the physical component, the plurality of forces being controlled dependent on at least one of: a further location on the physical component at which the external force is being applied to the physical component, a magnitude of the external force, a direction of the external force and an estimated elastic deformation of the physical component at the region-of-interest, the elastic deformation occurring as a result of the plurality of forces and of the external force.

[0009] According to an aspect of the invention, there is provided a positioning device comprising: a physical component with a target portion and a sensor component; a plurality of predetermined different locations at the physical component at which a respective one of a plurality of forces may be applied to the physical component, the plurality of predetermined different locations being higher in number than a minimum number needed to enable counteraction against a displacement of the physical component as a result of an external force being applied to the physical component and counteraction against a change of orientation of the physical component as a result of the external force; and a controller

adapted to: receive a signal indicative of a desired position of the physical component and a signal indicative of a measured position of the physical component generated using the sensor component; and control the application of at least one positioning force to at least one of the predetermined different locations to displace or re-orientate the physical component

5 according to a difference between the signal indicative of a measured position and the signal indicative of a desired position of the physical component; and determine an estimated magnitude of the external force applied to the physical component from the signal indicative of the measured position and total forces applied at each of the plurality of predetermined different locations at the physical component; determine an estimated position on the physical

10 component at which the external force is applied; and use the estimated magnitude and estimated position to: (i) to control an elastic deformation of the physical component at a region-of-interest at the physical component, the plurality of forces being controlled dependent on at least one of: a further location on the physical component at which the external force is being applied to the physical component, a magnitude of the external force, a

15 direction of the external force and an estimated elastic deformation of the physical component at the region-of-interest, the elastic deformation occurring as a result of the plurality of forces and of the external force being applied; and/or (ii) control the at least one positioning force to compensate for a change in relative position between the target portion and the sensor component due to any remaining elastic deformation of the physical

20 component, the remaining elastic deformation occurring as a result of the plurality of forces and of the external force being applied.

Brief Description of the Drawings

[0010] Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings in which corresponding reference

25 symbols indicate corresponding parts, and in which:

[0011] Figure 1 depicts a lithographic apparatus according to an embodiment of the invention;

[0012] Figure 2 depicts schematically a substrate table under a projection system of a lithographic apparatus;

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[0013] Figure 3 is a control system for the control of a substrate table;

[0014] Figure 4 shows deviations in z position versus x and y position of a substrate table for a prior art control system;

[0015] Figure 5 shows deviations in z position versus x and y position of a substrate table controlled using the method of the present invention;

[0016] Figure 6 is an example of the position dependent gain applied in the present invention;

5 [0017] Figure 7 is a Bode magnitude diagram showing servo error for the methods illustrated in Figures 4 and 5;

[0018] Figure 8 is a Bode magnitude diagram showing exposure error for the two methods illustrated in Figures 4 and 5;

10 [0019] Figure 9 shows deviations in z position versus x and y position of a substrate table for a prior art control system;

[0020] Figure 10 shows deviations in z position versus x and y positions for a substrate table controlled using the method of the present invention;

[0021] Figure 11 illustrates deviations in z position versus x and y position for a substrate table controlled using the method of the present invention followed by correction of the target portion position by displacement of the substrate table in the z direction;

15 [0022] Figure 12 is a Bode magnitude diagram showing servo error for the methods illustrated in Figures 9 to 11;

[0023] Figure 13 is a Bode magnitude diagram showing exposure error for the methods illustrated in Figures 9 to 11;

20 [0024] Figure 14 illustrates the exposure error in the time domain in a simulation for the methods of Figures 9, 10 and 11; and

[0025] Figure 15 shows the results of Figure 14 plotted as the average exposure error at different frequencies.

25 Detailed Description

[0026] Figure 1 schematically depicts a lithographic apparatus 10 according to an embodiment of the invention. The lithographic apparatus 10 includes an illumination system (illuminator) IL configured to condition a beam of radiation B (e.g. UV radiation or any other suitable radiation), a mask support structure (e.g. a mask table) MT constructed to support a patterning device (e.g. a mask) MA and connected to a first positioning device PM configured to accurately position the patterning device MA in accordance with certain parameters. The lithographic apparatus 10 also includes a substrate table (e.g. a wafer table) WT constructed to hold a substrate (e.g. a resist coated wafer) W and connected to a second positioning device PW configured to accurately position the substrate W in accordance with

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certain parameters. The lithographic apparatus 10 further includes a projection system (e.g. a refractive projection lens system) PS configured to project a pattern imparted to the beam of radiation B by patterning device MA onto a target portion C (e.g. including one or more dies) of the substrate W.

5 [0027] The illumination system IL may include various types of optical components, such as refractive, reflective, magnetic, electromagnetic, electrostatic or other types of optical components, or any combination thereof, for directing, shaping, or controlling radiation.

[0028] The mask support structure MT supports, i.e. bears the weight of, the patterning device MA. The mask support structure MT holds the patterning device MA in a
10 manner that depends on the orientation of the patterning device MA, the design of the lithographic apparatus 10, and other conditions, such as for example whether or not the patterning device MA is held in a vacuum environment. The mask support structure MT can use mechanical, vacuum, electrostatic or other clamping techniques to hold the patterning device. The mask support structure MT may be a frame or a table, for example, which may
15 be fixed or movable as required. The mask support structure MT may ensure that the patterning device MA is at a desired position, for example with respect to the projection system PS. Any use of the terms “reticle” or “mask” herein may be considered synonymous with the more general term “patterning device.”

[0029] The term “patterning device” used herein should be broadly interpreted as
20 referring to any device that can be used to impart the beam of radiation B with a pattern in its cross-section so as to create a pattern in a target portion C of the substrate W. It should be noted that the pattern imparted to the beam of radiation B may not exactly correspond to the desired pattern in the target portion C of the substrate W, for example if the pattern includes phase-shifting features or so called assist features. Generally, the pattern imparted to the
25 beam of radiation B will correspond to a particular functional layer in a device being created in the target portion C, such as an integrated circuit.

[0030] The patterning device MA may be transmissive or reflective. Examples of patterning devices include masks, programmable mirror arrays, and programmable LCD panels. Masks are well known in lithography, and include mask types such as binary,
30 alternating phase-shift, and attenuated phase-shift, as well as various hybrid mask types. An example of a programmable mirror array employs a matrix arrangement of small mirrors, each of which can be individually tilted so as to reflect an incoming radiation beam in different directions. The tilted mirrors impart a pattern in a radiation beam which is reflected by the mirror matrix.

[0031] The term “projection system” used herein should be broadly interpreted as encompassing any type of projection system PS, including refractive, reflective, catadioptric, magnetic, electromagnetic and electrostatic optical systems, or any combination thereof, as appropriate for the exposure radiation being used, 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”.

[0032] The illumination system IL may include an adjuster AD configured to adjust the angular intensity distribution of the radiation beam. Generally, at least the outer and/or inner radial extent (commonly referred to as σ -outer and σ -inner, respectively) of the intensity distribution in a pupil plane of the illumination system IL can be adjusted. In addition, the illumination system IL may include various other components, such as an integrator IN and a condenser CN. The illumination system IL may be used to condition the beam of radiation B, to have a desired uniformity and intensity distribution in its cross section. The illumination system IL may or may not be considered to form part of the lithographic apparatus 10. For example, the illumination system IL may be an integral part of the lithographic apparatus 10 or may be a separate entity from the lithographic apparatus 10. In the latter case, the lithographic apparatus 10 may be configured to allow the illumination system IL to be mounted thereon. Optionally, the illumination system IL is detachable and may be separately provided (for example, by the lithographic apparatus manufacturer or another supplier).

[0033] As here depicted, the lithographic apparatus 10 is of a transmissive type (e.g. employing a transmissive mask). Alternatively, the lithographic apparatus 10 may be of a reflective type (e.g. employing a programmable mirror array of a type as referred to above, or employing a reflective mask).

[0034] The lithographic apparatus 10 may be of a type having two (dual stage) or more substrate tables WT (and/or two or more mask support structures MT, e.g. mask tables). In such a “multiple stage” lithographic apparatus 10 the additional substrate tables WT and/or mask support structures MT may be used in parallel, or preparatory steps may be carried out on one or more substrate tables WT and/or mask support structures MT while one or more other substrate tables WT and/or mask support structures MT are being used for exposure.

[0035] The patterning device MA is held on the mask support structure MT. The beam of radiation B is incident on the patterning device MA. The beam of radiation B is patterned by the patterning device MA. After being reflected from the patterning device MA, the beam of radiation B passes through the projection system PS. The projection system PS

focuses the beam of radiation B onto a target portion C of the substrate W. The first positioner PM and a first position sensor (e.g., an interferometric device, linear encoder or capacitive sensor) can be used to accurately position the patterning device MA with respect to the path of the beam of radiation B. The first position sensor is not explicitly shown in Figure 1. With the aid of the second positioner PW and a second position sensor PS2 (e.g., an interferometric device, linear encoder or capacitive sensor), the substrate table WT can be moved accurately, e.g., so as to position different target portions C in the path of the beam of radiation B.

[0036] The patterning device MA may be aligned using mask alignment marks M_1 , M_2 . The substrate W may be aligned using substrate alignment marks P_1 , P_2 . Although the substrate alignment marks P_1 , P_2 as illustrated occupy dedicated target portions C, they may be located between target portions C (these are known as scribe-lane alignment marks). Similarly, in situations in which more than one die is provided on the patterning device MA, the mask alignment marks M_1 , M_2 may be located between the dies.

[0037] Immersion techniques can be used to increase the numerical aperture NA of the projection system PS. As depicted in Figure 1, in an embodiment the lithographic apparatus 10 is of a type wherein at least a portion of the substrate W 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. An immersion liquid may also be applied to other spaces in the lithographic apparatus 10, for example, between the patterning device MA and the projection system PS. The term “immersion” as used herein does not mean that a structure, such as the substrate W, must be submerged in liquid, but rather only means that a liquid is located between the projection system PS and the substrate W during exposure.

[0038] Referring to Figure 1, the illuminator IL receives a beam of radiation B from a source module SO. The source module SO and the lithographic apparatus 10 may be separate entities, for example when the source module SO is an excimer laser. In such cases, the source module SO is not considered to form part of the lithographic apparatus 10 and radiation is passed from the source module SO to the illumination system IL with the aid of a beam delivery system BD. In an embodiment the beam delivery system BD includes, for example, suitable directing mirrors and/or a beam expander. In other cases the source module SO may be an integral part of the lithographic apparatus 100, for example when the source module SO is a mercury lamp. The source module SO and the illumination system IL, together with the beam delivery system BD if required, may be referred to as a radiation system.

[0039] Arrangements for providing liquid between a final element of the projection system PS and the substrate W can be classed into three general categories. These are the bath type arrangement, the so-called localized immersion system and the all-wet immersion system. In a bath type arrangement substantially the whole of the substrate W and optionally part of the substrate table WT is submersed in a bath of liquid.

[0040] As depicted in Figure 1 the liquid supply system is provided with a liquid confinement structure IH which extends along at least a part of a boundary of the space between the final element of the projection system PS and the substrate W, substrate table WT or both.

[0041] There are many physical components in a lithographic apparatus which have an external force F_e applied on them. The position at which the external force F_e is applied to the physical component (known as a further location below) and/or the magnitude of the external force may be unknown and/or vary with time. The presence of an external force F_e being applied to a moveable physical component can cause difficulties in correctly positioning a target portion of the physical component.

[0042] The present invention will be hereinafter described with reference to a substrate table WT being the physical component to which the external force F_e is applied. In the example the external force is a force applied between a further physical component and the substrate table WT. Hereinafter the further physical component is the liquid confinement structure IH. However, the external force F_e may be applied in a different way and/or by a different further physical component. Equally the substrate table WT may not be a table for supporting a substrate W. The table may for example, be a table supporting measurement instruments, for example a measurement table. In one embodiment the physical component is a mask table MT.

[0043] Figure 2 illustrates schematically a detail of the lithographic apparatus 10. The substrate table WT is positioned under the projection system PS. Immersion liquid is confined to a space between a final element of the projection system PS and the substrate W on the substrate table WT or the top surface of the substrate table WT. The liquid is confined by the liquid confinement structure IH. An external force F_e is applied to the top surface of the substrate table WT by the liquid confinement structure IH.

[0044] The substrate table WT is moved under the projection system PS so that a target portion TP is positioned under the projection system PS, for example aligned with the optical axis O. The target portion TP may be a die of a substrate W mounted on the substrate

table WT or may be a sensor, such as a through image sensor (TIS) mounted on the substrate table WT.

[0045] A sensor component 50 is provided on the substrate table WT. The sensor component 50 is used to measure the position of the substrate table WT relative to a known fixed location of the lithographic apparatus, such as a reference frame RF. In the embodiment illustrated in Figure 2, the sensor component 50 comprises an emitter of the sensor and a detector of the sensor. The emitter of the sensor is for emitting a measurement radiation beam 55. The detector of the sensor is for detecting the reflected and/or refracted radiation beam 55. The radiation beam 55 is emitted by the emitter of the sensor component 50 towards a sensor target, such as a grating G, mounted in known position relative to the reference frame RF. The measurement radiation beam 55 is reflected and/or refracted by the grating G back to the detector of the sensor component 50. On the basis of the received measurement radiation beam 55, the position of the substrate table WT relative to the reference frame RF may be calculated. In order to know the position of the substrate table WT in three dimensions relative to the reference frame RF, at least three sensor components 50 are mounted on the substrate table WT. Only one sensor component 50 is illustrated in Figure 2 for clarity.

[0046] In an alternative embodiment, the sensor component 50 on the substrate table WT may comprise a sensor target, for example a grating G. In that case the emitter of the sensor and detector of the sensor are mounted in a known position relative to the reference frame RF.

[0047] The substrate table WT is positionable in 6 degrees of freedom. In the present embodiment, the external force F_e is only applied in the z direction (the direction of the optical axis). Therefore description of the present invention will be limited to consideration of actuation in the z translational direction and Rx and Ry rotational directions. However, the same principles can be applied to any number of degrees of freedom, either more than 3 or less than 3. In practice, the method is applied to a system in which the physical component such as a substrate table WT is actuated in 6 degrees of freedom.

[0048] Actuators are provided for applying a plurality of forces to the substrate table WT. In the embodiment of Figure 2 forces in the z direction can be applied to the substrate table WT at a plurality of predetermined different locations 60, 70, 80, 90. The forces are applied under the control of a controller 100. The forces applied at the plurality of predetermined different locations 60, 70, 80, 90 are for holding the substrate table WT in steady state, displacement of the substrate table WT and changing the orientation of the

substrate table WT. The actuators may be Lorenz actuators or reluctance actuators. The predetermined different locations 60, 70, 80, 90 may be the position of coils of the actuators or alternatively the position of the magnets of the actuators.

[0049] The forces applied at the plurality of predetermined different locations 60, 70, 80, 90 are made up of a plurality of forces F_1, F_2, F_3, F_4 for counteracting the external force F_e and achieving force equilibrium and moment equilibrium of the substrate table WT (i.e. steady state). The forces applied to the plurality of predetermined different locations 60, 70, 80, 90 also include any positioning force for displacing the substrate table WT and/or changing the orientation of the substrate table WT. The forces applied to the plurality of predetermined different locations 60, 70, 80, 90 may additionally include forces for counteracting forces due to gravity acting on the substrate table WT.

[0050] A respective one of the plurality of forces F_1, F_2, F_3, F_4 is applied at a respective one of the plurality of predetermined different locations 60, 70, 80, 90.

[0051] For the three degrees of freedom (z, R_x, R_y) considered here, it would be sufficient for three predetermined different locations to exist in order to counteract the external force and achieve force equilibrium and moment equilibrium. Those three predetermined different locations could also be used to position the substrate table WT in the three degrees of freedom (z, R_x, R_y). However, in the present invention, the substrate table WT is over actuated. In other words the substrate table WT is over determined (over actuated) in that the plurality of predetermined different locations 60, 70, 80, 90 at which forces may be applied to the substrate table WT is higher in number than a minimum number needed to counteract a displacement of the substrate table WT as a result of the external force F_e and to counteract a change in orientation of the substrate table WT as a result of the external force F_e .

[0052] Over actuation is advantageous from a point of view of servo control purposes. However, the over actuation can lead to undesirable elastic deformations of the substrate table WT. Such deformations are mostly torsional deformations in the case of the use of four out-of-plane actuators as illustrated in Figure 2. However, in theory different types of elastic deformation could be induced due to over-actuation. For example, if a fifth predetermined different location were provided on the substrate table WT, for example at a central location, in plan, a differently shaped deformation might arise, such as a bowing deformation.

[0053] Elastic deformations resulting from over actuation are particularly problematic for the z focus performance of the lithographic apparatus 10 and may also have a significant

effect on the x/y overlay performance of the lithographic apparatus. The present invention addresses the possibility of elastic deformations resulting from over actuation of the substrate table WT.

[0054] In a simple control system the controller 100 controls the forces applied to the plurality of predetermined different locations 60, 70, 80, 90 using feedback. Namely if the external force F_e moves the substrate table WT from a desired position, this is sensed by the measured position determined using the sensor component 50. In response the controller 100 changes the positioning forces applied to the plurality of predetermined different locations 60, 70, 80, 90 according to the difference between the desired position and the measured position. Such simple control assumes an infinitely stiff substrate table. Therefore, the control neglects elastic deformation of the substrate table WT. Elastic deformation may result from the application of the external force F_e and the plurality of forces counteracting the external force F_e . Ignoring any elastic deformation of the substrate table WT introduces errors in the position of target portion TP in the following way. The position of the target portion TP is not measured directly, but only with reference to the sensor component 50. Any elastic deformation of the substrate table WT results in a change in relative position of the target portion TP to the sensor component 50. This change in relative position results in an error introduced when calculating the position of the target portion TP from measurements of the position using the sensor component 50 if the possibility of elastic deformation is ignored.

[0055] First the origin of the elastic deformation is explained and then the way in which the present invention addresses this phenomenon will be described.

[0056] Take a system in which the number of predetermined different locations is the same as that needed to counteract a displacement of the substrate table WT and a change in orientation of the substrate table WT as a result of the external force (3 in the case of the Figure 2 scenario). In such a system, there is only one way in which forces can be applied to the plurality of predetermined different locations such as to achieve force equilibrium and moment equilibrium of the substrate table WT.

[0057] In the case where there is a further predetermined different location at which a force can be applied such that the system becomes over actuated, there are an infinite number of ways in which the plurality of forces can be applied to counteract the external force F_e . There must be some rule as to how the plurality of forces for counteraction are distributed between the plurality of predetermined different locations 60, 70, 80, 90 in order to achieve force equilibrium and moment equilibrium of the substrate table. In the prior art a fixed way

of distributing the forces applied by the actuators has been used. As will be described below, in the prior art the forces are calculated based on a gain balancing (GB) matrix which is invariable. The gain balancing (GB) matrix may be determined experimentally in a calibration process. Alternatively, the gain balancing (GB) matrix may be theoretically
5 determined for example based on the positions of the predetermined different locations 60, 70, 80, 90 relative to the centre of gravity of the substrate table WT.

[0058] The present inventors have realized that using the fixed gain balancing (GB) matrix results in an undesirable elastic deformation of the substrate table WT. The inventors have determined that the elastic deformation can be controlled by varying how the force to
10 counteract the external force F_e is distributed between the plurality of forces. The distribution is made according to one or more of: the further location on the physical component at which the external force F_e is being applied to the substrate table WT, a magnitude of the external force F_e , or a direction of the external force F_e , or based on an estimated elastic deformation of the substrate table WT. In this way it is possible to reduce
15 the elastic deformation of the substrate table WT compared to the case where only the fixed gain balancing (GB) matrix is used to distribute the force counteracting the external force. In an embodiment the elastic deformation is minimized.

[0059] In a further refinement of the system, any remaining elastic deformation of the substrate table WT is estimated. Based on this estimate, positioning forces are applied to the
20 plurality of predetermined different locations 60, 70, 80, 90 to account for the change in position of the target portion TP relative to the sensor component 50. That is, the difference in z position between the target portion TP and the sensor component 50 is estimated and the whole substrate table WT is moved in the z direction by that amount to compensate.

[0060] Figure 3 illustrates the control system applied by the controller 100. The
25 external force F_e is shown acting on the substrate table WT. The control system above the dashed horizontal line is that used in prior art systems. Here K_{fb} is a feedback controller which receives position signals of the point-of-control y(POC) measured using the sensor component 50. The signal r is indicative of the desired position (the set point) of the substrate table WT (as would be measured using the sensor component 50).

[0061] The servo error e is defined as $r-y$, namely the difference between the desired
30 position and the measured position. The feedback controller K_{fb} uses the signal indicative of the servo error e to apply forces u to the substrate table WT. The gain balancing GB matrix is designed to decouple the system in its rigid-body motion degrees of freedom. The gain balancing (GB) matrix transforms the forces u in the three degrees of freedom as represented

by (F_z , F_{Rx} and F_{Ry}) into the forces F_1 , F_2 , F_3 , F_4 to be applied at the four predetermined different locations 60, 70, 80, 90. This results in actuator signals u_0 which are the forces (in the z direction) applied at the plurality of predetermined different locations 60, 70, 80, 90 to the substrate table WT.

5 [0062] Output from the physical system are sensor signals y_0 generated using the sensor component 50 and indicative of the position of the substrate table WT. These signals are provided to the measurement system MS. The output of the measurement system is the position of the point-of-control ($y(POC)$).

10 [0063] The truly relevant position to be controlled, namely the position of target portion TP, has a position represented by $z(POI)$, namely the position of the point of interest.

[0064] The below equation represents how the out-of-plane part of the gain balancing (GB) matrix is designed to decouple the system in its rigid-body motion degrees of freedom.

$$GB = \begin{bmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\ \frac{1}{4} & -\frac{1}{4} & \frac{1}{4} \\ \frac{1}{4} & \frac{1}{4} & -\frac{1}{4} \\ \frac{1}{4} & -\frac{1}{4} & -\frac{1}{4} \end{bmatrix}, \quad \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} = GB \begin{bmatrix} F_z \\ F_{Rx} \\ F_{Ry} \end{bmatrix} \quad (1)$$

15 [0065] The gain balancing (GB) matrix is designed to translate the control signals from the feedback controller Kf_B (F_z , F_{Rx} , F_{Ry}) expressed in logical axes to actuator forces F_1 , F_2 , F_3 , F_4 such that the control system is decoupled into logical axes.

20 [0066] The matrix (GB) in equation 1 above is the idealized situation where the four predetermined different locations 60, 70, 80, 90 are distributed symmetrically around the center of gravity of the substrate table WT and assuming the density of the substrate table WT is constant. The gain balancing (GB) matrix may however be different according to the actual geometry of the substrate table WT or for a different reason. The gain balancing matrix (GB) may be calculated using a calibration run and/or from theory. The gain balancing matrix (GB) in equation 1 distributes the force to compensate for the external force F_e equally between the four actuators. However, this is not necessarily the case and the force
25 can be distributed in any way between the actuators (though it is usually distributed based upon the locations of the actuators relative to the center of gravity of the substrate table WT). Once the gain balancing (GB) matrix has been fixed, it is not changed. Therefore, the

difficulties described below with regard to the gain balancing (GB) matrix of equation 1 apply whatever form the gain balancing (GB) matrix takes.

[0067] The problem with the gain balancing matrix (GB) is exemplified in Table 1 below. Here the actuator forces F_1 , F_2 , F_3 , F_4 acting on the substrate table WT are represented as well as the external force F_e applied by the liquid confinement structure IH. In this example it is assumed that the external force F_e is applied above the first predetermined different location 60. The moments around the x axis and y axis are balanced so that the substrate table WT is in force equilibrium and moment equilibrium. The forces applied to achieve moment equilibrium are represented as M_x and M_y in Table 1.

	Location 60, F_1	Location 70, F_2	Location 80, F_3	Location 90, F_4
$\sum F_z$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$
$\sum M_x$	$\frac{1}{4}$	$-\frac{1}{4}$	$\frac{1}{4}$	$-\frac{1}{4}$
$\sum M_y$	$\frac{1}{4}$	$\frac{1}{4}$	$-\frac{1}{4}$	$\frac{1}{4}$
F_e	-1	0	0	-0
Total Force	$-\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$-\frac{1}{4}$

[0068] The actuator forces in Table 1 are calculated using the formula in equation 1.

In this case, actuator 1 provides 75% of the counteraction to the external force F_e and the remaining actuators provide 25% of the force. This results in the total force applied at each of the predetermined different locations illustrated in the final row of Table 1. The result is that a torsion moment remains. This is depicted in Figure 4 which shows elastic deformation of the substrate table WT due to the external force F_e and plurality of forces F_1 , F_2 , F_3 and F_4 applied at the predetermined different locations 60, 70, 80, 90. The elastic deformation occurs as a result of the plurality of forces and of the external force F_e being applied to the substrate table WT.

[0069] In the present invention, the controller 100 controls the plurality of forces F_1 , F_2 , F_3 , F_4 applied to the plurality of predetermined different locations 60, 70, 80, 90 so as to counteract the external force F_e and achieve force equilibrium and moment equilibrium of the substrate table WT (as is the case in equation 1 and Table 1). The controller 100 also controls the plurality of forces so as to control an elastic deformation at a region-of-interest at

the substrate table WT. This is achieved by controlling the plurality of forces depending on at least one of: the further location on the substrate table WT at which the external force F_e is being applied, the magnitude of the external force F_e , a direction of the external force F_e and an estimated elastic deformation of the substrate table WT at the region-of-interest.

5 [0070] If, in the above described case of the external force F_e being applied above one of the predetermined different locations 60, 70, 80, 90, all of the reaction force is applied through the actuator below the further location at which the external force F_e is applied, then zero deformation of the substrate table WT would occur. This is illustrated in Figure 5.

Varying how the reaction force to the external force F_e is distributed in the plurality of forces
10 F_1, F_2, F_3, F_4 in order to control elastic deformation of the substrate table WT is the principle of the invention. The way in which the reaction force is distributed in the plurality of forces F_1, F_2, F_3, F_4 may be to minimize the elastic deformation (it would not always be possible to avoid any elastic deformation at all). However, there may be cases where it is not possible or desirable to minimize elastic deformation as much as possible. In that case a reduction in the
15 amount of deformation may be achieved compared to the case where the reaction force to the external force is distributed in a fixed way.

[0071] In the case illustrated in Figure 2 with four predetermined different locations, use of a fixed gain balancing (GB) matrix results in a torsional deformation of the substrate table WT. The invention will be described below in relation to such a system. However, the
20 same principles can be used for differently shaped elastic deformations. Different shapes might be the result of different relative positioning of the predetermined different locations and/or a different number of predetermined different locations and/or a plurality of external forces being applied to the substrate table WT.

[0072] An implementation of the invention will be described in detail below and
25 relate to the torsion free distribution TFD part of the control system illustrated in Figure 3.

[0073] In the torsion free distribution TFD scheme, a position dependent gain $f_T(x, y)$ is applied to the forces determined from the gain balancing (GB) matrix. The position dependent gain $f_T(x, y)$ determines the degree of torsion compensation as a function of the further location at which the external force is applied. An example of the position dependent
30 gain is shown in Figure 6.

[0074] In the torsion free distribution TFD scheme, an estimate $F_{e_{est}}$ of the magnitude of the external force F_e is multiplied by the position dependent gain $f_T(x, y)$ and by a torsion compensation TC matrix according to equation (2). The position dependent gain $f_T(x, y)$ is described as a function of the further location. The position dependent gain $f_T(x, y)$ may

additionally or alternatively be a function of the magnitude and/or direction of the external force F_e . The torsion compensation TC matrix is a static matrix which serves to manipulate the internal torsion degree of freedom. The torsion compensation TC matrix distributes the forces to compensate for the external force F_e over the four predetermined different locations 60, 70, 80, 90. The torsion compensation TC matrix is chosen such that the forces generated do not influence the translational or rotational motion degrees of freedom. The forces so calculated are subtracted from the output of the grain balancing (GB) matrix thereby to result in the actuator forces u_0 actually applied at the predetermined different locations 60, 70, 80, 90.

$$TC = \begin{bmatrix} \frac{1}{4} \\ \frac{1}{4} \\ -\frac{1}{4} \\ -\frac{1}{4} \\ \frac{1}{4} \\ \frac{1}{4} \end{bmatrix}, \quad \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} = TC \cdot f_T(x, y) \cdot Fe_{est} \quad (2)$$

[0075] In the case of the external force F_e being applied between the liquid confinement structure IH and the substrate table WT, the further location can be assumed as being the position of the target portion TP which is the portion of the substrate table WT directly under the liquid confinement structure IH. So a signal indicative of the measured position or desired position of the target portion TP, or sensor component 50 or substrate table WT can be used for the estimate of the further location. Knowledge of the further location can be used by the controller 100 in calculating the outputs of the torsion free distribution TFD scheme. Thereby the plurality of forces applied at the respective plurality of predetermined different locations 60, 70, 80, 90 can be controlled to control, optionally minimize, the elastic deformation of the substrate table WT.

[0076] An observation block Obs uses signals indicative of the measured position of the physical component y(POC) and the vector u_0 which is indicative the forces applied at the plurality of predetermined different locations 60, 70, 80, 90. The vector u_0 includes the plurality of forces which are applied to the substrate table WT to counteract the external force and achieve force equilibrium and moment equilibrium. The vector u_0 also includes any forces for counteracting gravity acting on the substrate table WT and any positioning forces for displacing or re-orientating the physical component. The observer block Obs includes a model to make an estimate Fe_{est} of the magnitude of the external force F_e using the vector u_0

and/or position $y(\text{POC})$. The model may be based on a theoretical model and/or on a model based on a calibration of the apparatus. The model uses the forces applied to the substrate table WT and the position of the substrate table WT. From a knowledge of the physical parameters of the substrate table WT the model ascertains an estimate of the component of the force applied to the substrate table WT responsible for reacting against the external force F_e and a further location at which the external force F_e acts on the substrate table WT. The force may alternatively be derived by the model from the output of the feedback controller K_{fb} and/or the position of the substrate table WT may alternatively be derived from the signals inputted into the measurement system MS or from the desired position r .

[0077] However, other ways of estimating the magnitude and/or further location of the external force F_e may be used. For example, in an embodiment an estimate $F_{e\text{est}}$ of the magnitude of the external force F_e may be determined from a position control signal used for positioning the liquid confinement structure IH and/or an observed position signal indicative of an observed position of the liquid confinement structure IH. In an embodiment the estimate $F_{e\text{est}}$ of the magnitude of the external force F_e may be made using signals of a pressure sensor 110 which measures a pressure of fluid in a space between the liquid confinement structure IH and the substrate table WT. The pressure of fluid between the liquid confinement structure IH and substrate table WT is indicative of the external force F_e applied between the liquid confinement structure IH and substrate table WT.

[0078] Simulations have been performed on the system with a static external force F_e acting directly above a predetermined different location 60, 70, 80, 90. The simulations show that without the torsion free distribution TDF scheme, an exposure error of 0.3 nm steady state occurs for a substrate table WT (as illustrated in Figure 4) using gain balancing (GB) matrix and no torsion free distribution TFD scheme compensation. This exposure error can be completely compensated for by using the torsion free distribution TFD scheme.

[0079] Figures 7 and 8 are Bode magnitude diagrams illustrating the effect of the torsion free distribution TFD scheme compared to the case where the torsion free distribution TFD scheme is not applied. The torsion free distribution TFD scheme has a negligible effect on the servo error by design, due to the fact that the torsion compensation TC matrix spans the null space of the rigid body motions: the torsion free distribution TFD scheme only manipulates internal deformations of the substrate table WT. Figure 7 shows similar behavior in servo error across the frequency range between the scheme not using the torsion free distribution TFD scheme and that using the torsion free distribution scheme. Figure 8 illustrates the exposure error for the two schemes showing that for a frequency of between

zero and about 200 Hz a large reduction in exposure error results when the torsion free distribution TFD scheme is used.

[0080] The above described torsion free distribution TFD scheme uses signals indicative of the further location at which the external force is applied and the magnitude of the external force F_e . However, the invention is not limited to use of those two signals. For example, the torsion free distribution TFD scheme could use an estimate of the elastic deformation of the substrate table WT at the region-of-interest to control the plurality of forces so as to control (e.g. reduce) the elastic deformation of the substrate table WT. The estimated elastic deformation could be the result of a model using the same inputs as described above. In an embodiment, the estimated elastic deformation could be based on signals from a deformation sensor 120 which are indicative of elastic deformation of the substrate table WT at the region-of-interest. The deformation sensor 120 could for example comprise one or more strain gages in the substrate table WT and/or one or more displacement sensors on the substrate table WT. Alternatively or additionally a deformation sensor could comprise a high speed camera and/or acoustic sensors. In an embodiment the estimated elastic deformation could be determined from a look-up table generated by a calibration run.

[0081] If the external force F_e is applied at a location other than directly on top of one of the predetermined different locations 60, 70, 80, 90, some elastic deformation will remain. Any remaining elastic deformation will lead to a change in the relative position of the target portion TP relative to the sensor component 50 and so a difference in the desired location and actual location of the target portion TP.

[0082] From a knowledge of the amount of any remaining elastic deformation, a set point deformation compensation SDC scheme as illustrated at the bottom of Figure 3 may be implemented. In the set point deformation compensation SDC scheme positioning forces are applied to the substrate table WT. The positioning forces reposition the target portion TP to compensate for the change in relative position between the target portion TP and the sensor component 50 due to the remaining elastic deformation of the substrate table WT.

[0083] In order to compensate for position errors of the target portion TP as a result of the remaining elastic deformation of the substrate table WT, the set point deformation compensation SDC scheme is applied. In this scheme, as illustrated in Figure 3, the output of the measurement system $y(\text{POC})$ is adjusted to compensate for the change in relative position between the target portion TP and the output of the measurement system as measured using sensor component 50.

[0084] In the scheme of Figure 3, the set point deformation compensation SDC scheme uses the estimate Fe_{est} of the magnitude of the external force Fe and the further location at which the external force is applied. That is, the position of the substrate table WT is changed in the z direction to compensate for the fact that there is a remaining elastic deformation of the substrate table WT. The control block uses a position dependent gain $f_z(x,y)$ which is similar to the position dependent gain $f_t(x,y)$ as illustrated in Figure 6. The position dependent gain $f_z(x,y)$ may be determined experimentally in a calibration run or theoretically.

[0085] Figures 9, 10 and 11 show how the scheme of Figure 3 operates. The external force Fe is applied at a location not directly above one of the predetermined locations 60, 70, 80, 90. Figure 9 illustrates the deformation of the substrate table WT for the case where neither the torsion free distribution TFD scheme or the set point deformation compensation SDC scheme is used. Figure 10 shows the reduction in deformation of the substrate table WT when the torsion free distribution TFD scheme is employed. As can be seen, there is remaining elastic deformation of the substrate table WT due to the plurality of forces acting on the substrate table WT and the external force. When the set point deformation compensation SDC scheme is used, the whole substrate table WT is moved upwards in the z direction. This is achieved by the controller 100 by applying positioning forces to the plurality of predetermined different locations 60, 70, 80, 90 such that the target portion TP (in the near left hand corner of the graph) is moved to the desired location (zero displacement in the z direction) as shown in Figures 9-11.

[0086] In an embodiment the set point deformation compensation SDC scheme additionally rotates (re-orientates) the substrate table WT to account for the shape assumed by the substrate table WT due to the remaining elastic deformation. The remaining elastic deformation may be calculated as illustrated in Figure 3 or may be measured, for example using the deformation sensor 120.

[0087] Figures 12-15 illustrate the improvement which can be achieved by using the torsion free distribution TFD scheme and set point deformation compensation SDC scheme of Figure 3. Figures 12 and 13 correspond to the Bode plots of Figures 7 and 8 and show a further improvement in the frequency range of zero to 200 Hz where the set point deformation compensation SDC scheme is used in addition to the torsion free distribution TFD scheme. Figures 14 and 15 show the improvement in the time domain by using a pink noise disturbance with a 200 Hz cut-off frequency. That is representative of an external force Fe applied by a liquid confinement structure IH. As seen most clearly in Figure 15 which

shows an average exposure error plotted against frequency, a large reduction in exposure error is achieved by using the torsion free distribution TFD scheme. A further reduction exposure error can be achieved by additionally implementing the set point deformation SDC compensation scheme.

5 **[0088]** The controller 100 may be a computer programmed with suitable software to implement the method or may be hardware configured to implement the method.

10 **[0089]** In order to shorten the exposure wavelength and, thus, reduce the minimum printable size, it has been proposed to use an extreme ultraviolet (EUV) source of radiation. EUV radiation is electromagnetic radiation having a wavelength within the range of 10-20 nm, for example within the range of 13-14 nm. It has further been proposed that EUV radiation with a wavelength of less than 10 nm could be used, for example within the range of 5-10 nm such as 6.7 nm or 6.8 nm. Such radiation is termed extreme ultraviolet radiation or soft x-ray radiation. Possible sources include, for example, laser-produced plasma sources, discharge plasma sources, or sources based on synchrotron radiation provided by an electron storage ring.

15 **[0090]** Although specific reference may be made in this text to the use of lithographic apparatus in the manufacture of ICs, it should be understood that the lithographic apparatus described herein may have other applications, such as 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. The skilled artisan will appreciate that, in the context of such alternative applications, any use of the terms “wafer” or “die” herein may be considered as synonymous with the more general terms “substrate” or “target portion”, respectively. The substrate referred to herein may be processed, before or after exposure, in for example a track (a tool that typically applies a layer of resist to a substrate and develops the exposed resist), a metrology tool and/or an inspection tool. Where applicable, the disclosure herein may be applied to such and other substrate processing tools. Further, the substrate may be processed more than once, for example in order to create a multi-layer IC, so that the term substrate used herein may also refer to a substrate that already contains multiple processed layers.

20 **[0091]** The terms “radiation” and “beam” used herein encompass all types of electromagnetic radiation, including ultraviolet (UV) radiation (e.g. having a wavelength of or about 365, 248, 193, 157 or 126 nm) and extreme ultra-violet (EUV) radiation (e.g. having a wavelength in the range of 5-20 nm), as well as particle beams, such as ion beams or electron beams.

[0092] 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
5 departing from the scope of the claims set out below.

CLAIMS

1. A method of applying a plurality of forces to a physical component in response to an external force being applied to the physical component, wherein:

- 5 – each respective one of the plurality of forces is being applied at a respective one of a plurality of predetermined different locations at the physical component;
- the plurality of forces are higher in number than a minimum number needed to counteract a displacement of the physical component as a result of the external force and to counteract a change of orientation of the physical component as a result of the external
- 10 force;

– the method comprises applying the plurality of forces by:

(i) controlling the plurality of forces so as to counteract the external force and achieve force equilibrium and moment equilibrium of the physical component; and

- (ii) controlling the plurality of forces so as to control an elastic deformation of the
- 15 physical component at a region-of-interest at the physical component, the plurality of forces being controlled dependent on at least one of: a further location on the physical component at which the external force is being applied to the physical component, a magnitude of the external force, a direction of the external force and an estimated elastic deformation of the physical component at the region-of-interest, the elastic deformation occurring as a result of
- 20 the plurality of forces and of the external force being applied.

2. The method of claim 1, further comprising:

determining a further location on the physical component at which the external force is being applied to the physical component.

25

3. The method of claim 2, wherein the further location is determined from a signal indicative of a measured position and/or a signal indicative of a desired position of the physical component.

30 4. The method of claim 2 or 3, further comprising:

using the further location in controlling the plurality of forces so as to reduce the elastic deformation of the physical component.

5. The method of any of claims 1-4, further comprising:
determining a magnitude of the external force; and
using the magnitude of the external force to control the plurality of forces so as to
counteract the external force and achieve force equilibrium and moment equilibrium of the
5 physical component.
6. The method of claim 5, wherein the magnitude of the external force is determined
from the measured position of the physical component and the plurality of forces and/or any
positioning forces for displacing or re-orientating the physical component applied at the
10 plurality of predetermined different locations.
7. The method of claim 5 or 6, wherein the external force is applied between the
physical component and a further physical component.
- 15 8. The method of claim 7, wherein the magnitude of the external force is determined
from a position control signal used for positioning the further physical component and/or an
observed position signal indicative of an observed position of the further physical component.
9. The method of claim 7 or 8, wherein the magnitude of the external force is determined
20 from signals from a pressure sensor configured to measure pressure in a space between the
physical component and the further physical component.
10. The method of any of claims 5-7, further comprising:
determining the measured position of the physical component using a sensor
25 component on the physical component; and
controlling at least one positioning force applied at at least one of the predetermined
different locations to displace or re-orientate the physical component according to a
difference between the measured position and the desired position of the physical component
as measured using the sensor component.
30
11. The method of claim 10, wherein the sensor component is a detector of a sensor or
sensor target.

12. A method of positioning a target portion comprising the method of claim 10 or 11, wherein the target portion is on the physical component and the method further comprises:

adjusting the at least one positioning force to reduce position errors of the target portion due to remaining elastic deformation of the physical component, the remaining elastic deformation occurring as a result of the plurality of forces and of the external force being applied.

13. The method of claim 12, wherein the remaining elastic deformation is determined on the basis of the plurality of forces and/or any positioning forces for displacing or re-orientating the physical component applied at the plurality of predetermined different locations and the desired position or measured position and the magnitude of the external force.

14. The method of claim 1, wherein controlling the plurality of forces so as to reduce an elastic deformation of the physical component comprises:

determining an estimated elastic deformation of the physical component at the region-of-interest; and

using the estimated elastic deformation in controlling the plurality of forces so as to reduce the elastic deformation of the physical component.

15. The method of claim 14, wherein determining the estimated elastic deformation comprises receiving deformation signals from a deformation sensor indicative of elastic deformation of the physical component at the region-of-interest.

16. The method of any of claims 1-4 or 14 or 15, further comprising:

determining a measured position of the physical component using a sensor component on the physical component; and

controlling at least one positioning force applied at at least one of the predetermined different locations to displace or re-orientate the physical component according to a difference between the measured position and a desired position of the physical component as measured using the sensor component.

17. The method of claim 16, wherein the sensor component is a detector of a sensor or sensor target.

18. A method of positioning a target portion comprising the method of claim 16 or 17, wherein the target portion is on the physical component and the method further comprises:

5 adjusting the at least one positioning force to reduce position errors of the target portion due to remaining elastic deformation of the physical component, the remaining elastic deformation occurring as a result of the plurality of forces and of the external force being applied.

19. The method of claim 18, wherein the remaining elastic deformation is measured.

10

20. The method of any of claims 1-19, wherein the physical component is a table in a lithographic apparatus.

21. The method of claim 21, wherein the table is adapted to support one or more of a substrate, a patterning device for imparting a beam of radiation with a pattern, a detector of a sensor and a sensor target.

15

22. A device manufacturing method comprising projecting a patterned beam of radiation onto a substrate, wherein the device manufacturing method includes the method of any of claims 1-21 and the substrate is positioned on the physical component.

20

23. A method of positioning a target portion on a physical component, the method comprising:

25 applying a respective one of a plurality of forces at a respective one of a plurality of predetermined different locations at the physical component so as to counteract an external force being applied to the physical component and achieve force equilibrium and moment equilibrium on the physical component;

determining a measured position of the physical component using a sensor component on the physical component;

30 applying at least one positioning force to the physical component at at least one of the plurality of predetermined different locations at the physical component, the at least one positioning force being controlled according to a difference between the measured position and a desired position of the physical component as measured using the sensor component;

determining an estimated magnitude of the external force applied to the physical component from the measured position and the plurality of forces and/or any positioning forces for displacing or re-orientating the physical component applied at the plurality of predetermined different locations at the physical component;

5 determining an estimated position on the physical component at which the external force is applied; and

 using the estimated magnitude and estimated position to:

- 10 (i) to control an elastic deformation of the physical component at a region-of-interest at the physical component, the plurality of forces being controlled dependent on at least one of: a further location on the physical component at which the external force is being applied to the physical component, a magnitude of the external force, a direction of the external force and an estimated elastic deformation of the physical component at the region-of-interest, the elastic deformation occurring as a result of the plurality of forces and of the external force being applied; and/or
- 15 (ii) control the at least one positioning force to compensate for a change in relative position between the target portion and the sensor component due to any remaining elastic deformation of the physical component, the remaining elastic deformation occurring as a result of the plurality of forces and of the
- 20 external force being applied.

24. The method of claim 23, wherein the sensor component is a detector of a sensor or a sensor target.

25 25. A computer readable medium having computer executable instructions adapted to cause a computer system to perform the method of any of claims 1-24.

26. A positioning device comprising:
 a physical component;

30 a plurality of predetermined different locations at which a respective one of a plurality of forces may be applied to the physical component, the plurality of predetermined different locations being higher in number than a minimum number needed to enable counteraction against a displacement of the physical component as a result of an external force being

applied to the physical component and counteraction against a change of orientation of the physical component as a result of the external force; and

a controller adapted to:

control the plurality of forces so as to counteract the external force and
5 achieve force equilibrium and moment equilibrium on the physical component; and
control the plurality of forces so as to control an elastic deformation of the
physical component at a region-of-interest of the physical component, the plurality of
forces being controlled dependent on at least one of: a further location on the physical
component at which the external force is being applied to the physical component, a
10 magnitude of the external force, a direction of the external force and an estimated
elastic deformation of the physical component at the region-of-interest, the elastic
deformation occurring as a result of the plurality of forces and of the external force.

27. The positioning device of claim 26, wherein the controller is further adapted to
15 determine a further location on the physical component at which the external force is applied.

28. The positioning device of claim 26, wherein the controller is adapted to determine the
further location from a signal indicative of a measured position of the physical component
and/or a signal indicative of a desired position of the physical component.

29. The positioning device of claim 26 or 27, wherein the controller is adapted to use the
further location in the control of the plurality of forces so as to reduce the elastic deformation
of the physical component.

30. The positioning device of any of claims 26-28, wherein the controller is further
adapted to determine a magnitude of the external force and use the magnitude of the external
force in the control of the plurality of forces so as to counteract the external force and achieve
force equilibrium and moment equilibrium on the physical component.

31. The positioning device of claim 30, wherein the controller is adapted to determine the
magnitude of the external force from signals indicative of a measured position of the physical
component and the plurality of forces and/or any positioning forces for displacing or re-
orientating the physical component applied at the plurality of predetermined different
locations.

32. The positioning device of claims 30 or 31, further comprising a sensor component on the physical component; and

wherein the controller is further adapted to:

5 receive the signal indicative of a desired position of the physical component and the signal indicative of a measured position of the physical component generated using the sensor component; and

control the application of at least one positioning force to at least one of the predetermined different locations to displace or re-orientate the physical component according to a difference between the signal indicative of a measured position and the
10 signal indicative of a desired position of the physical component.

33. The positioning device of claim 32, wherein the sensor component is a detector of a sensor or a sensor target.

34. The positioning device of claim 32 or 33, further comprising a target portion on the physical component; and

the controller being further adapted to adjust the application of the at least one positioning force to reduce position errors of the target portion due to remaining elastic deformation of the physical component, the remaining elastic deformation occurring as a
20 result of the plurality of forces and of the external force being applied to the physical component.

35. The positioning device of claim 34, wherein the controller is adapted to determine the remaining elastic deformation on the basis of the plurality of forces and/or any positioning
25 forces for displacing or re-orientating the physical component applied at the plurality of predetermined different locations and the signal indicative of a desired position or the signal indicative of a measured position and the magnitude of the external force.

36. The positioning device of claim 26, wherein the controller is adapted to determine an estimated elastic deformation of the positioning device at the region-of-interest and to use the estimated elastic deformation in controlling the plurality of actuators so as to reduce the
30 elastic deformation of the physical component.

37. The positioning device of claim 36, wherein the controller is adapted to receive signals indicative of elastic deformation of the physical component at the region-of-interest and to use the signals indicative of elastic deformation in determining the estimated elastic deformation.

5

38. The positioning device of any of claims 26-29 or 36 or 37, further comprising a sensor component on the physical component; and

wherein the controller is further adapted to:

10

receive a signal indicative of a desired position of the physical component and a signal indicative of a measured position of the physical component generated using the sensor component; and

15

control the application of at least one positioning force to at least one of the predetermined different locations to displace or re-orientate the physical component according to a difference between the signal indicative of a measured position and the signal indicative of a desired position of the physical component.

39. The positioning device of claim 38, wherein the sensor component is a detector of a sensor or a sensor target.

20

40. The positioning device of claim 38 or 39, further comprising a target portion on the physical component; and

25

wherein the controller is further adapted to adjust the at least one positioning force to reduce position errors of the target portion due to remaining elastic deformation of the physical component, the remaining elastic deformation occurring as a result of the plurality of forces and of the external force being applied to the physical component.

41. A lithographic apparatus comprising the positioning device of any of claims 26-40.

30

42. The lithographic apparatus of claim 41, further comprising a further physical component, wherein the external force is applied between the physical component of the positioning device and the further physical component.

43. The lithographic apparatus of claim 42, wherein the further physical component is a liquid confinement structure for confining liquid to a space between a final element of a projection system and the physical component of the positioning device.

5 44. The lithographic apparatus of claim 42 or 43, wherein the controller is adapted to receive signals indicative of a position control signal used for positioning the further physical component and/or an observed position signal indicative of an observed position of the further physical component, the controller additionally being adapted to use the signals
10 indicative of a position control signal used for positioning the further physical component and/or an observed position signal to determine the magnitude of the external force.

45. The lithographic apparatus of any of claims 42-44, further comprising a sensor to measure a pressure in a space between the physical component and the further physical component, the controller being adapted to use the measured pressure to determine the
15 magnitude of the external force.

46. The lithographic apparatus of any of claims 41-45, wherein the physical component is a table.

20 47. The lithographic apparatus of claim 46, wherein the table is adapted to support a substrate or a patterning device for imparting a beam of radiation with a pattern.

48. The lithographic apparatus of claim 46 or 47, wherein the table comprises a detector of a sensor and/or a sensor target.

25 49. A positioning device comprising:
a physical component with a target portion and a sensor component;
a plurality of predetermined different locations at the physical component at which a respective one of a plurality of forces may be applied to the physical component, the plurality
30 of predetermined different locations being higher in number than a minimum number needed to enable counteraction against a displacement of the physical component as a result of an external force being applied to the physical component and counteraction against a change of orientation of the physical component as a result of the external force; and
and a controller adapted to:

receive a signal indicative of a desired position of the physical component and a signal indicative of a measured position of the physical component generated using the sensor component; and

5 control the application of at least one positioning force to at least one of the predetermined different locations to displace or re-orientate the physical component according to a difference between the signal indicative of a measured position and the signal indicative of a desired position of the physical component; and

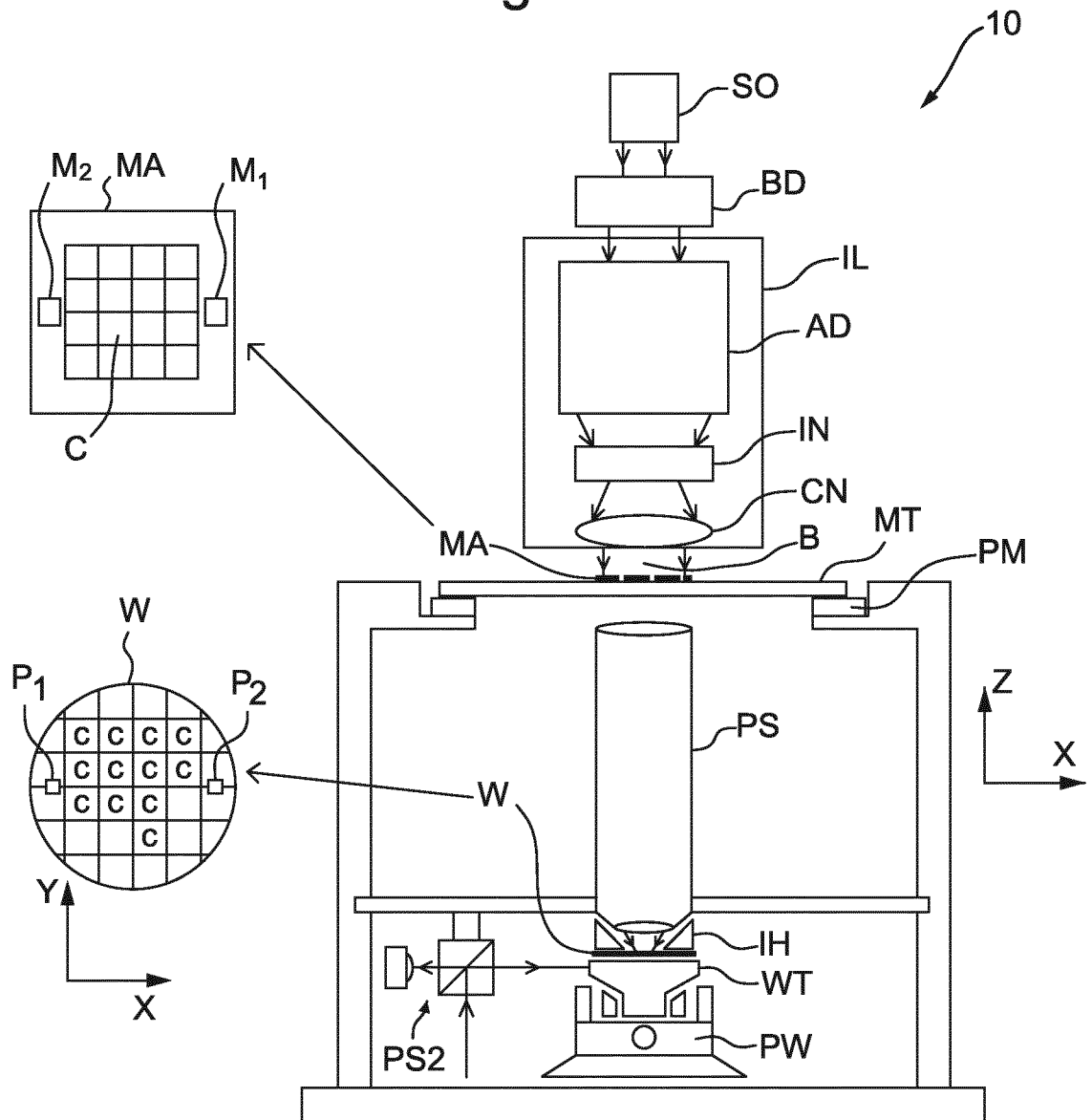
determine an estimated magnitude of the external force applied to the physical component from the signal indicative of the measured position and total forces
10 applied at each of the plurality of predetermined different locations at the physical component;

determine an estimated position on the physical component at which the external force is applied; and

use the estimated magnitude and estimated position to:

- 15 (i) to control an elastic deformation of the physical component at a region-of-interest at the physical component, the plurality of forces being controlled dependent on at least one of: a further location on the physical component at which the external force is being applied to the physical component, a magnitude of the external force, a direction of the external force and an
20 estimated elastic deformation of the physical component at the region-of-interest, the elastic deformation occurring as a result of the plurality of forces and of the external force being applied; and/or
- (ii) control the at least one positioning force to compensate for a change in relative
25 position between the target portion and the sensor component due to any remaining elastic deformation of the physical component, the remaining elastic deformation occurring as a result of the plurality of forces and of the external force being applied.

Fig. 1



2/9

Fig. 2

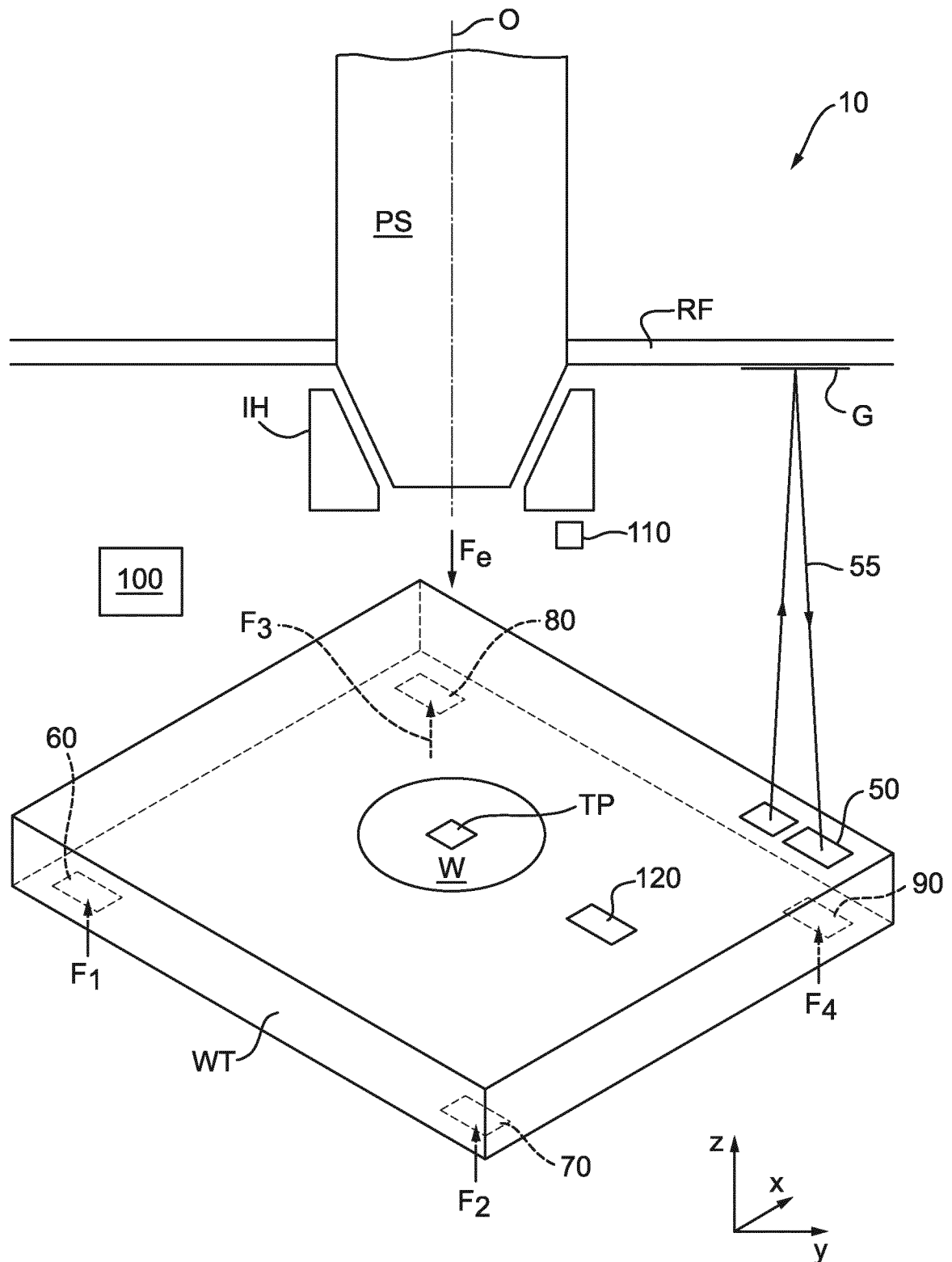
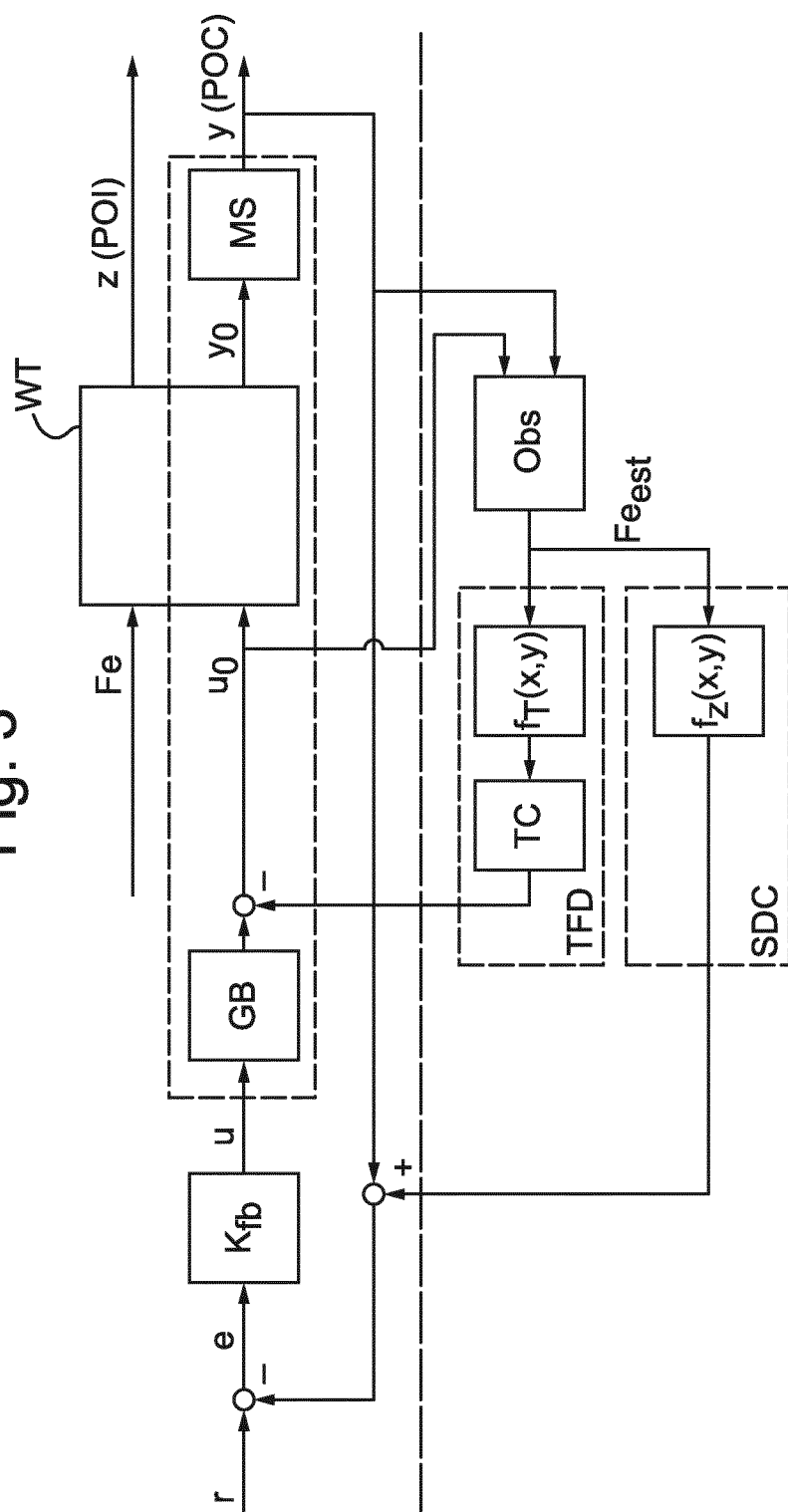


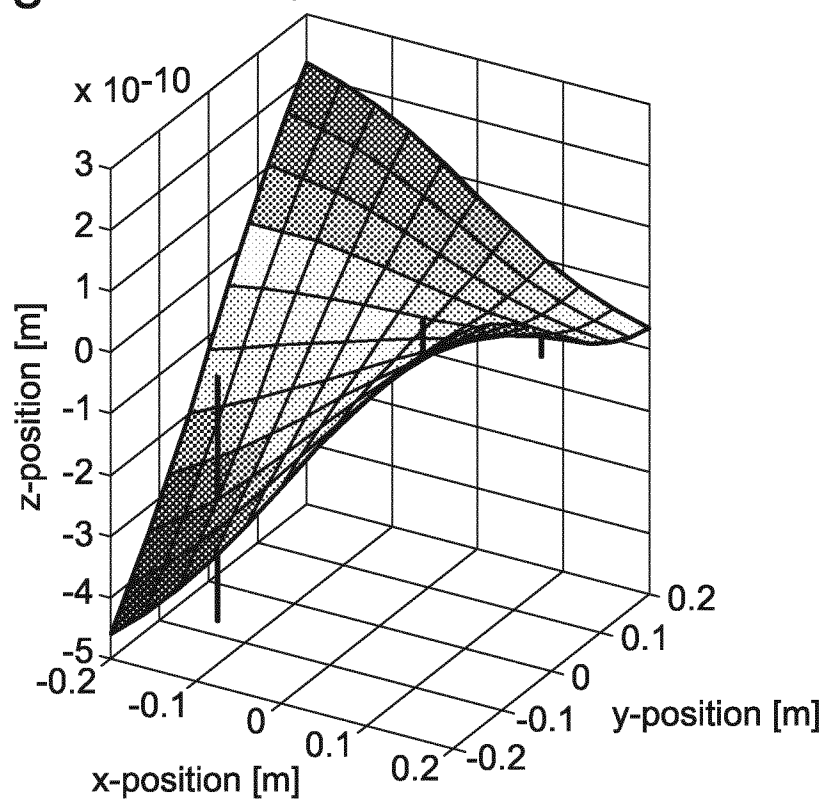
Fig. 3



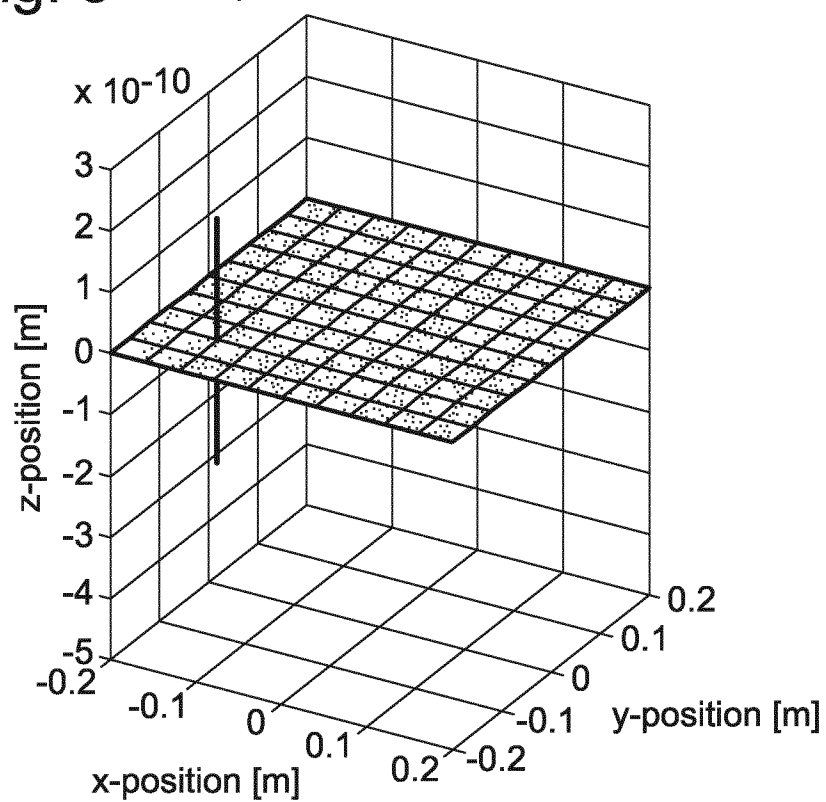
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Fig. 4

Expose error with GB

**Fig. 5**

Expose error with GB & TFD



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Fig. 6

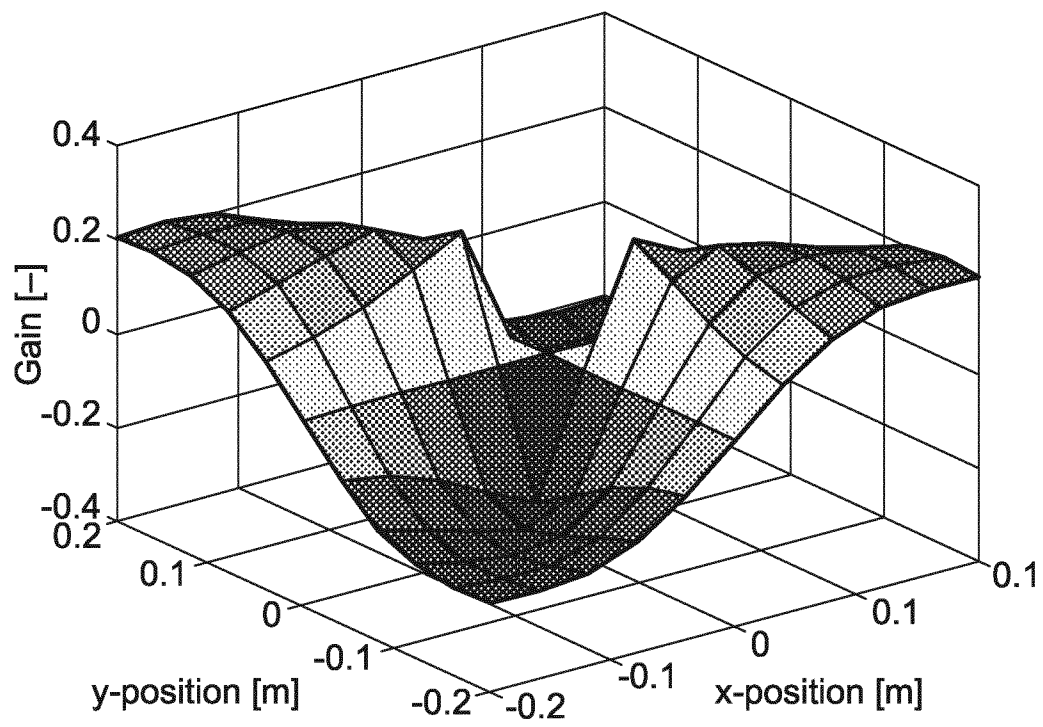


Fig. 7

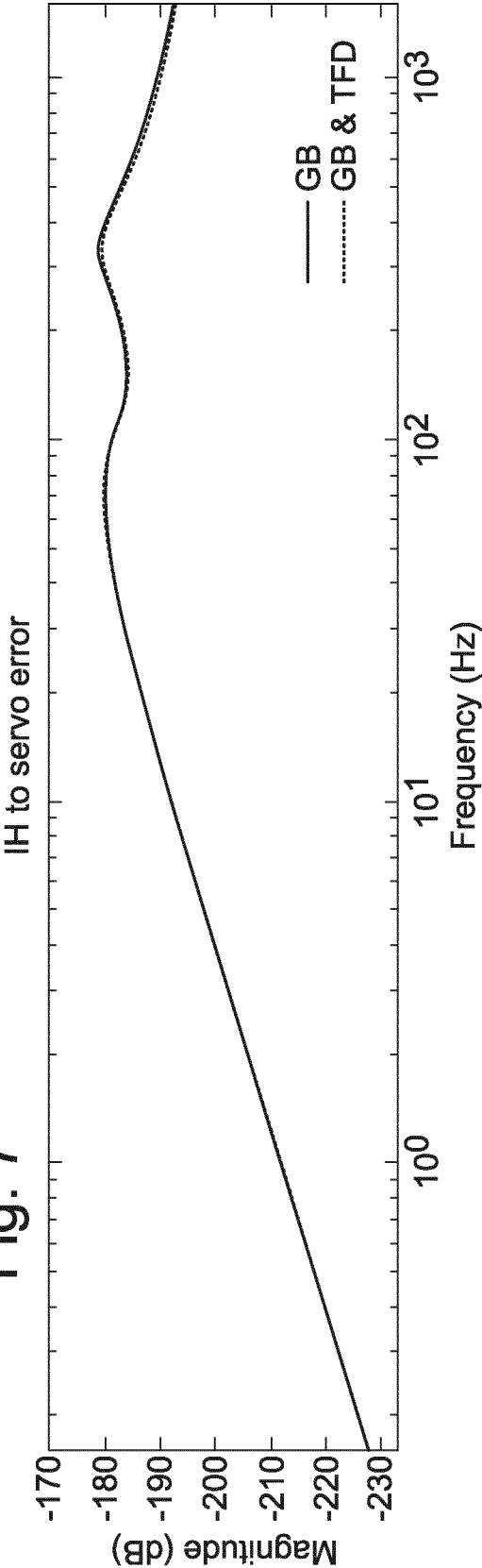


Fig. 8

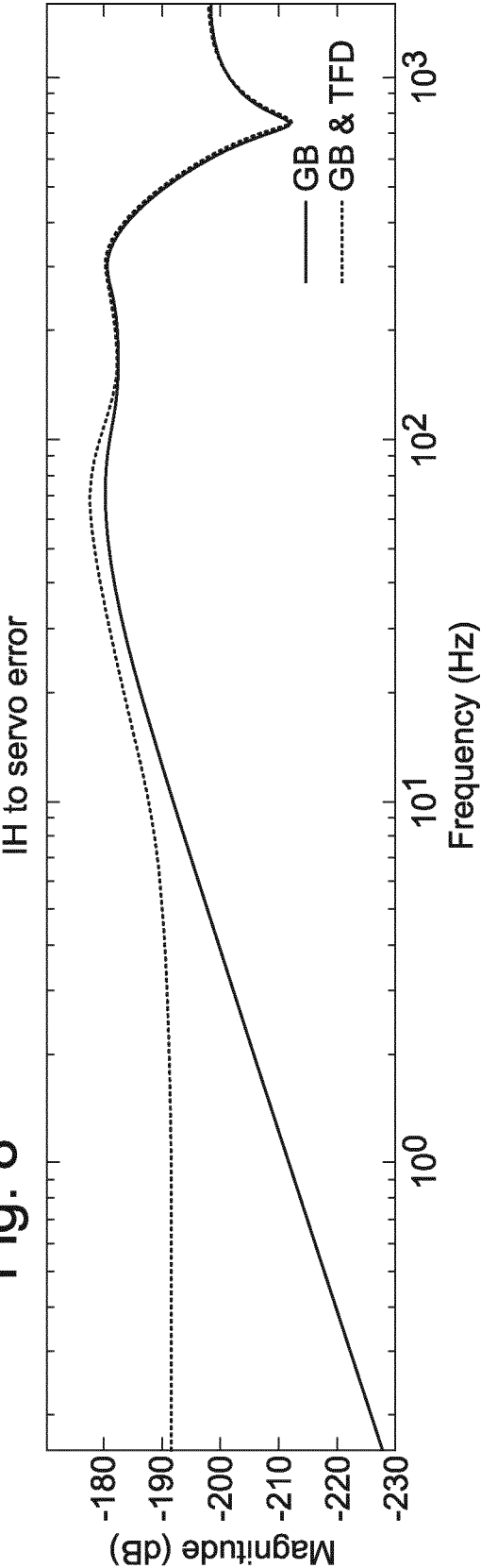


Fig. 9
Expose error with GB

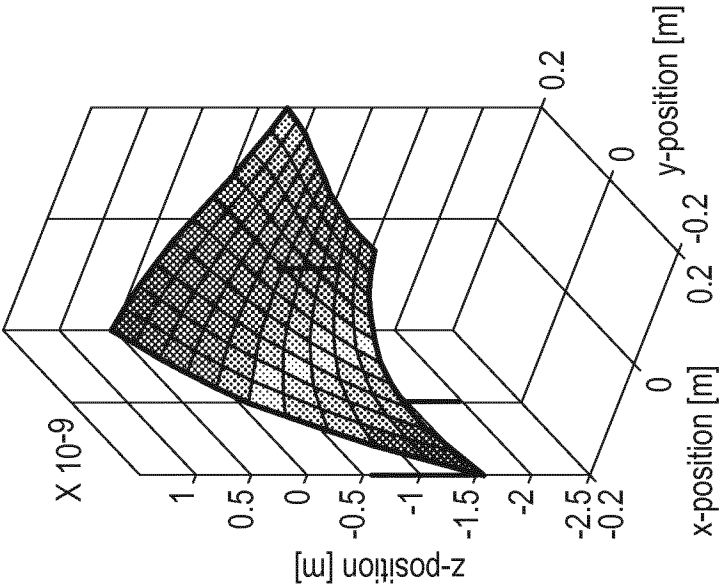


Fig. 10
Expose error with GB & TFD

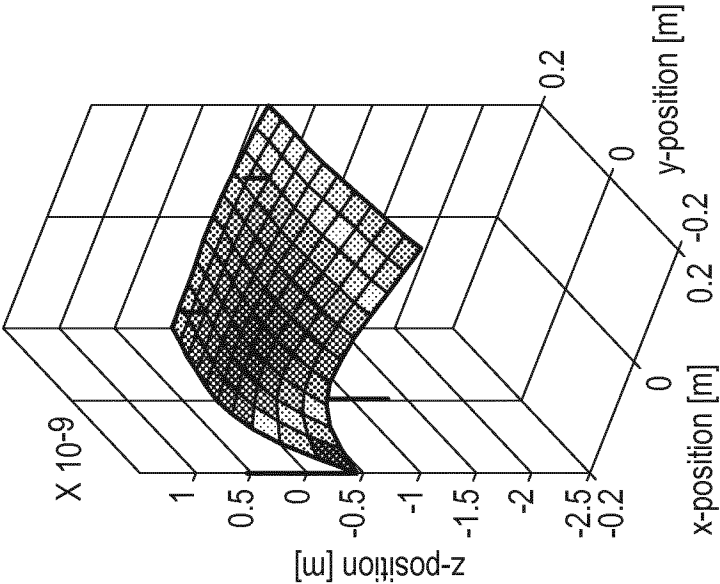


Fig. 11
Expose error with GB, TFD & SDC

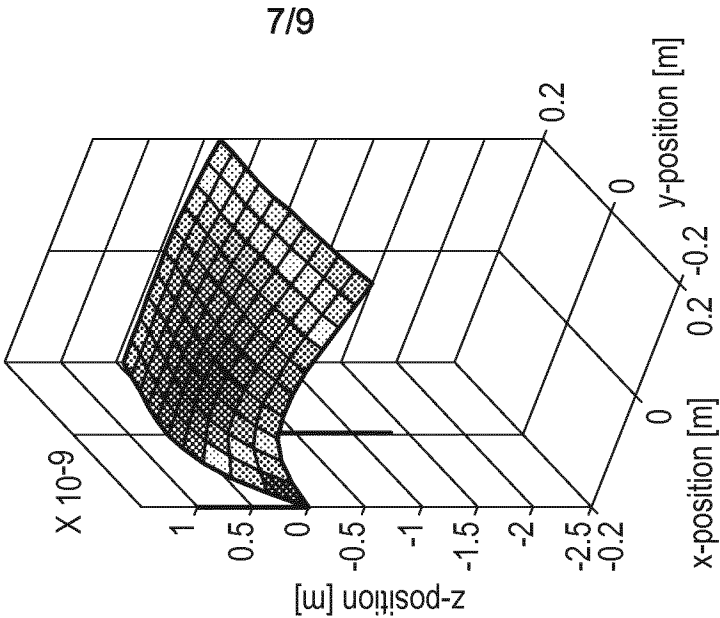


Fig. 12

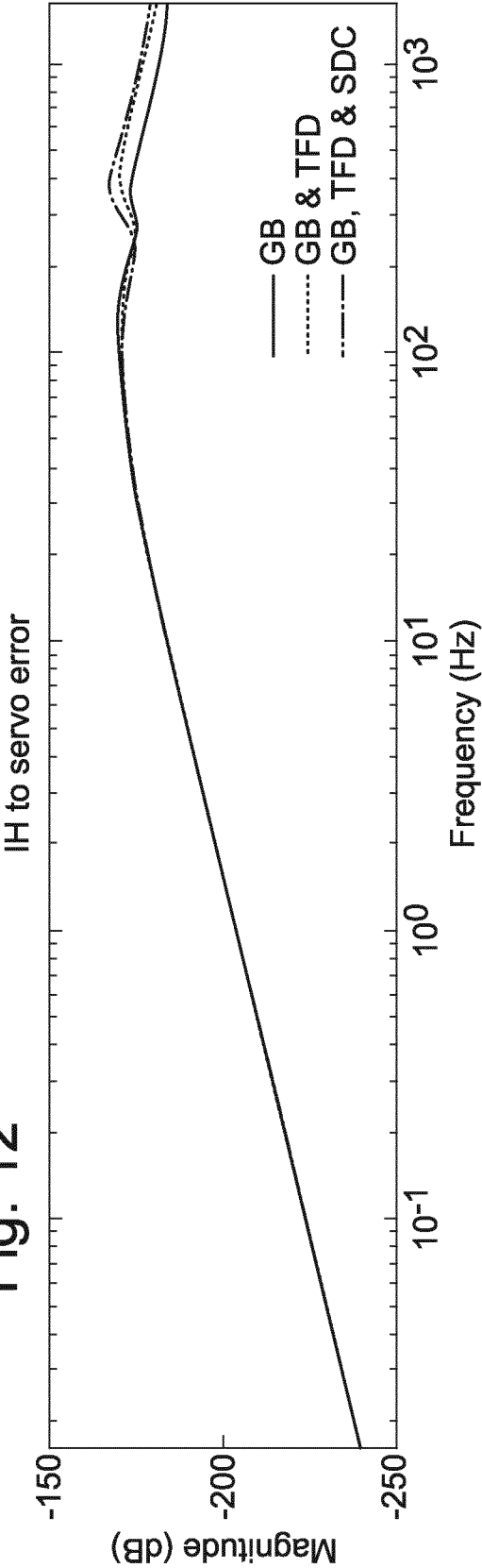


Fig. 13

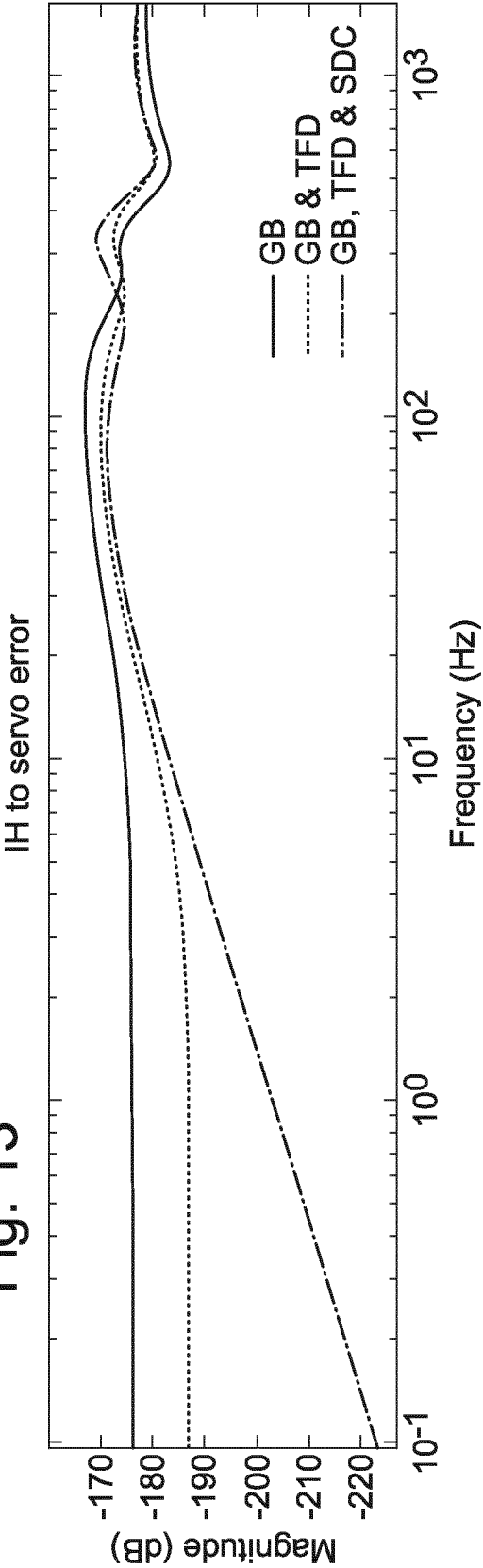


Fig. 14

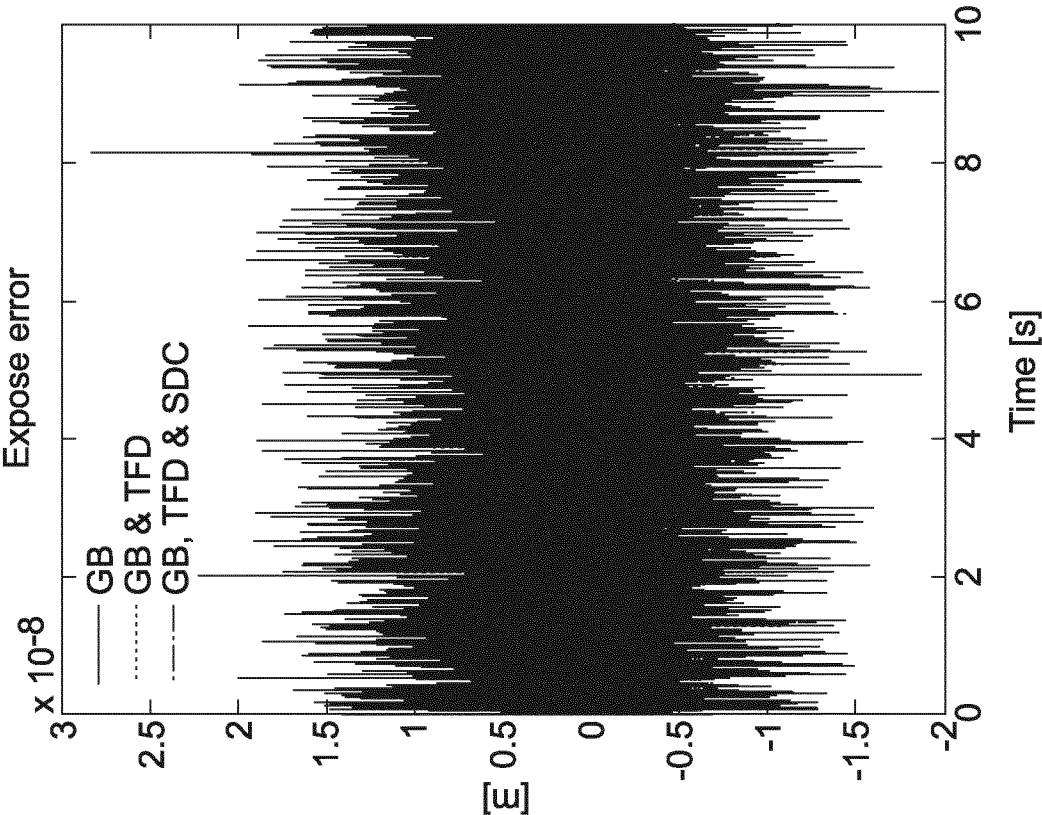


Fig. 15

