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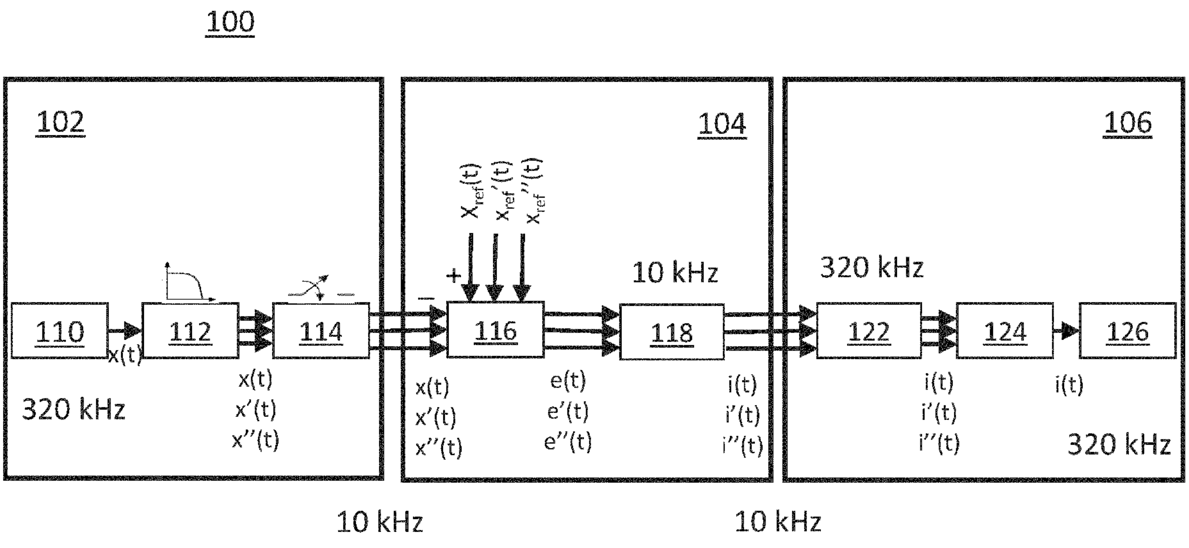

FIG. 5A

(57) Abstract: The present disclosure provides a method of controlling an actuator, the method comprising the steps of: providing a sequence of measurement samples (x(t)) at a first frequency; processing the sequence of measurement samples (at the first frequency) to provide at least one sequence of derivative measurement samples (x'(t), x''(t)); downsampling the sequence of measurement samples and the at least one sequence of derivative measurement samples to a second frequency, which is lower than the first frequency; transmitting the downsampled sequence of measurement samples and the at least one downsampled sequence of derivative measurement samples; using the downsampled sequence of measurement samples and the at least one sequence of derivative measurement samples to at least provide a sequence of control error samples; and using the sequence of control error samples to provide a sequence of actuator control samples at a third frequency, which exceeds the second frequency.

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SYSTEM AND METHOD FOR POSITION CONTROL

CROSS REFERENCE TO RELATED APPLICATION

[0001] The application claims priority of EP application 23157050.8 which was filed on 16 February, 2023, and which is incorporated herein in their entirety by reference.

FIELD

[0002] The present invention relates to a system and method for control. Control herein may in particular relate to position control of equipment. Position control can be used to control the position of equipment, such as a wafer stage, in a lithographic apparatus.

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] During the lithographic process, the position of various moveable parts of the lithographic apparatus is continuously measured. The substrate for instance is typically positioned on a movable wafer stage. To position multiple patterns correctly on top of each other, it is adamant that the position of the wafer stage is known as accurately as possible. Thus it can be ensured that an image is projected onto the correct location on the substrate.

[0006] Each movable part is typically provided with one or more actuators. The actuators in turn are controlled by a controller, which includes a control loop. The control loop typically compares a measured position with a position setting, and provides a correction if required. In its most general form, such setup may seem relatively straightforward. However, in a lithographic apparatus, the number of moveable parts to control, and the relative speed and acceleration of those relatively heavy parts (such as the wafer stage), results in a relatively large amount of measurement data samples at relatively high frequency. Also, other data may need to be transferred over the same data link, such as diagnostics data. Links to transfer data from one section of a machine to another, so for instance from a sensor to an actuator, typically have a limited bandwidth. Increasing the bandwidth may be an option, but has its limitations. For instance, costs of the data link are a limiting factor. On one hand, new hardware will be required, which may be expensive, bulky, and requires re-engineering. The data link has requirements, which in addition to speed may include stability and synchronicity. The latter significantly impact the sheer amount of time and effort required to set up a proper data link, and may be in the order of years of manhours. Also, during operation, relatively small changes in operating equipment, such as sensor or actuator sample rate, may impact and require recalibration of the data link. As a result, data signals are typically downsampled before transferring data, and at the final destination upsampled. Down-sampling however may involve certain disadvantages.

[0007] In a typical position control loop, control samples (for instance, to control an actuator) are generated at a downsampled frequency, based on measured samples that are typically obtained at a higher frequency. Control samples are thus updated at a lower frequency than the measurement frequency.

[0008] One of the most important disadvantages of realtime upsampling is delay in the effective upsampled signal. The latter is typically used to control an actuator, so any delay in the control signal translates in delay of the actuator response. For position control in real-time, it is an aim to minimize the delay in control. For state of the art equipment, every additional microsecond of reduced delay is worthwhile. Reduced delay enables more control loop bandwidth, and as a result higher throughput (via less settling time), but also increased precision. The precision may improve due to reduced position control error or residual error. Herein, in theory, multiple parameters can be controlled to reduce the delay. For instance, increasing the bandwidth of the data link may enable to increase the frequency of the control samples. This would reduce the downsampling ratio, and reduce the sample delay of the upsampled signal. However, for reasons as explained above, and for instance due to potential requirements to limit the frequency bandwidth in the controller to reject unwanted disturbances, the sample delay of the upsampled signal is - in practice - virtually the only parameter that can be controlled. Yet, it has proven very difficult to reduce said delay.

[0009] Various schemes are available to improve the subsequent upsampling. One thereof is a predictive first-order hold. Herein, in between consecutive control samples, predictive samples may be applied which are derived based on previous control samples. However, predictive first-order hold uses downsampled and thus low frequency input, and as a result introduces certain phase and gain errors.

[00010] US2008140343A1 discloses an all-in-one digital cantilever controller. The controller includes a post-processing unit 25 consisting of any post-processing software and/or hardware, as well as a Digital-to-Analog (D/A) converter 83. Among other things, the post-processing unit 25 adds a DC component 81 back to the signal. Furthermore, because the D/A converter usually runs at a much higher sampling rate than the sampling rate at which the driving signal is being updated, the driving signal is held by a hold algorithm 82. The most common hold algorithms are zero-order and first-order hold, but higher order hold algorithms are not excluded. Next, the held signal is converted to the analog domain using a D/A converter 83. The analog signal coming out of the D/A converter can then be scaled to a signal acceptable for the cantilever actuator using gain scaling 84.

[00011] The comparatively low update frequency of the control samples causes a delay which may be mitigated, typically by using zero-order hold or predictive first-order hold schemes. In predictive schemes, the derivatives are determined based on previous control samples, so on the samples which are only available at the comparatively low, down-sampled frequency. Inherently this results in delay, distortion, or both. An example of such as system is disclosed in US2008140343A1.

[00012] US4094959 discloses a method wherein in the measurement of a variable process parameter and control of the process in response thereto, a transform of a process parameter measurement signal that can be described as the time derivative of a second order or higher lagged process parameter measurement signal is utilized to provide predictive capability. This transform is combined with the output of a PI controller to the input of which the process parameter measurement signal has been fed, thereby generating a process variable signal that either directly or after passing through another controller is utilized as a process control signal for controlling the process in response to the measured parameter. US4094959 also introduces lag in the data processing, and as such is unsuitable for processes requiring real-time or at least faster data processing, such as for position control of relatively fast moving objects.

[00013] The present disclosure aims to provide an improved system and method for position control, able to transfer and process data in real time.

SUMMARY

[00014] The present disclosure provides a method of controlling an actuator, the method comprising the steps of:

providing a sequence of measurement samples (x(t)) at a first frequency;

processing the sequence of measurement samples (at the first frequency) to provide at least one sequence of derivative measurement samples (x'(t), x''(t));

downsampling the sequence of measurement samples and the at least one sequence of derivative measurement samples to a second frequency, which is lower than the first frequency;

transmitting the downsampled sequence of measurement samples and the at least one downsampled sequence of derivative measurement samples;

using the downsampled sequence of measurement samples and the at least one sequence of derivative measurement samples to at least provide a sequence of control error samples; and using the sequence of control error samples to provide a sequence of actuator control samples at a third frequency, which exceeds the second frequency.

[00015] In an embodiment, the step of processing the sequence of measurement samples to provide at least one sequence of derivative measurement samples is done at substantially the first frequency.

[00016] In an embodiment, the method includes the step of processing the sequence of measurement samples at the first frequency to provide at least two sequences of derivative measurement samples.

[00017] In an embodiment, the step of using the downsampled sequence of derivative measurement samples and the at least one sequence of derivative measurement samples to at least provide a sequence of control error samples comprises:

using the sequence of measurement samples for determining the sequence of control error samples at the second frequency;

using the at least one sequence of derivative measurement samples for determining at least one sequence of derivative control error samples at the second frequency;

upsampling the sequence of control error samples and the at least one sequence of derivative control error samples to the third frequency; and

filtering the upsampled sequence of control error samples and the at least one sequence of derivative control error samples the provide the sequence of actuator control samples.

[00018] In an embodiment, the step of using the sequence of derivative measurement samples for determining at least one sequence of derivative control error samples comprises the step of comparing the at least one sequence of derivative measurement samples with at least one sequence of derivative reference samples.

[00019] In an embodiment, the step of using the downsampled sequence of measurement samples and the at least one sequence of derivative measurement samples to at least provide a sequence of control error samples comprises:

upsampling the sequence of measurement samples and the at least one sequence of derivative measurement samples to a third frequency, which exceeds the second frequency;

filtering the upsampled sequence of measurement samples and the at least one sequence of derivative measurement samples to provide at least a sequence of upsampled measurement samples; and

using the sequence of upsampled measurement samples for determining the sequence of control error samples.

[00020] In an embodiment, the step of using the sequence of measurement samples for determining a sequence of control error samples comprises the step of comparing the sequence of measurement samples with a sequence of reference samples.

[00021] In an embodiment, the third frequency is in the range of 100 kHz to 5 MHz. The first frequency and the third frequency may be of the same order of magnitude. The second frequency may be an order of magnitude smaller than the first frequency and/or the third frequency.

[00022] In an embodiment, the step of using the downsampled sequence of measurement samples and the at least one sequence of derivative measurement samples to at least provide a sequence of control error samples comprises the steps of upsampling, and subsequently using the sequence of upsampled samples for an n-order hold filtering step, wherein n is an integer of 1 or more.

[00023] According to another aspect, the disclosure provides a system for controlling an actuator, the system comprising:

a measurement section for providing a sequence of measurement samples (x(t)) at a first frequency and for processing the sequence of measurement samples to provide at least one sequence of derivative measurement samples (x'(t), x''(t));

a downsampler for downsampling at least the sequence of measurement samples to a second frequency, which is lower than the first frequency;

a control section for transmitting the downsampled sequence of measurement samples and the at least one downsampled sequence of derivative measurement samples;

processing means for using the downsampled sequence of measurement samples and the at least one sequence of derivative measurement samples to at least provide a sequence of control error samples and for using the sequence of control error samples to provide a sequence of actuator control samples at a third frequency, which exceeds the second frequency.

[00024] In an embodiment, the processing means comprise a subtractor for comparing an input to at least one sequence of reference samples and to provide the sequence of control error samples.

[00025] In an embodiment, the processing means comprise an upsampler for upsampling at least one input sequence and providing at least one upsampled output sequence; and a filter for filtering the at least one upsampled output sequence and to provide the sequence of actuator control samples.

[00026] According to yet another aspect, the disclosure provides a position control system, provided with at least one system as described above.

[00027] According to another aspect, the disclosure provides a lithographic apparatus, provided with at least one system as described above.

BRIEF DESCRIPTION OF THE DRAWINGS

[00028] 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 shows an exemplary diagram of a conventional position control system;
- Figure 3 diagrammatically exemplifies delay caused by a zero-order hold filter;

- Figure 4 diagrammatically exemplifies delay caused by a conventional predictive first-order hold filter;
- Figures 5A to 5C show diagrams of respective embodiments of a system according to the present disclosure;
- Figure 6 shows a diagram exemplifying a signal provided by first-order hold using a method and system of the disclosure;
- Figure 7 shows a diagram exemplifying a signal provided by second-order hold upsampling using a method and system of the disclosure; and
- Figures 8A and 8B indicate examples of gain and phase behaviour respectively for the method of the present disclosure using first order hold, compared to classic zero-order hold and predictive first-order hold.

DETAILED DESCRIPTION

[00029] 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).

[00030] 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.

[00031] The term “up-sampling” or “down-sampling” as employed in this text relate to digital signal processing. Herein, upsampling, expansion, and interpolation are terms associated with the process of resampling in a multi-rate digital signal processing system. Upsampling can be synonymous with expansion, or it can describe an entire process of expansion and filtering (interpolation). When upsampling is performed on a sequence of samples of a signal or other continuous function, it produces an approximation of the sequence that would have been obtained by sampling the signal at a higher rate. Likewise, downsampling is the process of reducing the sample rate of a signal.

[00032] 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.

[00033] 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.

[00034] 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.

[00035] 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.

[00036] 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.

[00037] 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.

[00038] 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 mask 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.

[00039] 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.

[00040] Generally referring to Figure 2, in a typical control loop, a measurement system including a measurement section 102 periodically produces measurement samples $x(t)$. The measurement samples may be provided by a sensor 110. The measurement samples may be provided at a certain bitrate (which may be referred to as sample frequency, measurement frequency, or first frequency). Somewhere in the control loop, the measurement samples are compared to a set of reference samples $x_{ref}(t)$, typically setpoint values, and the result is used to drive an actuator 126. As described in the introduction, the data link between the sensor and the actuator poses various challenges. Typically, the data link includes a control section 104. The controller forwards the measurement samples to an actuator section 106. As such, in the present disclosure, the control section 104 may represent the data link between the sensor section 102 and the actuator section 106.

[00041] In control of equipment, for instance wafer stage position control, it is generally desired to have a servo tracking error which is as low as possible. Part of the servo tracking error is caused by disturbances. In the case of, for instance, wafer stage position control, disturbances may result from air pressure variations, forces exerted by connected cables and hoses, etc. For this reason, in general a certain minimum disturbance rejection of the control loop is strived for. The more disturbance rejection, the less sensitive a servo tracking error is to the disturbances.

[00042] Disturbance rejection may be achieved by means of a feedback controller. Herein, the quantity of interest (i.e. the quantity that is to be controlled) is measured, and the difference between the measured value and a setpoint (i.e. the desired value of the quantity) serves as input to a feedback controller. This difference is called the "servo error". The feedback controller converts this "servo error" signal to an actuation signal, which is transmitted to the actuator that is able to change the quantity of interest.

[00043] In general, the so-called servo "bandwidth" frequency of the control loop has a large effect on disturbance rejection. The exact relation between the servo bandwidth and the disturbance rejection depends on the spectral content of the disturbances. Nevertheless, one can state that in practice, a certain minimum servo bandwidth is strived for, in order to meet the required disturbance rejection. As explained below, to optimize the data link at a certain bandwidth, the phase delay of the final actuator control signal with respect to the original measurement signal is preferably limited.

[00044] The control loop may comprise, for instance, a filter 112 and a downsampler 114. The controller may be provided with a subtractor 116 to compare the measurement samples with a reference value $x_{ref}(t)$ and to output a difference or error value $e(t)$. The controller may comprise a feed through controller 118 providing control samples $i(t)$.

[00045] To improve results of subsequent upsampling, a predictive first-order or second order hold scheme may be used. Herein, the control section 104 may comprise a derivative estimator 120. The estimator can provide estimated values of n^{th}-order derivatives of control samples $i(t)$. The value of n herein may be an integer of 1 or higher, such as 1 or 2. The n^{th}-order derivatives of the control samples $i(t)$ are estimated. The upsampling scheme of the control loop shown in Fig. 2 may be referred to as predictive n^{th}-order hold.

[00046] An actuator section 106 may receive the values of control samples $i(t)$ and the optional n^{th}-order derivatives thereof. The actuator section 106 may comprise an up-sampler 122. The up-sampler can increase the sample rate of the value $i(t)$ and the optional n^{th}-order derivatives thereof to a third frequency. Typically the third frequency may be substantially similar to, or be of the same order of magnitude as the first frequency or sample frequency. The actuator section 106 may further comprise one or more filters 124. The filter 124 may include an anti-aliasing filter. In a practical embodiment, the upsampler 122 and filter 124 may be combined in a single unit. The actuator section 106 may comprise, or control, an actuator 126.

[00047] As referenced in the introduction, in complex state of the art machines, such as a lithographic apparatus, a vast multitude of sensor signals is provided to the controller 104. In turn the controller needs to control a multitude of actuators. To enable the data link, represented by controller section 104, to cope with the data streams, typically sample rates are down-sampled, for instance using down-sampler 114. In practice, the downsampling ratio may be significant, to enable the data transfer and controller to cope. For instance, in practice, the measurement samples may be sampled at a sample rate or frequency exceeding 100 kHz, for instance about 300 to 350 kHz. The data link of the controller 104 may process the measurement samples at a much lower sample rate or frequency, for instance below 25 kHz, such as for instance 10 kHz. The up-sampler may aim to restore the measurement frequency, aiming for a third frequency exceeding 100 kHz, for instance about 300 to 350 kHz.

[00048] Generally speaking, the first or measurement frequency is typically at least a few times as fast as the second frequency or control frequency (also referred to as $f_{s,MO}$ or "MO") of the controller 104. The controller then converts this measurement signal to a desired actuation signal $i(t)$ (at sample rate $f_{s,MO}$), which is transmitted to the actuator section 106 that drives the actuator 126. The actuation section 106 typically runs at a third sample frequency much larger than the second sample frequency $f_{s,MO}$ of the control section 104. Therefore, during most of the actuation section samples, no new "desired actuation" sample is received from the controller.

[00049] There are a few strategies that are currently commonly used to fill in these missing samples. Herein, please note that acausal systems, such as a "Basic first order hold (FOH)" scheme, cannot be used for real-time signal processing, as required for control of relatively fast moving equipment in a lithographic apparatus. An acausal system is a system that is not a causal system. An acausal system depends on future input values and possibly on some input values from the past or present. This is in contrast to a causal system which depends only on current and/or past input values. For instance in sound or video processing, buffering of signals enables the use of causal up-sampling systems, allowing to provide near-perfect restoration of the original signal. However, for control of moving equipment, the delay necessary for buffering is unacceptable, ruling out acausal systems.

[00050] Thus, in predictive n-order hold (Figure 2), derivatives of the actuation signal are estimated in the control section 104 using previous MO actuation samples. These derivatives are used to predict the actuator signal until the next MO sample. The drawback of using previous MO samples is that MO runs at the relatively low second frequency or control frequency. Hence, older samples are needed to estimate the derivatives. This negatively impacts the phase behavior of the resulting actuation signal.

[00051] Figures 3 and 4 exemplify sample delay caused by conventional causal upsampling.

[00052] Referring to Figure 3, the original measurement signal may be represented by a substantially continuous line 140. The up-sampler 122 of the actuator section 106 may use a "zero order hold" (ZOH) scheme. Herein, the actuation value 142 that is computed at time t is used by the actuator section during the entire time interval $[t, t + T_{s,MO}\rangle$. Herein $T_{s,MO}$ is the duration between consecutive samples (i.e. $T_{s,MO}$ [s] $= 1/f_{s,MO}$ [s^{-1}]) . As apparent from the graph in Fig. 3, holding the sample value causes an effective phase delay equivalent to $Ts,MO/2$ (curve 144). Herein, curve 144 is a representation of the effective upsampled or restored signal. The effective delay of the upsampled signal 144 with respect to the original signal 140 is usually referred to as the 'half sample delay' of a zero-order hold (ZOH) scheme.

[00053] Referring to Figure 4, another scheme uses so-called Predictive First Order Hold (Predictive FOH). It uses the difference between the most recent and the one-but-most recent controller sample $i(t)$

to estimate the time derivative of the actuation signal. The time derivative is used as an input 146 to control the actuator. A predictive first order hold may be included in the estimator 120 in Figure 2. As shown in Figure 4, the effective estimated signal 148 has a smaller effective phase delay 150 with respect to the original measurement signal 140 than zero-order hold (Fig. 3). However, predictive first-order hold introduces a gain error 152. The latter implies that effective control signal 148 may have a different amplitude than the measurement signal 140.

[00054] Another option, "Delayed first-order hold” is causal, and thus can be used. This option however introduces a full sample delay, and so in that sense it is worse than ZOH.

[00055] In practice, often designers tend to increase the sampling frequency of the data link, optionally including the control section 104, to reduce the “half sample delay”. However, as mentioned in the introduction, increasing the sample rate of the data link may not be viable, for various reasons. Given the sheer amount of data, and in view of the costs of related equipment to process the data, this inevitably increases the costs of data processing equipment and space required to position said equipment. In a state of the art lithographic apparatus, said costs and space often render this solution economically unviable, or at least have limitations. Increasing the sampling frequency results in increased technical complexity, as computation and communication must be done faster.

[00056] Figure 5A shows an embodiment of a system 100 for controlling an actuator according to the present disclosure. The measurement section 102 may include a filter 112. The filter may convert the sensor samples $x(t)$ from the sensor 110 to n^th^-order derivatives thereof. For instance, a first order and/or second order derivative, i.e. $x(t)$, $x'(t)$, $x''(t)$, etc. Note that the filter to derive the 0^{th} order derivative, so x(t) from x(t) itself, is not necessarily the identity filter. x(t) at the output may or may not be a filtered version of x(t) at the input of the filter.

[00057] The 1^{st} order derivative and higher order derivatives of the sensor samples may be generated at, substantially, the first frequency. The first sample frequency is substantially equal to the sample frequency of the measurement section 102. However, it may also be possible to generate the n^{th} order derivatives of the measurement samples at a lower frequency, for instance at the second frequency. Herein, instead of downsampling the derivatives, the derivatives can be provided at the downsampled bitrate. Herein, although all measurement samples can be used to determine the n^{th} order derivatives of the measurement samples, the derivatives may be generated at a lower bitrate, typically at the intended frequency for downsampling. The latter saves computing power while preserving improved accuracy.

[00058] The filter 112 may be an anti-aliasing filter. An anti-aliasing filter (AAF) is a filter used before a downsampler 114. The filter 112 may be a low-pass filter to filter the (derivative) measurement signal in order to reduce its sensitivity, for instance to measurement noise. The filter 112 restricts the bandwidth of the measurement signal to satisfy the Nyquist–Shannon sampling theorem over the band of interest. Since the theorem states that unambiguous reconstruction of the signal from its samples is possible when the power of frequencies above the Nyquist frequency is zero, a brick wall filter is an idealized but impractical AAF. A practical AAF makes a trade-off between reduced bandwidth and increased aliasing. A practical anti-aliasing filter will typically permit some aliasing to occur or attenuate or otherwise distort some in-band frequencies close to the Nyquist limit. For this reason, many practical systems sample higher than would be theoretically required by a perfect AAF in order to ensure that all frequencies of interest can be reconstructed, a practice called oversampling.

[00059] The filter 112 provides filtered measurement signal samples and their n-th order derivatives to the downsampler 114. The downsampler reduces the sample rate of the measurement signal samples to a second frequency which is lower than the first frequency. In a practical embodiment, the second frequency may be significantly lower than the first frequency.

[00060] The downsampled samples are transferred via a data link to, eventually, an actuator section, where the samples are upsampled. Herein, the downsampled samples may be provided to the control section 104. The control section may, in an embodiment, comprise processing means to provide control error samples. For instance, the control section 104 may comprise a subtractor 116. The subtractor compares the measurement samples $x(t)$ and the n-th order derivatives thereof, such as $x'(t)$, $x''(t)$, to a reference value or setpoint value, i.e. $x_{ref}(t)$, $x_{ref}'(t)$, $x_{ref}''(t)$, etc. The subtractor basically compares the measured signal and its derivatives to the setpoint by subtracting one signal from the other. The subtractor outputs the difference between the measured signal and the reference, basically an error value $e(t)$ and higher order derivates of the error value $e'(t)$, $e''(t)$, etc.

[00061] The error values provided by the subtractor may be provided to a feedthrough controller 118. The feedthrough controller may basically be a controller in state-space, not in the frequency domain. The controller 118 may, for instance, convert the control error samples $e(t)$, $e'(t)$, $e''(t)$, etc., to converted error samples $i(t)$, $i'(t)$, $i''(t)$. The converted error samples or actuator samples may represent a value suitable to control an actuator, such as a value of electrical current [in Ampere]. Additional processing may be included at various locations preceding or following the controller 118, as exemplified with respect to Figures 5A to 5C.

[00062] Result of processing in the control section 104, all done at the second frequency of operation of the processing board, is a sequence of actuator control signals $i(t)$, and n-th order derivatives thereof $i'(t)$, $i''(t)$ etc. Said actuator control signals and derivatives are provided to a respective actuator section 106 of respective actuators. Herein, as mentioned before, a typical state of the art machine may comprise any number of actuators 126 and corresponding position sensors 110. However, for sake of simplicity, the drawings and corresponding description relate to a single sensor and actuator and the data link therebetween.

[00063] The actuator section 106 may comprise an upsampler 122 for upsampling the signals as provided by the controller 104 to a third frequency exceeding the second frequency. In a practical embodiment, the third frequency may be of the same order of magnitude as the first frequency. In practice, the third or actuation frequency may be substantially similar to the measurement or first frequency.

[00064] The actuator section 106 may typically comprise a filter 124 for filtering the upsampled actuator control signals and derivatives $i(t)$, $i'(t)$, $i''(t)$. The filter 124 may be regarded as a reconstruction filter, sometimes called an anti-imaging filter. The filter 124 may be used to construct a smooth analog signal from a digital input, as in the case of a digital to analog converter (DAC) or other sampled data output device. Alternatively, the filter may provide a digital and (significantly) upsampled output. Said reconstructed signal may comprise, for instance, a sequence of upsampled actuator control samples.

[00065] In a practical embodiment, upsampling and anti-imaging are not separate processing steps. At the moment of upsampling, this is typically done using a certain anti-imaging filter (or reconstruction filter). Thus, the upsampler 122 and anti-imaging filter 124 may typically be combined.

[00066] The reconstructed signal provided by the filter 124 may be provided to the actuator 126 for control thereof.

[00067] The sensor 110 may typically comprise a position sensor. The position sensor may include an interferometer. The sensor 110 may include a phase measurement device, for measuring phase difference between two interferometer light beams. The phase measurement device, or phase measurement board, of the interferometers converts photo detector signals from encoders and/or interferometers to fringe counts. Herein, the phase measurement board may generate fringe count samples, typically at or about the same sample frequency as the first frequency of the measurement samples.

[00068] The actuator section 106, which drives the actuator 126, internally generates actuator samples $i(t)$ at a much higher sampling rate than the frequency of the data transfer and, optionally, the control section frequency MO. The method of the disclosure uses the derivatives that resulted from the fit by the anti-aliasing filter 112. These derivatives are downsampled, transferred, and used by the actuator section 106 to predict the actuator samples in between subsequent control samples, i.e. up to the next control sample becomes available. See Figure 5A.

[00069] Figure 5B shows an embodiment, whereby the feedthrough controller 118 is positioned on, and runs on the actuator section 106 (so after the up-sampler 122 and the anti-imaging filter 124). Herein, the control section 104 generated control error samples and derivatives thereof. The latter are transferred to the actuator section and upsampled. The transmitted control error signal, at the second frequency, and its derivatives, also at the second frequency, are used to reconstruct the upsampled control error signal using a reconstruction filter / anti-imaging filter. The upsampled control error samples are, at the third frequency, provided to the feedthrough controller. The controller 118 converts the control error samples to actuator samples or an actuator signal for controlling the actuator 126.

[00070] In the embodiment of Fig. 5C, data streams are centrally collected and distributed, via data link represented by section 104. The control function of comparing the measurement sample values to a reference sample value and the subsequent use of the difference, i.e. an error sample value, for actuator control may be positioned in the actuator section 106. The actuator section 106 comprises the upsampler 122 and filter 124. As mentioned above, upsampling and filtering may be combined in a single step, and the upsampler 122 and the filter 124 may, in practice, be combined. The comparison step, e.g. the subtractor 116, can be arranged subsequent to the filter 124. The controller block 118 may be positioned after the subtractor. The controller 118 may be connected to the actuator 126.

[00071] Figure 5C shows an embodiment wherein the comparison to a setpoint, for instance including subtraction of the signal sample value from a reference value in subtractor 116, is carried out in the actuator section 106. Herein, the control function effectively runs in the actuator section 106, so after the up-sampler 122 and the anti-imaging filter 124. The control section 104, shown in Figure 5C, effectively functions as a data transfer link at a downsampled data bitrate. As described above, the transfer of data at a downsampled bitrate has various advantages with respect to the alternative of data transfer at the higher bitrate of the measurement samples. Or, alternatively worded, data transfer at the same bitrate as the measurement sample bitrate poses certain challenges which in practice make it unattractive and/or economically unviable, for instance due to increased capital expenditure and operating expenditure.

[00072] In the embodiment of Fig. 5C, the upsampler 122 (typically combined with the filter 124) receives the measurement samples $x(t)$ and the n-th order derivatives of the measurement samples $x'(t)$, $x''(t)$, etc. at the second frequency. The filter 124 provides a filtered upsampled sequence of measurement samples $x(t)$. The filtered sequence x(t) is derived from the sequence of measurement samples $x(t)$ and the sequence of n-th order derivative measurement samples $x'(t)$, $x''(t)$. The filtered sequence of measurement samples $x(t)$ can be provided to the subtractor 116. The subtractor 116 compares the filtered and upsampled sequence of measurement samples $x(t)$ to a sequence of reference samples $x_{ref}(t)$. The subtractor 116 provides a sequence of control error samples $i(t)$. The sequence of control error samples $i(t)$ can be provided to a feedthrough controller 118, which may turn said sequence into a sequence of actuator control samples or an actuator control signal. The latter may be provided to the actuator 126 for controlling the actuator. The control signal may be analog or digital, depending on the actuator. In the embodiment of Fig. 5C, the sequence of upsampled measurement sample values and the reference sample values, as provided to the subtractor 116, may typically be in the digital domain.

[00073] Please note that the indication of respective sample sequences, such as i(t), e(t), x(t) etc., may change depending on its function in the control loop. Said indication may depend on the function of the respective unit which provides the respective sequence of samples.

[00074] The solution proposed is to apply a predictive n-order hold scheme in between two consecutive control signals. Herein, the predictive n^{th}-order hold scheme uses the values of the measurement samples and its derivatives, rather than using previous control samples.

[00075] Figure 6 shows an example of a first-order hold scheme according to the method and system of the disclosure. Herein, line 140 represents a continuous, analog measurement signal. An ideal reconstructed measurement signal would be identical to the original measurement signal. The system of the present disclosure provides, in the digital domain, a sequence of actuator samples *i(t)* 160. Represented in the analog domain, or converted to the analog domain, the system of the disclosure provides an actuator control signal 162. Comparing the actuator control signal 162 to the actuator control signal 148 in Fig. 4, signal 162 - using a first-order hold scheme according to the method and system of the disclosure - provides a reduction of the phase error 164 and gain error 166.

[00076] Figure 7 shows an example of a second-order hold scheme according to the method and system of the disclosure. Herein, line 140 represents a continuous, analog measurement signal. The system of the disclosure produces a sequence of actuator control samples *i(t)* 170. Represented in analog form, said actuator control samples turn into actuator control signal 172. As shown in Fig. 7, the actuator control signal 172 is relatively close to the original measurement signal 140, with limited gain and phase error.

[00077] Figure 8A shows the gain behaviour and Figure 8B shows the phase behaviour respectively of classic ZOH and predictive first order hold compared to the first order hold according to the method of the disclosure. In Figs. 8A and 8B, the horizontal axis represents frequency content in the measurement signal provided by the sensor. In Fig. 8A, the vertical axis represents the gain error of the actuator control signal. In Fig. 8B, the vertical axis represents the phase error of the actuator control signal (expressed in, for instance, radians or rad). In the figures, line 180 exemplifies behaviour using zero-order hold. ZOH is the same for both the conventional system and the system of the disclosure. Line 182 represents the conventional system using predictive first-order hold. Line 184 represents anti-aliasing filtering with a fit to a first derivative, including a first-order hold, using a system of the disclosure. Line 186 represents a conventional system using predictive first-order hold, and using a fit to two derivatives. Line 188 represents the system of the present disclosure, using first-order hold and a fit to a first derivative and a second derivative.

[00078] The first-order hold using a system of the disclosure has better phase behaviour. Improved phase behaviour in turn is, as mentioned above, beneficial for achieving a sufficiently large control loop bandwidth. The gain behaviour can also significantly improve, within a bandwidth up to a threshold frequency 190. The system and method of the disclosure can provide a significant improvement of data transfer at downsampled bitrates in a control loop. The improvement is most significant for frequencies up to said threshold frequency.

[00079] An significant advantage of the system and method of the disclosure concern the increased amount of data available to reconstruct the measurement signal. In the example provided, the amount of data has increased with a factor 32x (vis. 320 kHz versus 10 kHz). Consequently, there are more parameters available for tuning, allowing to find an optimum between frequency behaviors and reconstruction error on one hand (imperfection of the reconstruction of a sinusoidal input), and noise sensitivity on the other hand (relating to the amplification of noise between input and output of the system).

[00080] The system and method of the disclosure can be beneficial in every feedback loop where actuators but also other real-time applications are driven and stringent phase delay requirements are valid. The latter may include, but are not limited to, position control of the wafer stage, reticle stage, electron beam deflection coils, optical elements such as lenses or mirrors, wafer handlers, mask handlers, control systems, lasers, precision motion control, automated manufacturing systems, et cetera

[00081] 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.

[00082] 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.

[00083] 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.

[00084] 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.

[00085] 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. For instance, features of one embodiments may be combined with another embodiment. Other aspects of the invention are set-out as in the following numbered clauses.

1. Method of controlling an actuator, the method comprising the steps of:

providing a sequence of measurement samples (x(t)) at a first frequency;

processing the sequence of measurement samples to provide at least one sequence of derivative measurement samples (x'(t), x"(t));

downsampling at least the sequence of measurement samples to a second frequency, which is lower than the first frequency;

transmitting the downsampled sequence of measurement samples and the at least one dowsampled sequence of derivative measurement samples;

using the downsampled sequence of measurement samples and the at least one sequence of derivative measurement samples to at least provide a sequence of control error samples; and

using the sequence of control error samples to provide a sequence of actuator control samples at a third frequency, which exceeds the second frequency.

2. Method of controlling a real-time application, the method comprising the steps of:

providing a sequence of measurement samples (x(t)) at a first frequency;

processing the sequence of measurement samples to provide at least one sequence of derivative measurement samples (x'(t), x"(t));

downsampling the sequence of measurement samples and at least one sequence of derivative measurement samples to a second frequency, which is lower than the first frequency;

using the downsampled sequence of measurement samples and the at least one downsampled sequence of derivative measurement samples to provide a sequence of control error samples and at least one sequence of derivative control error samples;

using the sequence of control error samples and the at least one sequence of derivative control error samples to at least provide a sequence of control error samples; and

using the sequence of control error samples to provide a sequence of real-time application control samples at a third frequency, which exceeds the second frequency.

3. The method of clause 1 or 2, wherein the step of processing the sequence of measurement samples to provide at least one sequence of derivative measurement samples is done at substantially the first frequency.

4. The method of any of clauses 1 to 3, including the step of processing the sequence of measurement samples at the first frequency to provide at least two sequences of derivative measurement samples.

5. The method of one of the previous clauses, wherein the step of using the downsampled sequence of measurement samples and the at least one sequence of derivative measurement samples to at least provide a sequence of control error samples comprises:

using the sequence of measurement samples for determining the sequence of control error samples at the second frequency;

using the at least one sequence of derivative measurement samples for determining at least one sequence of derivative control error samples at the second frequency; and

upsampling and filtering the sequence of control error samples and the at least one sequence of derivative control error samples to the third frequency to provide the sequence of actuator or real-time application control samples.

6. The method of one of the previous clauses, the step of using the sequence of derivative measurement samples for determining at least one sequence of derivative control error samples comprising the step of comparing the at least one sequence of derivative measurement samples with at least one sequence of derivative reference samples.

7. The method of one of clauses 1 to 4, wherein the step of using the downsampled sequence of measurement samples and the at least one sequence of derivative measurement samples to at least provide a sequence of control error samples comprises:

upsampling and filtering the sequence of measurement samples and the at least one sequence of derivative measurement samples to a third frequency, which exceeds the second frequency, to provide at least a sequence of upsampled measurement samples;

using the sequence of upsampled measurement samples for determining the sequence of control error samples.

8. The method of one of the previous clauses, the step of using the sequence of measurement samples for determining a sequence of control error samples comprising the step of comparing the sequence of measurement samples with a sequence of reference samples.

9. The method of one of the previous clauses, the third frequency being in the range of 100 kHz to 5 MHz.

10. The method of one of the previous clauses, the first frequency and the third frequency being of the same order of magnitude.

11. The method of clause 10, the second frequency being an order of magnitude smaller than the first frequency and/or the third frequency.

12. The method of any of the previous clauses, the step of using the downsampled sequence of any of the combination of a) measurement samples and the at least one sequence of derivative measurement samples or b) control error samples and the at least one sequence of derivative control error samples to at least provide a sequence of control error samples comprising the steps of upsampling and using the sequence of upsampled samples for an n-order hold filtering step, wherein n is an integer of 1 or more.

13. System for controlling an actuator, the system comprising:

a measurement section for providing a sequence of measurement samples (x(t)) at a first frequency and for processing the sequence of measurement samples to provide at least one sequence of derivative measurement samples (x'(t), x''(t));

a downsampler for downsampling at least the sequence of measurement samples to a second frequency, which is lower than the first frequency;

a control section for transmitting the downsampled sequence of measurement samples and the at least one downsampled sequence of derivative measurement samples;

processing means for

using the downsampled sequence of measurement samples and the at least one sequence of derivative measurement samples to at least provide a sequence of control error samples and for using the sequence of control error samples to provide a sequence of actuator control samples at a third frequency, which exceeds the second frequency.

14. System for controlling a real-time application, the system comprising:

a measurement section for providing a sequence of measurement samples (x(t)) at a first frequency and for processing the sequence of measurement samples to provide at least one sequence of derivative measurement samples (x'(t), x''(t));

a downsampler for downsampling the sequence of measurement samples and at least one sequence of derivative measurement samples to a second frequency, which is lower than the first frequency;

a control section for using the downsampled sequence of measurement samples and the at least one downsampled sequence of derivative measurement samples to provide a sequence of control error samples and at least one sequence of derivative control error samples;

processing means for

using the sequence of control error samples and the at least one sequence of derivative control error samples to at least provide a sequence of control error samples and for using the sequence of control error samples to provide a sequence of real-time application control samples at a third frequency, which exceeds the second frequency.

15. The system of clause 13 or 14 , the processing means comprising:

a subtractor for comparing an input to at least one sequence of reference samples and to provide the sequence of control error samples.

16. The system of any of clauses 13 to 15, the processing means comprising

an upsampler for upsampling at least one input sequence and providing at least one upsampled output sequence; and

a filter for filtering the at least one upsampled output sequence and to provide the sequence of actuator or real-time application control samples.

17. Position control system, provided with at least one system according to one of clauses 13 to 16.

18. An exposure apparatus such as a lithographic apparatus, provided with at least one system according to one of clauses 13 to 16.

CLAIMS

1. Method of controlling an actuator, the method comprising the steps of:

providing a sequence of measurement samples (*x(t)*) at a first frequency;

processing the sequence of measurement samples to provide at least one sequence of derivative measurement samples (*x'(t), x''(t)*);

downsampling at least the sequence of measurement samples to a second frequency, which is lower than the first frequency;

transmitting the downsampled sequence of measurement samples and the at least one dowsampled sequence of derivative measurement samples;

using the downsampled sequence of measurement samples and the at least one sequence of derivative measurement samples to at least provide a sequence of control error samples; and

using the sequence of control error samples to provide a sequence of actuator control samples at a third frequency, which exceeds the second frequency.

2. Method of controlling a real-time application, the method comprising the steps of:

providing a sequence of measurement samples (x(t)) at a first frequency;

processing the sequence of measurement samples to provide at least one sequence of derivative measurement samples (x'(t), x''(t));

downsampling the sequence of measurement samples and at least one sequence of derivative measurement samples to a second frequency, which is lower than the first frequency;

using the downsampled sequence of measurement samples and the at least one downsampled sequence of derivative measurement samples to provide a sequence of control error samples and at least one sequence of derivative control error samples;

using the sequence of control error samples and the at least one sequence of derivative control error samples to at least provide a sequence of control error samples; and

using the sequence of control error samples to provide a sequence of real-time application control samples at a third frequency, which exceeds the second frequency.

3. The method of claim 1 or 2, wherein the step of processing the sequence of measurement samples to provide at least one sequence of derivative measurement samples is done at substantially the first frequency.

4. The method of any of claims 1 to 3, including the step of processing the sequence of measurement samples at the first frequency to provide at least two sequences of derivative measurement samples.

5. The method of one of the previous claims, wherein the step of using the downsampled sequence of measurement samples and the at least one sequence of derivative measurement samples to at least provide a sequence of control error samples comprises:

using the sequence of measurement samples for determining the sequence of control error samples at the second frequency;

using the at least one sequence of derivative measurement samples for determining at least one sequence of derivative control error samples at the second frequency; and

upsampling and filtering the sequence of control error samples and the at least one sequence of derivative control error samples to the third frequency to provide the sequence of actuator or real-time application control samples.

6. The method of one of the previous claims, the step of using the sequence of derivative measurement samples for determining at least one sequence of derivative control error samples comprising the step of comparing the at least one sequence of derivative measurement samples with at least one sequence of derivative reference samples.

7. The method of one of claims 1 to 4, wherein the step of using the downsampled sequence of measurement samples and the at least one sequence of derivative measurement samples to at least provide a sequence of control error samples comprises:

upsampling and filtering the sequence of measurement samples and the at least one sequence of derivative measurement samples to a third frequency, which exceeds the second frequency, to provide at least a sequence of upsampled measurement samples;

using the sequence of upsampled measurement samples for determining the sequence of control error samples.

8. The method of one of the previous claims, the step of using the sequence of measurement samples for determining a sequence of control error samples comprising the step of comparing the sequence of measurement samples with a sequence of reference samples.

9. The method of one of the previous claims, the third frequency being in the range of 100 kHz to 5 MHz.

10. The method of one of the previous claims, the first frequency and the third frequency being of the same order of magnitude.

11. The method of claim 10, the second frequency being an order of magnitude smaller than the first frequency and/or the third frequency.

12. The method of any of the previous claims, the step of using the downsampled sequence of any of the combination of a) measurement samples and the at least one sequence of derivative measurement samples or b) control error samples and the at least one sequence of derivative control error samples to at least provide a sequence of control error samples comprising the steps of upsampling and using the sequence of upsampled samples for an n-order hold filtering step, wherein n is an integer of 1 or more.

13. System for controlling an actuator, the system comprising:

a measurement section for providing a sequence of measurement samples (x(t)) at a first frequency and for processing the sequence of measurement samples to provide at least one sequence of derivative measurement samples (x'(t), x''(t));

a downsampler for downsampling at least the sequence of measurement samples to a second frequency, which is lower than the first frequency;

a control section for transmitting the downsampled sequence of measurement samples and the at least one downsampled sequence of derivative measurement samples;

processing means for

using the downsampled sequence of measurement samples and the at least one sequence of derivative measurement samples to at least provide a sequence of control error samples and for using the sequence of control error samples to provide a sequence of actuator control samples at a third frequency, which exceeds the second frequency.

14. System for controlling a real-time application, the system comprising:

a measurement section for providing a sequence of measurement samples (x(t)) at a first frequency and for processing the sequence of measurement samples to provide at least one sequence of derivative measurement samples (x'(t), x''(t));

a downsampler for downsampling the sequence of measurement samples and at least one sequence of derivative measurement samples to a second frequency, which is lower than the first frequency;

a control section for using the downsampled sequence of measurement samples and the at least one downsampled sequence of derivative measurement samples to provide a sequence of control error samples and at least one sequence of derivative control error samples;

processing means for

using the sequence of control error samples and the at least one sequence of derivative control error samples to at least provide a sequence of control error samples and for using the sequence of control error samples to provide a sequence of real-time application control samples at a third frequency, which exceeds the second frequency.

15. The system of claim 13 or 14 , the processing means comprising:

a subtractor for comparing an input to at least one sequence of reference samples and to provide the sequence of control error samples.

16. The system of any of claims 13 to 15, the processing means comprising

an upsampler for upsampling at least one input sequence and providing at least one upsampled output sequence; and

a filter for filtering the at least one upsampled output sequence and to provide the sequence of actuator or real-time application control samples.

17. Position control system, provided with at least one system according to one of claims 13 to 16.

18. An exposure apparatus such as a lithographic apparatus, provided with at least one system according to one of claims 13 to 16.

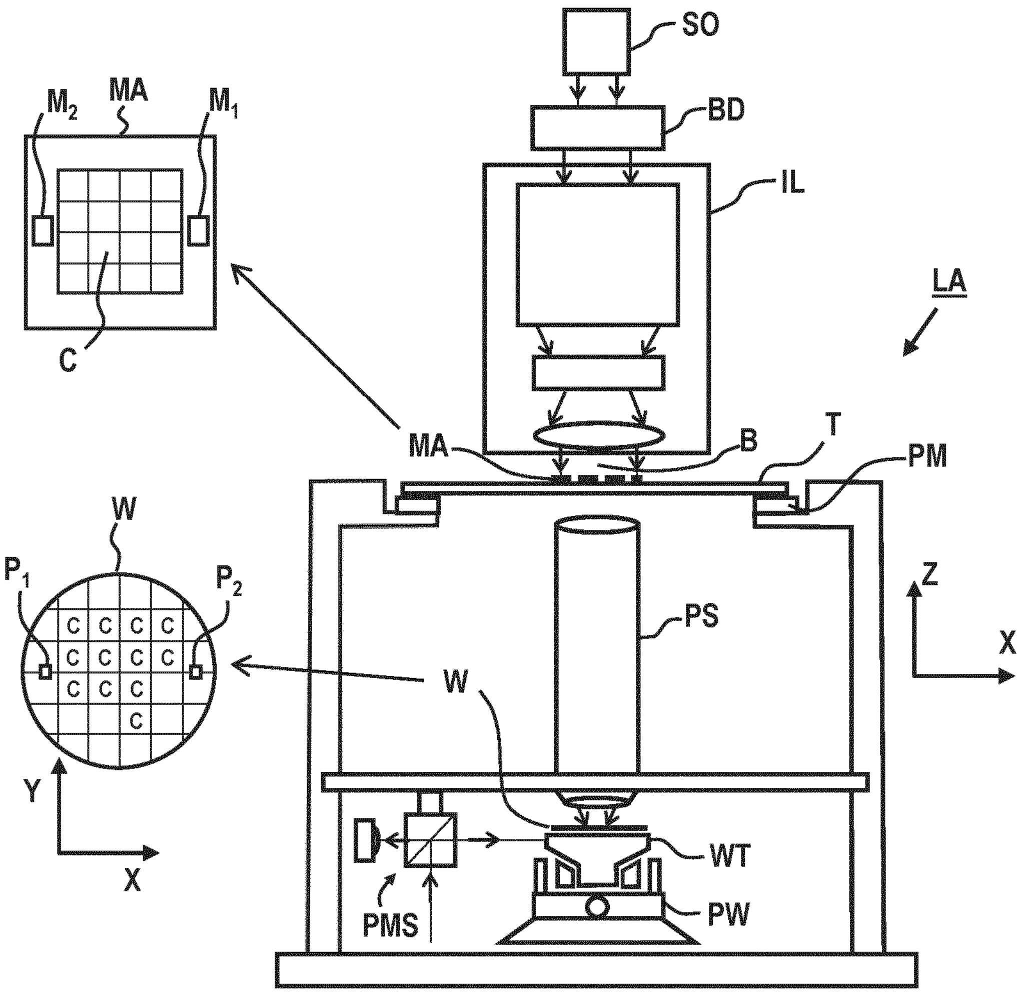

Fig. 1

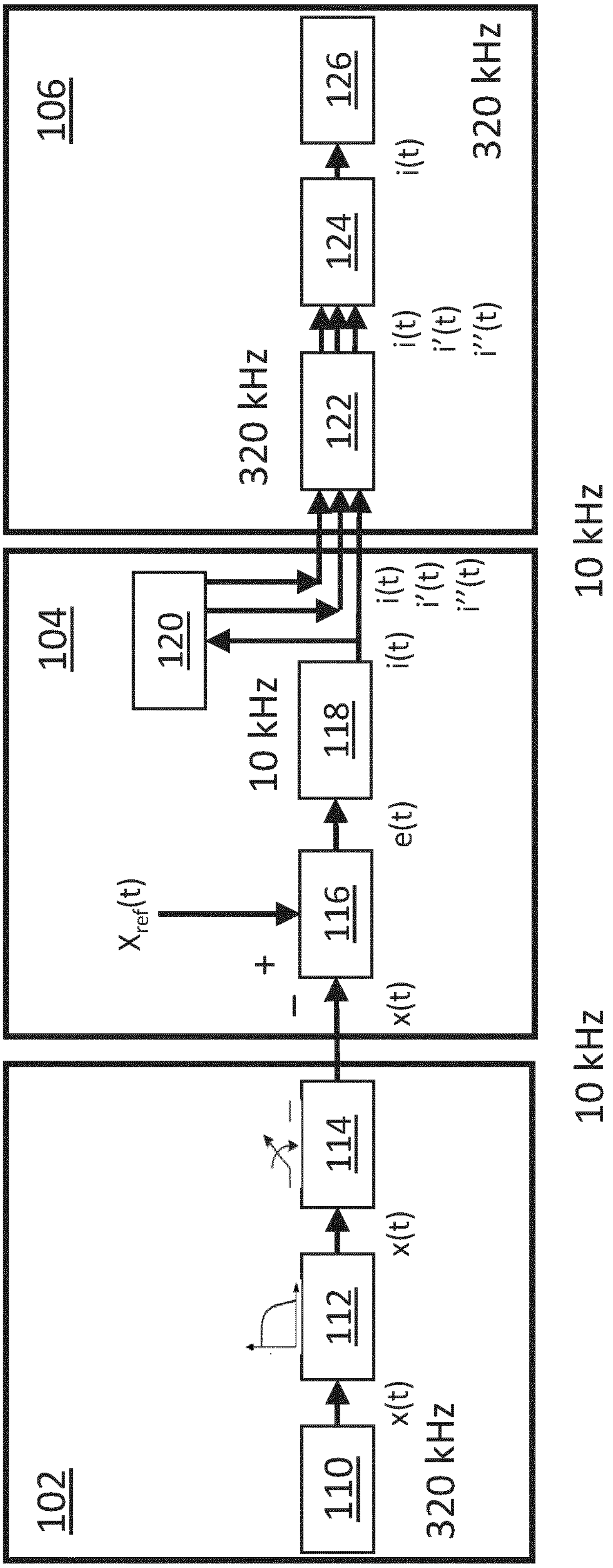
102
110
320 kHz
x(t)
112
x(t)
114
10 kHz
104
x(t)
−
+
$X_{ref}(t)$
116
e(t)
10 kHz
118
i(t)
120
i(t)
i'(t)
i''(t)
10 kHz
106
320 kHz
122
i(t)
i'(t)
i''(t)
124
i(t)
126
320 kHz

FIG. 2

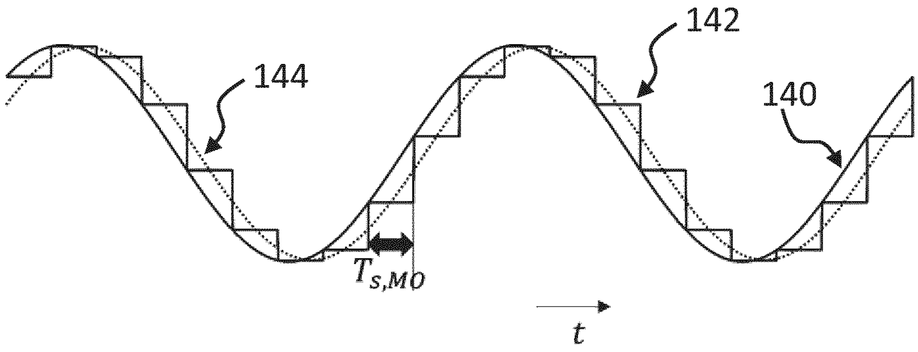

FIG. 3

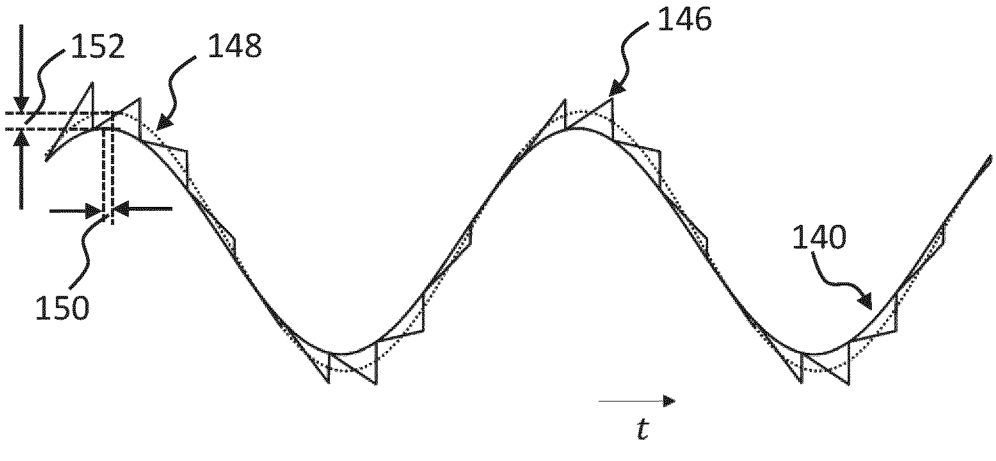

FIG. 4

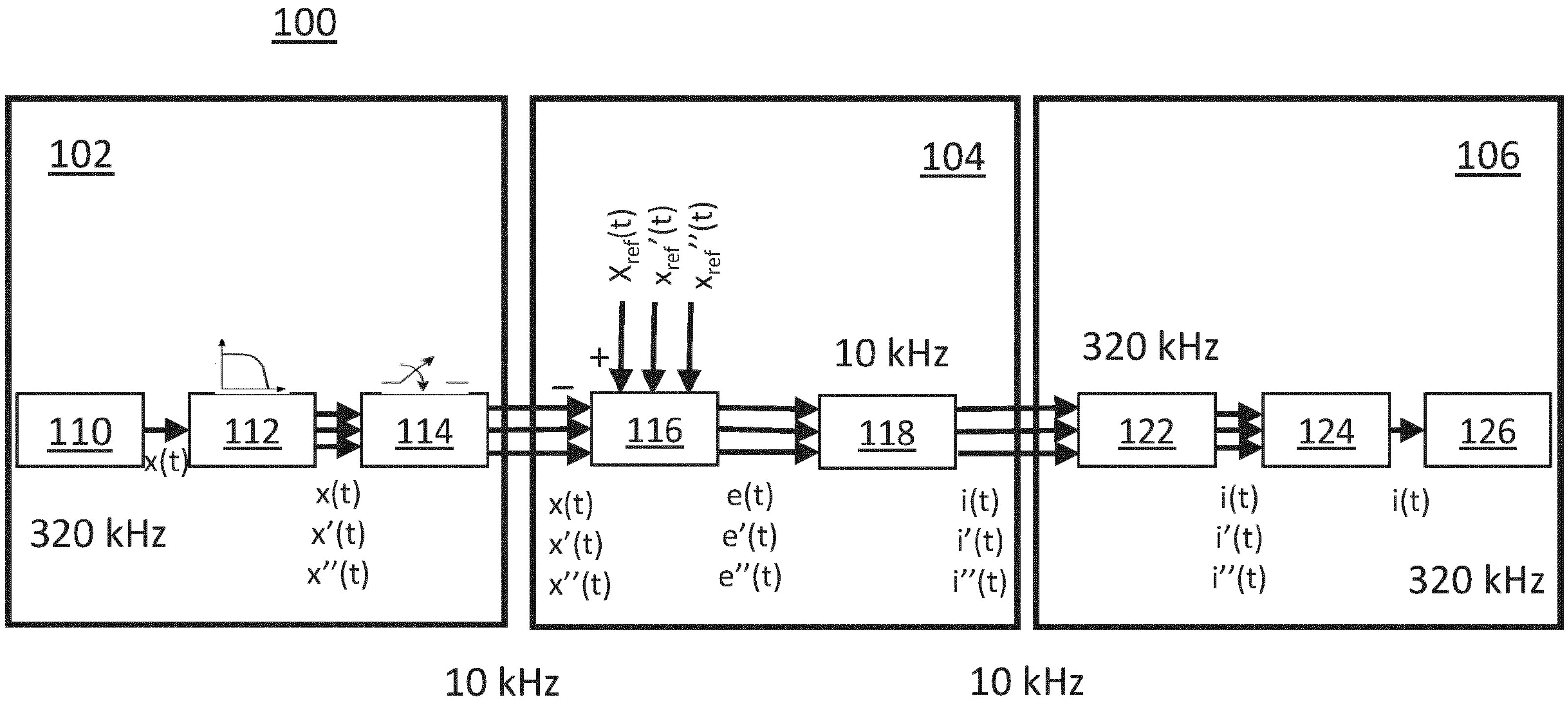
100
102
104
106
110
112
114
116
118
122
124
126
x(t)
320 kHz
x(t)
x'(t)
x''(t)
+
−
$X_{ref}(t)$
$x_{ref}'(t)$
$x_{ref}''(t)$
x(t)
x'(t)
x''(t)
e(t)
e'(t)
e''(t)
10 kHz
i(t)
i'(t)
i''(t)
320 kHz
i(t)
i'(t)
i''(t)
i(t)
320 kHz
10 kHz
10 kHz

FIG. 5A

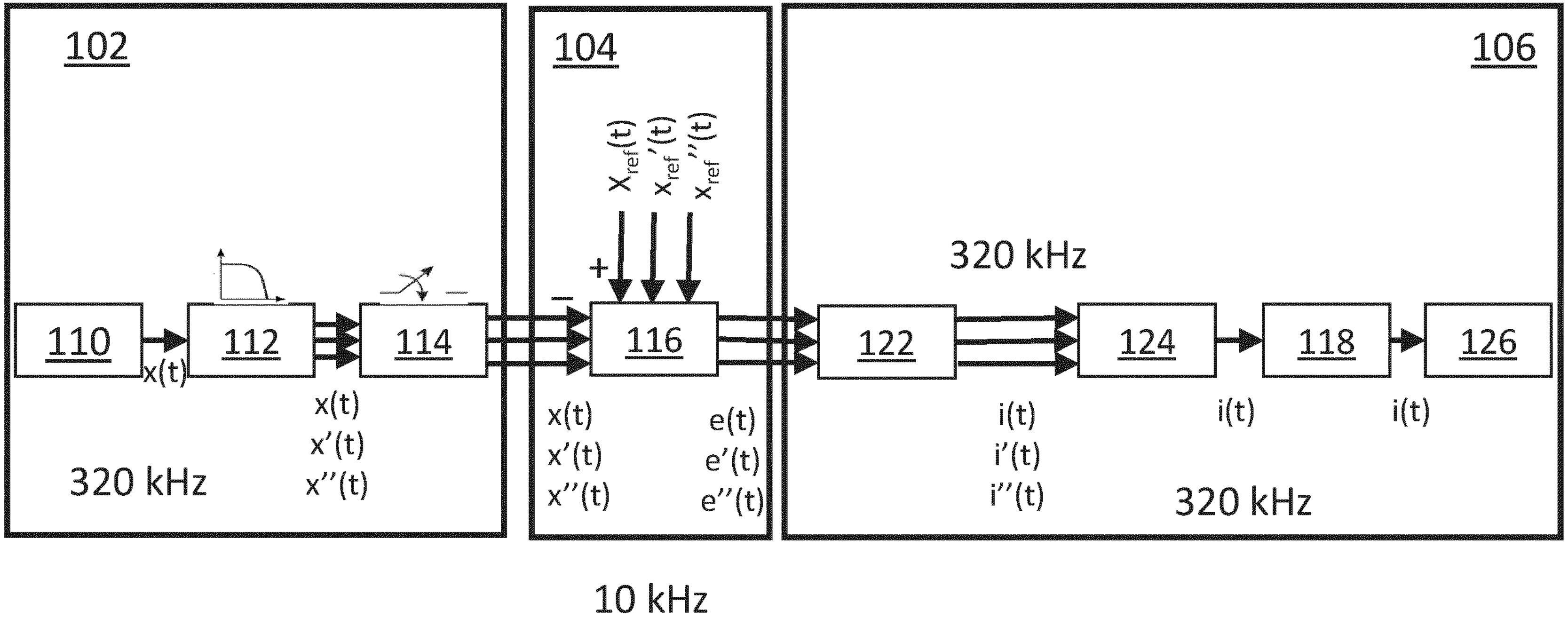
102
104
106
110
x(t)
112
114
x(t)
x'(t)
x''(t)
320 kHz
$X_{ref}(t)$
$x_{ref}'(t)$
$x_{ref}''(t)$
+
−
116
x(t)
x'(t)
x''(t)
e(t)
e'(t)
e''(t)
10 kHz
320 kHz
122
124
118
126
i(t)
i'(t)
i''(t)
i(t)
i(t)
320 kHz

FIG. 5B

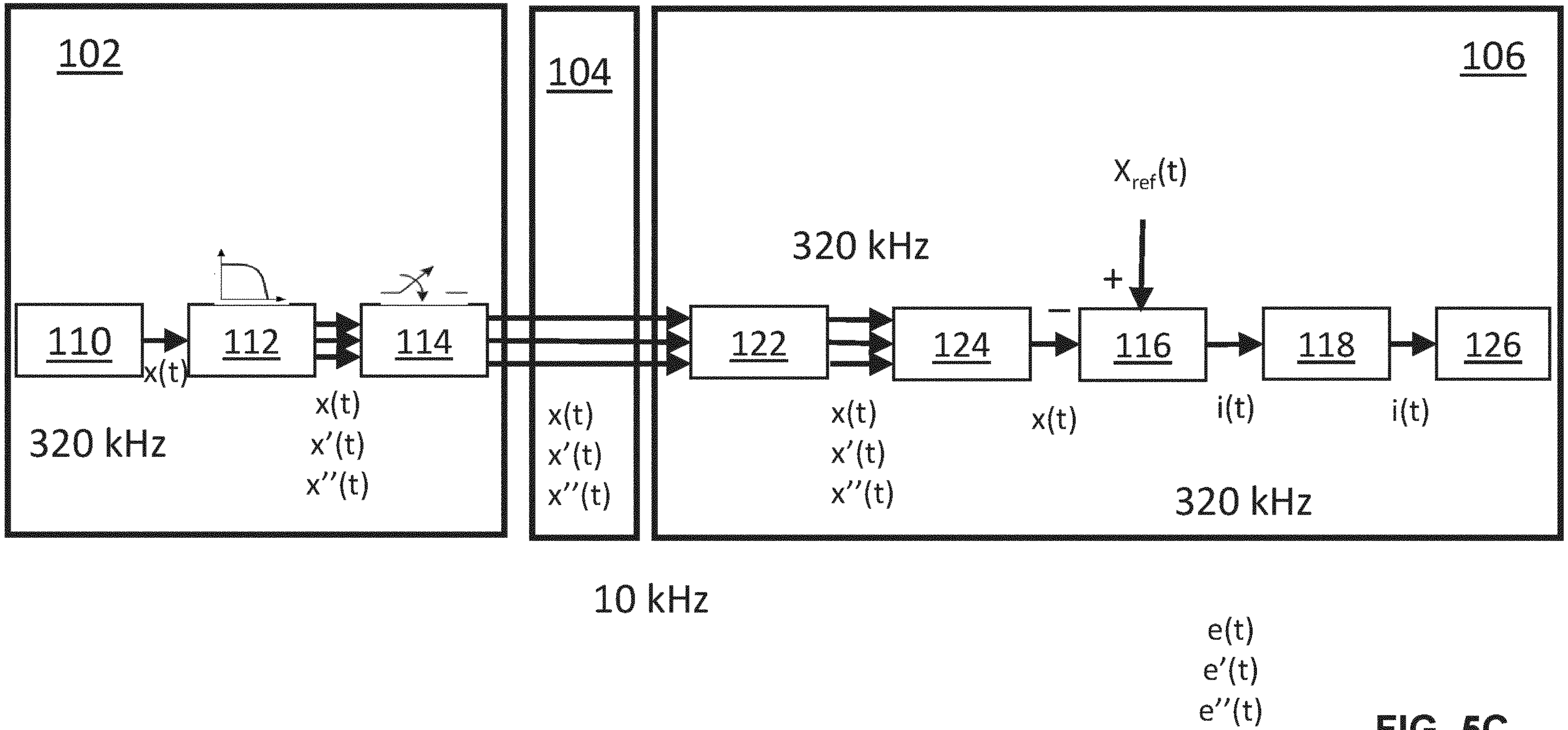
102
110
x(t)
112
114
x(t)
x'(t)
x''(t)
320 kHz
104
x(t)
x'(t)
x''(t)
10 kHz
106
320 kHz
122
x(t)
x'(t)
x''(t)
124
x(t)
$X_{ref}(t)$
+
−
116
i(t)
118
i(t)
126
320 kHz
e(t)
e'(t)
e''(t)

FIG. 5C

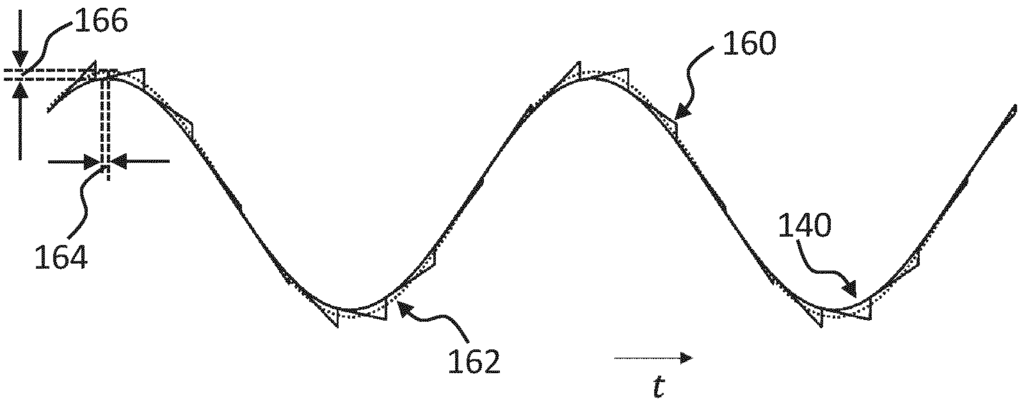

FIG. 6

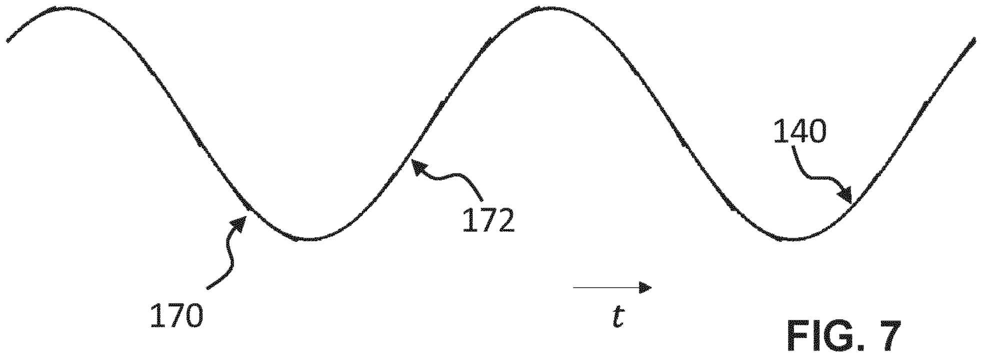

FIG. 7

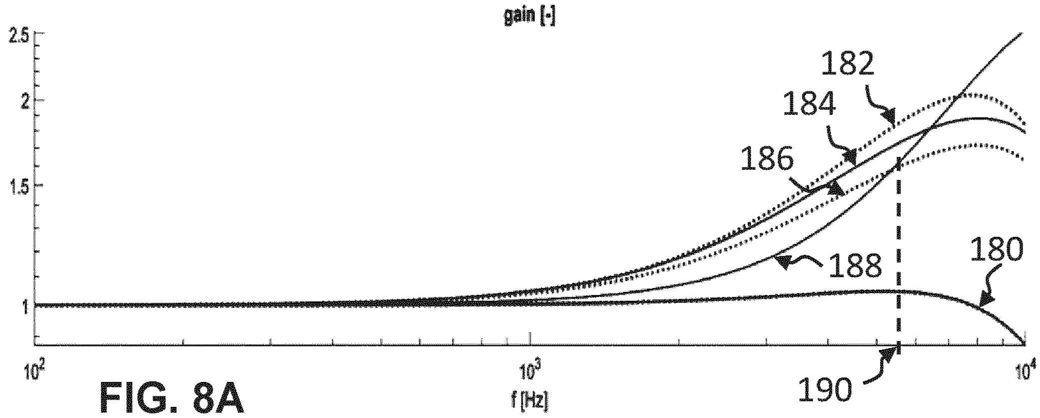

FIG. 8A

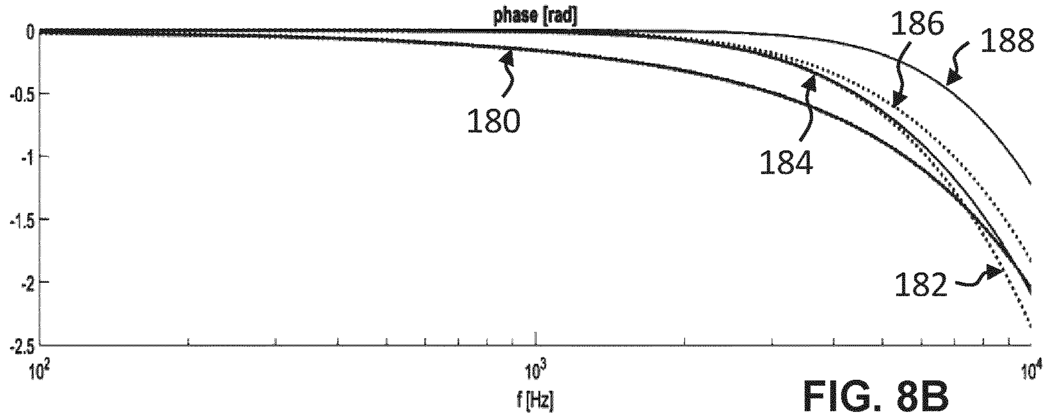

FIG. 8B

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2024/053340

A. CLASSIFICATION OF SUBJECT MATTER
INV. G05B19/042
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)
G05B

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	US 2017/290095 A1 (PEREIRA ARVIND ANTONIO DE MENEZES [US] ET AL) 5 October 2017 (2017-10-05)	1-4,6, 8-11, 13-15, 17,18
A	paragraph [0006] paragraph [0039] paragraph [0061] - paragraph [0093] paragraph [0176] figures 1, 3, 5 claim 1 -----	5,7,12, 16

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

☒ See patent family annex.

* Special categories of cited documents :

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

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

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

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"&" document member of the same patent family

Date of the actual completion of the international search 6 May 2024	Date of mailing of the international search report 27/05/2024
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Marrone, Fabrizio

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2024/053340

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2017290095 A1	05-10-2017	AU 2017241445 A1	05-07-2018
		AU 2018260976 A1	29-11-2018
		BR 112017024420 A2	24-07-2018
		CA 3007593 A1	05-10-2017
		CN 108700307 A	23-10-2018
		EP 3380790 A1	03-10-2018
		JP 6535824 B1	26-06-2019
		JP 2019519744 A	11-07-2019
		KR 20180091935 A	16-08-2018
		US 2017290095 A1	05-10-2017
		US 2018098381 A1	05-04-2018
		US 2020260529 A1	13-08-2020
		WO 2017172539 A1	05-10-2017