Impact of amplifier errors on position loop accuracy of high-precision moving stages

Citation for published version (APA):

Settels, S. J., Duarte, J. L., & van Duivenbode, J. (2017). Impact of amplifier errors on position loop accuracy of high-precision moving stages. In *2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe)*, 11-14 September 2017, Warsaw, Poland (pp. P.1 - P.10). [8099009] Institute of Electrical and Electronics Engineers. <https://doi.org/10.23919/EPE17ECCEEurope.2017.8099009>

DOI:

[10.23919/EPE17ECCEurope.2017.8099009](https://doi.org/10.23919/EPE17ECCEEurope.2017.8099009)

Document status and date:

Published: 13/09/2017

Document Version:

Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Impact of Amplifier Errors on Position Loop Accuracy of High-Precision Moving Stages

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Keywords

«Amplifiers», «Mechatronics», «Modelling», «Motion control».

Abstract

To maximise essential system performance parameters, this research combines electrical, mechanical and position control models of a high-precision mechatronic system. The degradation of system performance induced by identified amplifier errors is analysed to reveal the significance of each error mechanism. The simplified outline of a mechatronic system is given to which models of the power amplifier are added in order to emulate the error mechanisms. Analysis of the impact of each error mechanism on the position accuracy of the mechatronic system is given from which specifications for the power amplifier can be obtained for a certain required position accuracy. Ensuing properly targeted requirements provide focused amplifier optimisation.

Introduction

Industrial applications using fast-moving high-precision stages, e.g. lithographic equipment (see Fig. 1 [1]), require power amplifiers with high-precision output current generation capabilities. Errors produced by the amplifier with respect to the current reference influence the stationary and dynamic positioning accuracy of a high-precision mechatronic system [2, 3]. Current research focuses on the improvement of the performance of high-precision amplifiers, e.g. [4, 5], and position control of high-precision stages, e.g. [1, 6, 7], independently. However, the influence of the performance of the amplifier on the position accuracy of the moving stage has not been analysed yet.

This research combines (simplified) models of mechanical, electrical and position control systems and provides insight in the significance of error mechanisms incorporated in the amplifier. This allows to

Fig. 1: Outline of high-precision wafer positioning system. (Courtesy of ASML [1])

deduce a set of requirements for the performance of the amplifier for a given maximum allowed position error for the complete system. Furthermore, it enables a more efficient design process of the power electronics, where errors are anticipated and resolved before the design is cast into costly prototypes.

A generic approach to model the position control of an electromechanical system is introduced [8], to which models for the amplifier are added in order to emulate error mechanisms. The starting point is the ideal amplifier represented by a gain of one and zero phase distortion, to which the respective error mechanisms are added: offset current, gain error and non-linearity error; the latter being modelled using current-spatial frequencies [9]. Furthermore, a model of a current-controlled current amplifier with load, comprising closed-loop output current control, is used to simulate the bandwidth limitation and corresponding phase-shift of the amplifier [3]. For each error mechanism, the resulting influence on the positioning accuracy of the mechatronic system is evaluated. Requirements for the performance of the power amplifier can then be deduced for given required stationary and dynamic position accuracies.

Position control of electromechanical systems

A model of a high-precision moving stage, as shown in Fig. 1, incorporating movement in a single direction, is analysed in this research. The global outline of the position control system of the electromechanical system is shown in Fig. 2. The electromechanical plant $P(s)$ consists of a (simplified) motor model with a motor constant k_m to calculate the force from the current generated by the amplifier, and a mass m and damping c to which the force is applied [10]. The actual position x_{out} of the moving mass m , obtained from the transfer function of $P(s)$, is fed back to the position controller $C(s)$. Together with a feed forward transfer function $H_{FF}(s)$, consisting of an inverse of estimates of the actual electromechanical plant, the current setpoint i_{set} for the amplifier is generated [8]. The position controller $C(s)$ is a standard PID controller which is designed for an open-loop bandwidth $f_{bw,pos}$. The corresponding transfer functions are defined as

$$P(s) = \frac{k_m}{ms^2 + cs} \quad (1)$$

$$H_{FF}(s) = \frac{1}{\hat{P}(s)} = \frac{\hat{m}s^2 + \hat{c}s}{\hat{k}_m} \quad (2)$$

$$C(s) = \frac{K_D s^2 + K_P s + K_I}{\hat{k}_m s}. \quad (3)$$

The values of the estimated parameters $\hat{m}$, $\hat{c}$ and $\hat{k}_m$, are taken equal to the actual parameter values as the aim is to assess amplifier error impact only. Note that the transfers of (2) and (3) are still noncausal.

Fig. 2: Global outline of the position control system.

To obtain very high positioning accuracy, it is essential that the input position setpoint x_{set} is delayed with the same amount as the total time delay in the feed forward path, comprising of $H_{FF}(s)$, the amplifier and $P(s)$ [6]. In order to achieve this when the system is transformed to the discrete domain with a sample frequency of $f_{s,pos}$, the input of the feedback subtractor is delayed with a fixed integer number of samples β and the input of $H_{FF}(s)$ is delayed with a tunable fractional number of samples α using the interpolating delay function

$$H_{delay}(z) = \alpha + (1 - \alpha)z^{-1}. \quad (4)$$

Fig. 3 shows the resulting discrete position control model with the added delays $H_{\text{delay}}(z)$ and $z^{-\beta}$, and a Zero-Order Hold (ZOH) block to convert the actual position from the continuous domain to the discrete domain with sample frequency $f_{s,\text{pos}}$. $H_{\text{FF}}(z)$ and $C(z)$ represent the discrete time models of the feedforward transfer function and position controller to which additional delays are added to make them causal.

Fig. 3: Outline of the discrete position control model including delays $H_{\text{delay}}(z)$ and $z^{-\beta}$.

A 3rd order motion profile with trapezoidal acceleration, consisting of velocity v , acceleration a , and jerk j , is used for the position input setpoint x_{set} (see Fig. 4 for a normalized representation).

Fig. 4: Normalized representation of the 3rd order motion profile used as position input.

Amplifier error modelling

Non-idealities of the amplifier are modelled in this research by means of two types of errors: additive current errors (offset, gain and non-linearity), and bandwidth limitation. Potential sources of amplifier errors are for instance non-idealities in current sensors, inductors, switching end-stages, signal processing and control [9].

Additive current errors

The potential current errors discussed in this research are offset current, gain error and non-linearity error [9]. A schematic outline of the amplifier additive current error model is shown in Fig. 5. A generic model is depicted that is independent from actual implementation of the amplifier. The respective error currents i_{offset} , $i_{\text{gainerror}}$ and i_{nonlin} are added, resulting in i_{error} which is added to i_{set} to obtain the modelled amplifier output current. A ZOH block is added at the input to convert i_{set} from the sample rate of the position loop $f_{s,\text{pos}}$ to the sample rate of the current loop $f_{s,\text{cur}}$, which corresponds with the fixed-step size at which the discrete amplifier and mechanical plant models are simulated.

While the implementation of the offset current and gain error is straightforward, for the generation of i_{nonlin} more explanation is required. A dimensionless current-spatial frequency f_{spat} [A/A] is defined to obtain non-linear components as a function of i_{set} . A single frequency component, induced by non-linear behaviour of the amplifier (e.g. originating from current sensor or switching end-stage), is thereby

Fig. 5: Schematic representation of the amplifier model, containing additive current errors.

superimposed to the spectrum of i_{set} . The performance of the system is subsequently evaluated for a range of current-spatial frequencies corresponding to the applicable frequency range of i_{set} .

Even and odd functions of i_{nonlin} as a function of i_{set} and f_{spat} are defined and given by

$$i_{\text{nonlin,even}} = I_{\text{NL}} \cdot \cos\left(2\pi f_{\text{spat}} \frac{i_{\text{set}}}{I_{\text{max}}}\right) \quad (5)$$

$$i_{\text{nonlin,odd}} = I_{\text{NL}} \cdot \sin\left(2\pi f_{\text{spat}} \frac{i_{\text{set}}}{I_{\text{max}}}\right) \quad (6)$$

where I_{NL} is the non-linearity current amplitude and I_{max} defines the applicable current range.

Example plots of both equations for $f_{\text{spat}} = 0.5$ [A/A] and $f_{\text{spat}} = 3$ [A/A] are shown in Fig. 6 and Fig. 7 for the even and odd functions respectively.

Fig. 6: Example plot of i_{nonlin} as a function of i_{set} for $f_{\text{spat}} = 0.5$ A/A and $f_{\text{spat}} = 3$ A/A, regarding even non-linearity.

Fig. 7: Example plot of i_{nonlin} as a function of i_{set} for $f_{\text{spat}} = 0.5$ A/A and $f_{\text{spat}} = 3$ A/A, regarding odd non-linearity.

Bandwidth limitation

The generic control outline of a current-controlled current amplifier is shown in Fig. 8 with an electrical plant P_e , an output current controller C_e with a direct feed forward path, and an anti-aliasing filter H_{AA} [3]. The anti-aliasing filter is required in a practical implementation, and since it influences the closed-loop control characteristics of the system, it is therefore included in the model. Furthermore, a ZOH block is added at the input to convert the sample rate of i_{set} from $f_{\text{s,pos}}$ to $f_{\text{s,cur}}$, the fixed-step size at which the model is simulated.

An equivalent electrical circuit schematic of P_e is shown in Fig. 9 with output capacitor C_f , load characteristics R_o , L_o , and a voltage source emulated EMF. The resonance of C_f and L_o is actively damped to a Butterworth characteristic by subtracting the measured capacitor voltage v_{Cf} , multiplied with damping

Fig. 8: Outline of the amplifier current control model.

Fig. 9: Schematic representation of electrical plant P_e .

factor K , from i_{set}^* , leading to

$$i_{amp} = i_{set}^* - K \cdot v_{Cf} \quad (7)$$

$$K = \sqrt{2 \cdot \frac{C_f}{L_o}}. \quad (8)$$

A state-space model is derived from the differential equations of the actively damped circuit in Fig. 9, resulting in

$$\begin{bmatrix} \dot{i}_{Lf} \\ \dot{v}_{Cf} \end{bmatrix} = \begin{bmatrix} -\frac{R_o}{L_o} & \frac{1}{L_o} \\ -\frac{1}{C_f} & -\frac{K}{C_f} \end{bmatrix} \begin{bmatrix} i_{Lf} \\ v_{Cf} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{C_f} \end{bmatrix} i_{set}^*. \quad (9)$$

The current controller C_e is of the PID type, with

$$C_e(s) = \frac{K_D s^2 + K_P s + K_I}{s}, \quad (10)$$

which is tuned for an open-loop bandwidth $f_{bw,cur}$ for the example in this section. The Bode diagrams of the discrete-time models with sample frequency $f_{s,cur}$ for the electrical plant P_e , current controller C_e , anti-aliasing filter H_{AA} , and resulting open-loop gain $H_{AA}P_eC_e$ are shown in Fig. 10. The anti-aliasing filter is a 2nd order Butterworth low-pass filter with a cut-off frequency of $f_{co} = 4f_{bw,cur}$.

Simulation results

To obtain insight in the influence of amplifier errors on positioning accuracy, the mechanical, electrical and control system models are combined into a single simulation platform. The resulting position error x_{error} is determined after a settling time of $t_{settling} = 3$ ms when acceleration $a = 0$ m/s² and jerk $j = 0$ m/s³ after accelerating from standstill to constant speed (see Fig. 11).

For imaging (lithographic) applications, two aspects of the position error of the moving stage are critical to its dynamic performance: low-frequency position error defined by MA (Moving Average), determining the absolute error; and a high-frequency part defined by MSD (Moving Standard Deviation),

Fig. 10: Bode diagram of the discrete-time models with sample frequency $f_{s,cur}$ for the electrical plant P_e , current controller C_e , anti-aliasing filter H_{AA} , and resulting open-loop gain $H_{AA}P_eC_e$.

determining image contrast loss; as defined in [10]. The MA/MSD cross-over frequency between low-frequency and high-frequency position error is $f_{co} = 273$ Hz for the system presented in this research. The respective position errors $MA(t)$ and $MSD(t)$ are defined as

$$MA(t) = \frac{1}{T} \int_{t-T/2}^{t+T/2} e(\tau) d\tau \quad (11)$$

$$MSD(t) = \sqrt{\frac{1}{T} \int_{t-T/2}^{t+T/2} (e(\tau) - MA(t))^2 d\tau} \quad (12)$$

where T represents the imaging expose time window, and $e(t)$ the stage position error x_{error} as a function of time t [10]. When determining the MA and MSD positioning error, the peak value of the respective definition is taken after the settling time $t_{settling}$ until deceleration, designated with $t_{MA/MSD}$ (see Fig. 11).

Fig. 11: Motion profile with designated $t_{settling}$ and $t_{MA/MSD}$.

When an ideal amplifier is used in the simulation platform with the parameters from Table I, the MA and MSD position errors are determined by the more than adequate numerical accuracy of the simulation run in MATLAB Simulink: $MA = 0.968$ fm and $MSD = 0.691$ fm. The desired position accuracy of the complete system of this research is in the order of 100 pm.

The parameters of the mechatronic system analysed in this research, representing a moving stage as shown in Fig. 1 and discussed above, are shown in Table I. Note that the maximum achievable acceleration

$$a_{\max} = \frac{k_m I_{\max}}{m} = 267 \text{ m/s}^2 \quad (13)$$

is more than the specified acceleration a . This leaves excitation room required for control and/or tolerances in the system.

Table I: System parameters

Parameter	Value	Unit	Description
k_m	200	N/A	Electromechanical plant
m	75	kg	
c	200	Ns/m	
v	3	m/s	Acceleration profile
a	200	m/s ²	
j	$3 \cdot 10^4$	m/s ³	
$f_{s,\text{pos}}$	20	kHz	Position controller
$f_{bw,\text{pos}}$	500	Hz	
R_o	5	Ω	Electrical plant
L_o	20	mH	
C_f	10	μF	
$f_{s,\text{cur}}$	1	MHz	Current controller
$f_{bw,\text{cur}}$	10	kHz	
I_{NL}	0.04	A	Non-linearity current error
$I_{\max}$	100	A	

Each individual error mechanism discussed in the previous paragraph has been simulated separately. The analysis of the resulting MA en MSD position errors as a function of the corresponding error is discussed in the next paragraphs.

Additive errors

Offset error

The current offset error range for which the simulation is run, is set from -1 A to $+1$ A, corresponding with 1% of a ± 100 A output current range, for which the results are shown in Fig. 12. Current offset errors are compensated by the high low-frequency gain of the position controller, causing no significant MA and MSD position errors.

Gain error

Fig. 13 shows the MA and MSD position errors for a modelled gain error ranging from -0.01 A/A to $+0.01$ A/A. From the results can be concluded that gain error, originating for instance from the current sensor, has a significant influence on position accuracy, increasing to the nanometer range for even relatively small gain errors.

Fig. 12: MA and MSD position error vs. current offset.

Fig. 13: MA and MSD position error vs. gain error.

Non-linearity error

Both even and odd non-linearity error functions are simulated for a spatial frequency f_{spat} range from 0 A/A to 50 A/A, and the respective graphs are shown in Fig. 14 and Fig. 15. The resulting MA and MSD position errors are again in the nanometer range. From the waveforms in both graphs can be concluded that distinct current-spatial frequencies are dominant and determine the potential position error, and thereby the acceptable upper limit for i_{NL} . A correlation exists between f_{spat} and the spectral content of i_{set} , the latter depending on the mechatronic system parameters. The significance of applying the combined modelling approach for evaluating the performance of the power amplifier is clearly observed.

Fig. 14: MA and MSD position error for even non-linearity as a function of f_{spat} .

Fig. 15: MA and MSD position error for odd non-linearity as a function of f_{spat} .

Bandwidth limitation

In order to obtain the bandwidth limitation of the current-controlled amplifier in the positioning system, the model for the current-controlled current amplifier as described above is simulated for an open-loop bandwidth $f_{\text{bw,cur}}$ ranging from 5 kHz to 20 kHz. The resulting MA and MSD position errors for each simulated $f_{\text{bw,cur}}$ are shown in Fig. 16, and the values increase significantly for a decreasing bandwidth from 8 kHz and lower. For a bandwidth of 7 kHz or higher, the resulting MA and MSD position errors remain in the order of 10 pm – 50 pm, which is relatively small.

The minimum at around 7.75 kHz occurs around a frequency for which most error frequency components cancel out. The location of the minimum is depending on the spectral content of the current reference i_{set} which depends on the mechatronic system parameters.

Fig. 16: MA and MSD position error vs. bandwidth.

Conclusions

A combined model containing electrical, mechanical and control systems is presented that is used to obtain specifications for the performance of a power amplifier in a mechatronic system with position accuracy requirements. An amplifier error model is incorporated that contains additive error components, i.e. current offset, gain error and non-linearity of the output current, and a generic model for a current-controlled current amplifier to emulate bandwidth limitation. For a 3rd order motion profile, the MA and MSD position error is determined for a range of values of each individual error mechanism in order to determine its significance.

The added offset current has no significant influence on the resulting position error for a mechatronic system actuated by a linear motor, as it is compensated by the position controller. On the contrary, even a slight gain error results in a significant position error. The same holds for introduced non-linearity errors, though from the simulation results can be concluded that a dependency exist with the specific mechatronic system parameters. Regarding bandwidth limitation, an optimal bandwidth for the analysed system seems to exist for the analysed system. Decreasing the bandwidth below the optimum results in a significant increase in position error.

A generic platform has been presented on which extended amplifier error analysis can be conducted and from which boundary specifications can be derived when the required position accuracy of the complete mechatronic system is known. The platform can be extended with increased level of detail in e.g. mechanical model and amplifier electrical model to obtain results that are more correlated to practical applications. Ensuing properly targeted amplifier requirements provide focused amplifier optimisation and mechatronic system design.

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