Acceleration Feedback in a Stage Having Paired Reluctance Linear Actuator with Hysteresis

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Abstract. The hysteresis force in the reluctance linear actuator limits its applications in the lithographic equipment for nanometer positioning. Acceleration feedback increases the mass of a system as experienced by disturbance force. In this paper, acceleration feedback is designed for the fine stage having paired reluctance linear actuator with hysteresis. The feature of this method lies in that by treating the hysteresis force as a disturbance force, we can design the acceleration feedback loop to reduce the influence of the hysteresis force. The proposed method can improve the process sensitivity at low frequency. Acceleration feedback implementation in digital controller and control for a fine stage mounted on a coarse stage are discussed. Simulation results show that the proposed method is effective in overcoming the hysteresis force and promising in precision stage control.

Introduction

In integrated circuit (IC) manufacturing, lithographic scanner usually uses the fine stage to achieve high velocity and high precision positioning during quick synchronous scanning [1]. The more functionality is packed into each IC, the smaller the feature size (indicative of the smallest component that can be manufactured in one IC) is required. Today, the minimum feature size is about 15 nm [2]. These requirements make the fine stage in the lithographic scanner challenging from a position control perspective. The next generation fine stage actuator should provide a larger force density and higher force accuracy.

Due to its low efficiency and high power dissipation, the voice coil actuator is no longer the best choice as the main driving actuator for the next-generation fine stage [3]. Since the reluctance force is proportional to the square of the excitation current, the reluctance linear actuator has a unique property of small volume, low current and high power, it can provide a solution for driving the fine stage [4]. However, the reluctance linear actuator has non-negligible hysteresis [5] between the input current and output force, which may introduce an expected force error in the nanometer positioning. So we need to study the control method to obtain a predictable reluctance force for the high accuracy requirements.

Conventionally, the positioning control design of a stage falls into two parts: (1) the actuator dynamics is omitted and the force is designed, (2) the current reference is computed from the designed force based on their static nonlinear relation [6]. But it does not consider the effect of hysteresis and parameter uncertainty on the force accuracy. For the hysteresis compensation, using the inverse hysteresis model [7] is the most noticeable approach. Reference [8] proposed an inverse hysteresis model and obtained a good performance for the reluctance linear actuator. However, the above methods both need precise hysteresis model, which is generally complex and hardly to obtain. Owing to its online self-learning ability, the adaptive neural network [9] is used to compensate the hysteresis. Due to the fact that neural network has a complex algorithm; it is not easy to apply in the real-time digital controller.

Meanwhile acceleration feedback increases the virtual mass of a system as experienced by disturbance force. Acceleration feedback has been applied to land gears [10] and the voice coil actuator [11] as an auxiliary to position control. The acceleration feedback added in an existing position controller for a wafer stage control has been proposed in [12], which splits the acceleration
controller into a forward and backward path to create the original process behavior for position controller, and removing the high-bandwidth requirement.

The hysteresis influence in reluctance linear actuator introduces is mainly in the low frequencies [13]. In this paper, we regard the hysteresis force as a disturbance force and design the acceleration feedback [12] for the fine stage having paired reluctance linear actuator with hysteresis. The proposed method can improve the process sensitivity at low frequency and remove the high-bandwidth requirement. The proposed method does not need the inverse hysteresis model and can be easily applied in the real time digital controller. Simulation results show that the proposed method is effective in overcoming the hysteresis force and promising in precision stage control.

This paper is organized as follows. In Section 2, reluctance actuator models with and without hysteresis are briefly reviewed. A fine stage having paired reluctance linear actuator control is presented in Section 3. Acceleration feedback designed for the fine stage having paired reluctance linear actuator is proposed in Section 4. Finally, simulation results are illustrated in Section 5.

**Reluctance Linear Actuator**

Reluctance linear actuator is a type of electric motor that induces non-permanent magnetic poles on the ferromagnetic rotor and produces temporary magnetic. The reluctance actuator is named as such because it uses magnetic reluctance to generate force, which can be called reluctance force. The E/I core actuator is a kind of most basic linear reluctance linear actuator [14]. As shown in Figure 1, the actuator includes a generally Cobalt-Iron shaped electromagnet and an I shaped target. The electromagnet has an electrical coil wound around the center section. Current flowing through the coil generates a magnetic flux and this flux creates a reluctance force on the target. The amount of current determines the amount of reluctance force. The reluctance force $F$ acting on the I target is described by:

$$ F = \eta \frac{i^2}{x_g} $$  

where $\eta = \frac{\mu_0 N^2 A}{4}$ is the electromagnetic constant, $\mu_0$ is the permeability of air, $N$ is the number of turns in coil on the center leg of the E-core and $A$ is the area of the air gap. It is a lumped model which disregards unmodeled effects such as hysteresis leakage, fringing and saturation.

However, the E-core coil uses soft magnetic material, which has magnetic hysteresis [5] between the magnetic field $H$ and the bulk magnetic flux density $B$. The hysteresis can be defined as a loop in the input-output map and it is shown that the hysteretic $B$-$H$ can be modeled [8] by a hysteresis operator. Then

![Figure 1. Sketches of the E-core Actuator.](image-url)
We get a reluctance linear actuator model with hysteresis as:

$$F = \eta \left[ H_{\text{hys}} \left( i, \lambda_1, \lambda_2 \right) \right]^2$$

(2)

where $H_{\text{hys}} \left( i, \lambda_1, \lambda_2 \right)$ is the parametric hysteresis operator and defined as follows:

Let $r(k), y(k)$ be bounded, $\lambda_1, \lambda_2 > 0$. Then the parametric hysteresis operator

$$y(k) = H_{\text{hys}} \left[ r(k), \lambda_1, \lambda_2 \right]$$

is defined as follows: when $M_z = \frac{z^{(r+y)}}{m_z}$,

$$(k) = r(k) + y_x - r_x + m - \frac{1}{\lambda_2} W(\lambda_2, m \cdot e^{(r(y(m+r)))})$$

(4)

When $(k+1) - r(k) < 0$,

$$(k) = r(k) + y_x - r_x - n + \frac{1}{\lambda_2} W(\lambda_2, n \cdot e^{(r(n-(k+r)))})$$

(5)

where $m = \lambda_1 + r_x - y_x$ and $n = \lambda_1 - r_x + y_x$, $r_x = r(k^\prime)$ and $y_x = y(k^\prime)$. The indicator $k^\prime$ denotes the last time instant before $k$ when the difference of $r$ changed sign, i.e. an extremum occurred, which corresponds to a corner point of the $y-r$ curve. The parameter $\lambda_x$ represents the amount of hysteresis around the straight line $r(k) = y(k)$ and defines the asymptotes, while the parameter $\lambda_y$ defines the smoothness of the hysteresis loops, i.e. the rate of convergence towards the left or right asymptote. $W$ is the principal branch of the Lambert W function [15].

This model contains both the hysteresis and obvious square linearity between the input current $i$ and output force $F$. Since the gap distance is related to the hysteresis in the reluctance linear actuator, the parameter $\lambda_x$ in Equation (2) can be selected as $\lambda_x = \frac{\lambda}{x_g}$ with $\lambda > 0$. If the reluctance actuator is modeled by Equation (2), the curves of input current and the corresponding output force are obtained as shown in Figure 2. It can be seen that the hysteresis model Equation (2) provides a good approximation for the hysteresis phenomenon between the input current $i$ and output force $F$. 

Figure 2. Shapes of an input current and the corresponding output force based on the reluctance actuator model with hysteresis.

Figure 3. Paired E/I core actuator.
Control for a Fine Stage Having Paired Reluctance Linear Actuator

Fine Stage Having Paired Reluctance Linear Actuator

Usually, fine stage in a lithographic tool has six degrees of motion [1] and six single-input single output controllers are used to control each motion. In this article, only one motion is considered, such as the scanning direction.

Due to the nature of reluctance force, an E/I core actuator can only generate a unidirectional attractive force. To generate an active force in the opposite direction, a second actuator needs to be placed on the opposite side. Figure 3 illustrates a simplified one motion fine stage [4] having paired reluctance actuators E-core 1 and E-core 2. The gaps between the E-core 1,2 and the stage are \( g_1 \) and \( g_2 \), which can be measured by suitable sensors such as capacitor sensor. The force \( F_1 \) and \( F_2 \) are nonnegative, while the difference between \( F_1 \) and \( F_2 \) can take any value and direction. In the initial state, the gaps are \( x_{g1} = x_{g0} \) and \( x_{g2} = x_{g0} \), where \( x_{g0} \) is the initial gap. In Figure 3, we define the right as the positive direction. Furthermore, when the stage moves to the positive direction, the gaps become \( x_{g1} = x_{g0} - x \) and \( x_{g2} = x_{g0} + x \) respectively where \( x \) is the global placement and can be measured by position sensor such as a laser interferometer [4].

Control of Paired Reluctance Linear Actuator

A conventional control scheme is depicted in Figure 4, in which the controller \( C(s) \) is formed by a proportional integral-derivative (PID) controller, a low-pass filter and a lead compensator. In the feedback loop, the controller uses the position of the stage to generate the force. The filter \( Q(s) \) generates a feedforward force based on the set-point position. When \( P(s) \) can be properly described by \( 1/\text{ms}^2 \), \( Q(s) = \text{ms}^2 \), generating a force that is proportional to the set-point acceleration.

The final position accuracy is determined by the measurement error, disturbance forces including the nonlinearity force caused by the hysteresis which has an effect on the closed loop performance. Rejection of output (measurement) disturbance and input (force) disturbances is judged by, respectively, the output sensitivity

\[
G_{ou} = \frac{1}{1 + P(s)C(s)}
\]

and the process sensitivity

\[
G_{pu} = \frac{P(s)}{1 + P(s)C(s)}
\]

Based on the conventional controller shown in Figure 4, the proposed control loop for the fine stage having paired E/I core actuator is shown in Figure 5. \( C_1(s) \) denotes the position controller, \( Q_1(s) \) denotes the feedforward controller, \( P_1(s) \) denotes the fine stage process, “EI1” and “EI2” denote the E-core 1 and E-core 2, “NC1” and “NC2” denote nonlinear current compensator and “FD” denotes the force distributor.

Figure 4. Basic control scheme.
In Figure 5, “FD” distributes the desired force to each E/I core actuator as follows:

\[ F_{d1} = F_0 + F_a / 2, \]
\[ F_{d2} = F_0 - F_a / 2 \]

where \( F_0 \) is the bias force generated by paired E/I core actuator respectively in the opposite direction, which provides a zero net force on the stage, thus maintaining the position of the stage. In this paper, \( F_0 \) is determined as \( F_0 = F_{\text{max}} / 2 \), in which \( F_{\text{max}} \) is the maximum force corresponding the maximum acceleration. More details about how to select the bias force \( F_0 \) can be found in patent [6].

Since there exits strong linearity between the input current \( i \) and output force \( F \), from Equation (1), direct nonlinear current compensator “NC1” and “NC2” can be obtained as:

\[ i_1 = \frac{F_{d1} \cdot x_{g1}^2}{\eta_d}, \]
\[ i_2 = \frac{F_{d2} \cdot x_{g2}^2}{\eta_d} \]

where \( \eta_d \) is the estimate of real constant \( \eta \). However, the reluctance actuator use soft magnet material, there exists a hysteresis between the input current \( i \) and output force \( F \) in reluctance actuators “EI1” and “EI2” as shown in Figure 5. Since the nonlinear current compensators “NC1” and “NC2” cannot compensate the hysteresis between the input current \( i \) and output force \( F \) in each E/I actuator, a hysteresis force results in between the position controller force command \( F_d \) and the real output force \( F \). However, the hysteresis influence must be considered in the high-precision positioning [8]. So, it is necessary to find the hysteresis compensation method for the reluctance linear actuator. In the following, the acceleration feedback control will be introduced to reduce the hysteresis influence.

**Acceleration Feedback Control**

**Basic Idea**

Consider the relationship between the force command \( F_j(d) \) and output force \( F \) and define the hysteresis force error \( F_{\text{hys}} \) as \( F_{\text{hys}} = F_j - F \). Then from Figure 5, a simplified control scheme is shown in Figure 6, in which the stage transfer function \( M_s(s) \) is simplified into two integrators and the fine stage mass \( m \), ignoring extra dynamics in \( M_s(s) \) and the other disturbance force. From Equation (7), if the mass of the fine stage is increased while keeping the position control band width equal, we can get the same output sensitivity but improved process sensitivity. Since a larger mass is generally not expected for high acceleration control in the fine stage, increasing the virtual mass instead by the feedback of the acceleration in addition to the position, and may hence improve the process sensitivity by reducing the influence of the hysteresis force.
Design of Acceleration Feedback in Frequency Domain

A control structure as shown in Figure 7 using the acceleration feedback method [12] is applied to reduce the influence of the hysteresis in paired reluctance linear actuator. It is better that the acceleration feedback loop introduced does not cause any change in the process behavior. So the acceleration loop filter $H_1(s)$ and $H_2(s)$ are designed as such that the transfer function from the position controller output to stage acceleration remains the same, namely $1/m_v$:

$$\frac{H_1(s)/m_v}{1+H_1(s)H_2(s)/m_v} = \frac{1}{m_v}$$  \hspace{1cm} (10)

It follows that

$$H_1(s) = 1 + \frac{1}{m_v} H_a(s)$$ \hspace{1cm} (11)

$$H_2(s) = \frac{H_a(s)}{1+H_a(s)/m_v}$$ \hspace{1cm} (12)
Satisfy such requirement, where $H_a(s) = H_1(s)H_2(s)$. The hysteresis force rejection only depends on $H_a(s)$, which can be designed as a second-order low-pass filter or an integrator.

**Acceleration Feedback Implementation for Discretization**

So far, the acceleration feedback used in paired reluctance actuator is considered in continuous-time. In this section, the discretization method [12] is used in the acceleration feedback for the reluctance linear actuator as shown in Figure 9.

Since the sampling effect must be taken into account when the digital controller is applied in reality. Usually, there exits a $p$-sample delay in the process transfer function and a $q$-sample delay caused by the acceleration measurement. From Equation (10), we have

$$
\frac{z^{-p}H_1(z)}{1 + \frac{z^{-(p+q)}}{m_s}H_1(z)H_2(z)} = \frac{z^{-p}}{m_s}
$$

(13)

The discrete acceleration feedback filter $H_1(z)$ and $H_2(z)$ corresponding to the delays $p$ and $q$ can be obtained

$$
H_1(z) = 1 + \frac{z^{-(p+q)}}{m_s}H_a(z)
$$

(14)

$$
H_2(z) = \frac{H_a(z)}{1 + \frac{z^{-(p+q)}}{m_s}H_a(z)}
$$

(15)

The feedback acceleration $a_n$ is computed from the measured position $x_s$ by a digital double different

$$
a_n = T(z)x_s = \frac{(1-z^{-1})^2}{T_s^2}x_s
$$

(16)

where $T_s$ is the sample time. A disadvantage of double differentiation is its sensitivity to noise. But the closed acceleration loop has a low-pass characteristic, so it can reduce the noise. In addition, the least-squared filter used as filter may reduce the noise impact [16].

As shown in Figure 8, in order to reduce the increased position settling error, a relative acceleration is used by the deviation between the acceleration feedforward and the acceleration feedback [12] by shifting the feedforward entry point can reduce the increased position settling error caused by $H_1(z)$ and $H_2(z)$. A delay of $p+q$ samples must be used to match the acceleration feedback delay from the acceleration feedforward, so $M_z = \frac{z^{-(p+q)}}{m_s}$. 

![Figure 9. Total feedback scheme for coarse stage and fine stage using acceleration feedback.](image-url)
**Acceleration Feedback in a Fine Stage Mounted on a Coarse Stage**

The true reluctance linear actuator has a moving range of only about 1 \( \text{mm} \), which is insufficient for the stage in the lithographic equipment. This problem is solved by introducing a coarse stage actuated by the linear motor [1], which can travel over large distances with moderate micrometer-range accuracy, and moves the fine stage actuated by the reluctance linear actuator [6]. Usually the E/I core part is mounted on the coarse stage to avoid crossover of cables and cooling hoses to the accurate fine stage.

A total basic control scheme, which combines the fine stage and coarse stage controllers with acceleration feedback loop, is shown in Figure 9. Since the fine stage has a key role in the final position accuracy, the acceleration feedback is added into the fine stage control loop. In Figure 9, \( P_c(z) \) represents the coarse stage process system. The coarse stage is required to track the fine stage to keep the E/I core and fine stage close together. To this end, the gap sensors measure the gap distance between the coarse stage and fine stage by the “gd” signal. Since the fine stage is decoupled from the coarse stage by tracking the interferometer, the coarse stage controller \( C_c(z) \) is designed based on the dynamics of the coarse stage without taking the fine stage into account. In the feedforward path, since a reaction force is added to the coarse stage while the fine stage is accelerated, the mass of the fine stage must be included to accelerate the coarse stage.

**Simulations**

In order to verify whether the proposed acceleration feedback configuration can be applied in high-precision systems, we do the following simulations. For comparison the no acceleration feedback case is used.

The reluctance linear actuator with hysteresis is modeled by Equation (2), whose parameters are chosen as in the patent [4]: the maximum force is about 200 \( \text{N} \), the maximum gap \( x_g \) between the E-core and I-target is 0.4 \( \text{mm} \) and the constant \( k = 7.73 \times 10^{-8} \). Here, the hysteresis operator parameters are chosen \( \lambda_1 = 0.02 \) and \( \lambda = 10 \).

The fine stage mass is 10 \( \text{kg} \) and the bias force is \( F_0 = 150 \text{N} \), which is applied on both E/I core actuators. The gaps \( x_{g1} \) and \( x_{g2} \) between the E-core 1, 2 and the stage are in the range of 0 \( \mu \text{m} \) to 400 \( \mu \text{m} \) and the initial gap is \( x_{g0} = 400 \mu \text{m} \). The coarse stage mass is 20 \( \text{kg} \).

A typical set point position profile [1], which is used during exposing in lithographic equipment, is determined by the 3rd order trajectory planning method [17]. The position and velocity are shown in Figure 10. Further, we define the scanning velocity settling time as the time instants after which the position tracking error is less than 10 \( \text{nm} \). The scanning velocity is 0.25 \( \text{m/s} \), the acceleration is \( 2 \times 10^{-3} \text{m/s}^2 \).

In the practical application, the position controller is designed as a PI controller and a lead compensator, which make the position-controlled fine stage system having about a 100 \( \text{Hz} \) bandwidth corresponding the mechanical structure. The acceleration feedback filters \( H_1(z) \) and \( H_2(z) \) are designed as follows. \( H_1(z) \) is chosen as an integrator with a gain that creates a closed acceleration loop bandwidth of \( f_{\text{acc}} = 130 \text{Hz} \).

\[
H_1(z) = \frac{2\pi m \, f_{\text{acc}} T_s}{1 - z^{-1}}
\]

(17)

By assuming that the process delay is \( p = 1 \) and the acceleration measurement delay is \( q = 1 \), we obtain \( M(z) = z^{-2}/m_1 \). From Equation (14) and (15), it follows that

\[
H_1(z) = 1 + \frac{2\pi m \, f_{\text{acc}} T_s}{1 - z^{-1}} z^{-2}
\]

(18)

\[
H_2(z) = 1 + \frac{2\pi m \, f_{\text{acc}} T_s}{1 - z^{-1} + 2\pi f_{\text{acc}} T_s} z^{-2}
\]

(19)
The control objective is to make the stage position $m_s$ follow the reference position $x$ and has a quickly scanning velocity settling time. Figure 11 shows the position tracking error with and without acceleration feedback. The scanning velocity settling time is about 56 ms without acceleration feedback which is slower than 46 ms of acceleration feedback.

Figure 12 shows the fine stage position loop process sensitivity, defined by Equation (7) which indicates the influence of the hysteresis force to the position. From Figure 12, the fine stage position loop process sensitivity without acceleration feedback is about $-170 dB$ and with acceleration feedback decreases to about $-230 dB$ at low frequency. It can be seen that, the acceleration feedback provides a low process sensitivity for the hysteresis force.

The closed control loop bode plots of the fine stage with and without acceleration feedback is shown in Figure 13 (a). It can be seen that, the acceleration feedback loop added into the system loop does not change the fine stage close loop for low frequencies, the magnitude increases a little for high frequencies. The closed control loop bode plots of the coarse stage with and without acceleration feedback is shown in Figure 13 (b) and the coarse stage close loop.

**Conclusion**

This paper has proposed a new acceleration feedback control method for the fine stage having paired reluctance linear actuator with hysteresis. Noting that we treat the hysteresis in the reluctance linear actuator as a disturbance force to design the acceleration feedback loop. The practical implementation has been discussed for the digital controller. The simulation results show that by properly choosing $H_1$ and $H_2$, the acceleration feedback can provide a low process sensitivity and a short scanning velocity settling time. The proposed method is effective in overcoming the reluctance linear actuator with hysteresis and promising in high-precision control applications.
Figure 12. Position loop process sensitivity of the fine stage.

Figure 13. Fine stage close control loop bode plots.

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