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# Comparative Analysis of Generalized Model predictive Controller and PID plus feed-forward controller for wafer stage motion in Lithography.

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**Abstract**

In IC manufacturing, the process of printing IC patterns on silicon wafer by using an opt-mechanical approach is called lithography [2]. Precise wafer stage movement in the wafer scanning process is one of the determining factors to improve the performance of IC manufacturing. This stringent precision requirement of the wafer scanning process is backed by an advanced controlling algorithm to meet its precision requirement. The wafer stage, which holds the wafer moves precisely to transfer the circuit pattern (reticle) into the wafer.

In this paper, the wafer stage in lithography modeled as second-order linear Time invariant system; then generalized model predictive controller (MPC) and PID plus feed-forward controller designed and its performance compared to track two dies wafer stage scanning process. Scanning trajectory of the wafer stage during wafer scanning designed based on the velocity and acceleration limit of the wafer stage. This trajectory is used as a reference trajectory for the feed-forward controller and the model predictive controller. Trajectory to scan two dies designed; then the PID plus feed-forward controller and MPC controller employed to track this trajectory. By varying the trajectory, the performance of those controllers is compared in various metrics to evaluate the controller performance which are; Integrated absolute error (IAE), total variation (TV), and vibration reduction. The model predictive controller and PID plus feed-forward controller trajectory tracking performance are verified via the MATLAB/Simulink. The simulation proved that; though PID plus feed-forward controller and MPC controller can have proximate; Model predictive controller approach performs better than PID plus feed-forward controller in trajectory tracking and vibration avoidance.

**Keywords: Lithography, wafer stage, Model predictive controller (MPC), PID plus feed-forward controller, dies, reticle.**

## I. INTRODUCTION

The larger part of all IC manufacturing makes use of the so-called wafer stepper, which is an opt-mechanical system used to produce IC in mass [1]. This process of printing IC patterns on silicon wafers by using an opt-mechanical approach is called lithography. Figure 1.1 shows a schematic set-up of a wafer-stepper which used for mass production of IC's [2]. A beam of low wavelength (ultra-violet) light or even an ion- or electron beam is projected through a mask (reticle) and a lens system onto a silicon disc, called the wafer, containing a light-sensitive layer. The pattern of this reticle will result in an exposure of a photographic imprint of the IC on the silicon disc. Nowadays, the wafer stage is subject to increasing requirements on the tracking performance due to smaller critical dimensions and larger throughput capacity [3]. Two degrees-of-freedom (2-DOFs) control structure combining feedback and feed-forward control is widely used in precision motion systems [4,5].in general feedback control is used to robustly stabilize the system and enhance the disturbance rejection ability, whereas feed-forward control is to improve the tracking performance. Plenty of papers have been working on precision motion control of the wafer stage. Different researchers use different controlling approaches and system analysis methods. B-J. Hou, J-S. Gao and et al proposed repetitive plus PID plus feed-forward control to improve the trajectory-tracking performance of linear motors in the wafer stage of lithography [6]. M. Li, Y. Zhu, and et al proposed an integrated model-data-based zero-phase error tracking feed-forward control strategy for the ultra-precision wafer stage [3]. L. Hong and et al wrote a paper on a particular mechanical servo system presented based on the design requirement of scanning wafer stage of 0.1µm lithography. They propose; to achieve high accuracy and high speed, linear motor and voice coil motor is employed to control long-stroke motions and short stroke motions, respectively [7]. This paper employs a general model predictive controller and PID plus feed-forward controller approach to control the precision motion of the wafer stage; which is driven by a linear motor and the result is compared.

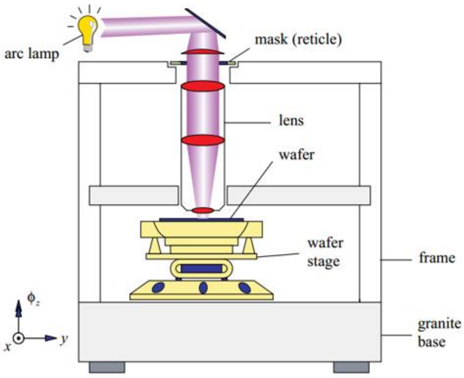

Figure 1-1: Schematic overview of a wafer-stepper [1].

## II. MATERIAL AND METHODS

This prospective controller comparative study was carried out on a lithography wafer stage prototype system placed in new energy and smart grid Automation technology laboratory in university of electronics science and technology of china (UESTC) for experimental verification of precision control methods. A picture of the stage is shown in Fig. 1-2. This test-bed setup is meant to imitate one axis of the wafer stage part of a full industrial wafer scanner.

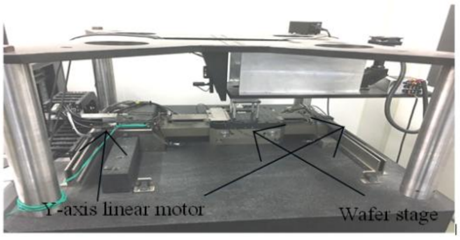

Figure 1-2 Lithography wafer stage prototype experimental setup

The wafer stage system in Fig. 1-2 is composed of three movable parts: one in the X direction; two in the Y direction. The actuator placed in the x-axis holds the wafer stage and it moves to x-direction during scanning. The other two actuators in the y-direction are responsible to move the x-axis actuator including the wafer stage to Y-direction. The wafer stage has guide rails, and it is floated on an air bearing to reduce friction. The stator of the Y direction linear motor is fixed on the rotor of the X-direction linear motor. The stator of the X-direction linear motor is fixed on a granite flat marble.

One wafer has a 200 to 300 mm diameter. Because of the limitation of the lens; it cannot expose the whole wafer at one time [8-10]. So that, this wafer should be partitioned into multiple square areas, so-called dies then each individual dies scan at a time. To expose a single die the linear motor in the X direction holding the wafer stage accelerates to constant velocity; which is used for scanning. Then a constant scan velocity the exposure will make and the motor placed in Y direction step the wafer stage to next die position. This process will repeat until the whole wafer area will expose and the chrome patterns transfer to the whole wafer.

### Procedure methodology

To compare the performance of the PID plus feed-forward and generalized model predictive controller in wafer stage movement; this Paper follows the following procedure. As I described above the prospective controller comparison carried out on lithography wafer stage prototype system placed in new energy and smart grid Automation technology laboratory in University of electronics science and technology of China (UESTC). This prototype is considered as a plant and its mathematical modeling is analyzed. Then reference trajectory that resembles the scanning of two dies is designed and finally; PID plus feed-forward and the generalized model predictive controller is designed and its performance on tracking the given reference trajectory compared.

### i. System Modeling

The wafer stage of the lithography is attached directly to the mover of a linear motor; so we can consider the stage as the load of the system and the linear permanent magnet iron less magnet synchronous motor (LPMILSM) as an actuator. By combining the electromagnetic force with the wafer stage model we can model the overall system model. The overall system model should also include the disturbance force that will occur in linear permanent magnet motors. To obtain precise positioning and high tracking speeds, the working stage is driven by a linear motor with an air bearing, and thus viscosity and friction can be neglected. The open-loop model for a single wafer stage driven by a linear motor is shown in Figure 1-3 below. [13]

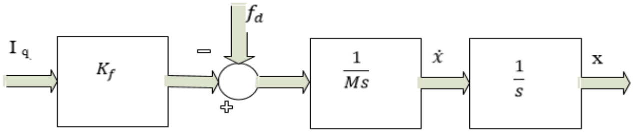

Figure 1-3 Simplified open loop-model of linear motor and working stage (wafer stage)

M-----------------Mass of the moving parts, including the wafer stage and a linear motor rotor,
$i_q$-----------------Input current
$K_f$----------------Force constant
$I_q$ --------------- Input current
$f_d$----------------Disturbance force

So, the model can be described by combining Newton motion law and electromagnetic force of linear motor.

$$F_e = M\frac{dx^2}{dt} = K_t * i_q \quad (1\text{-}1)$$

## System simulation model

The wafer stage needs to track the desired trajectory with a given accuracy for a successful lithographic exposure. The motion control system deals with the servo-control problem for accurately following such a trajectory, which needs accurate modeling of the plant and a high-performance controller approach. The closed-loop position control of the overall system can be described in the block diagram below.

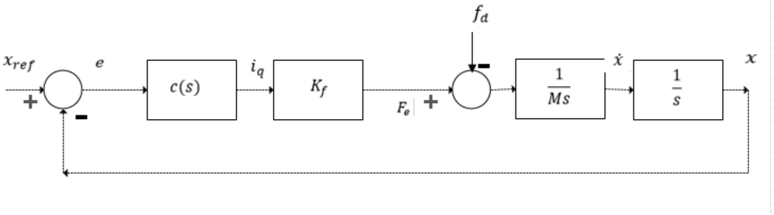

Figure 1-4 Control model of the wafer stage

Where $x_{ref}$ and $x$ are the reference command and the actual position respectively. The error between the reference and the output feed to the controller and the controller manipulates the manipulated variable to minimize the error and follow the reference trajectory based on the control objectives.

## Scanning trajectory

In the typical operation of an industrial wafer scanner, the wafer stage performs a step and scan motion – the stage scans at constant velocity for the length of one die in the x-axis direction, then the stage steps to the next die in the y-axis direction and repeats the constant-velocity scan back in the opposite direction [2]. In the x-axis, a typical scanning motion of the wafer stage consists of a short acceleration to the desired scan velocity, a constant velocity scan over some distance, and then a deceleration to rest, then a short wait time while the stage is stepped in the y-direction. This is followed by the same motion in the return direction. Therefore the wafer stage scanning motion can be considered as an example of point-to-point motion in terms of velocity. I generate a polynomial spline scanning trajectory using Mat lab script. This paper designs two different trajectory profiles; which individual differ by the acceleration it takes to reach the constant scanning velocity. The form of the trajectory is similar; it differs by the time takes to scan two dies.

- **0.5 m/s$^2$ stage acceleration trajectory profile**

This trajectory profile indicates the wafer stage have 0.5m/s$^2$ acceleration to reach constant scanning velocity. By taking the maximum displacement the wafer stage covers and the maximum scanning velocity; the required parameter to design the trajectory is determined . Table 3-1 shows significant parameters used to design 0.5 m/s$^2$ wafer acceleration trajectory profile to scan two dies.

Table 3-1: Parameters to design 0.5 m/s2 stage maximum acceleration trajectory profile.

| Parameter | Max- Displacement | Max- Velocity | Max-Acceleration | $t_{\bar{a}}$ | $t_{\bar{v}}$ | $t_{\bar{d}}$ |
|---|---|---|---|---|---|---|
| Value | 0.25m | 0.1875m/s2 | 0.5m/s$^2$ | 0.375 s | 0.958 s | 0.375 s |

Where,
$t_{\bar{a}}$ **:** Acceleration time to reach constant scan velocity
$t_{\bar{v}}$: Time to conductscanning
$t_{\bar{d}}$: Declaration time

- **2.5 m/s$^2$ stage acceleration trajectory profile**

This trajectory profile indicates the wafer stage takes 2.5m/s$^2$ acceleration to reach constant scanning velocity. The calculated parameter to design the trajectory and the generated trajectories are depicted in the following table.

Table 3-2 Parameters to design 2.5 m/s2 stage maximum acceleration trajectory profile

| Parameter | Max- Displacement | Max- Velocity | Max-Acceleration | $t_{\bar{a}}$ | $t_{\bar{v}}$ | $t_{\bar{d}}$ |
|---|---|---|---|---|---|---|
| Value | 0.25m | 0.1875m/s2 | 2.5m/s$^2$ | 0.707 s | 1.258 s | 0.707s |

Those trajectories have the same shape, but different time intervals to conduct the scanning. As you see in the above trajectory tables; the total time covered to scan two consecutive dies; times is decreased as the acceleration of the stage increase. Which means the time taken to conduct scanning (tv) is decreasing when the acceleration to reach to maximum constant velocity increase. This means the amount of IC manufacturing will increase while the scanning time decreases. The 5m/s$^2$wafer stage acceleration trajectory profile also calculated based on the above two trajectory profiles.

### ii. PID plus feed-forward controller

A good feedback controller design is necessary for stabilizing systems, improving tracking performance, and making performance robust to disturbances (such as gravity, random disturbances, etc.) However, because feedback control by definition uses sensor information feedback to correct for errors, it is limited to being reactive. When a set point change is needed, the feedback controller takes some time to correct it. On the other hand, feed-forward controllers use prior known information about the desired trajectory and plant dynamics to predict the necessary controller action. For high-precision motion control applications, both well-designed feedback and feed-forward controllers are needed.This paper combines the advantage of both PID feedback and feed-forward control to achieve the stringent precision requirement of the wafer stage motion control system. The control objective of those controllers is to minimize the tracking error of the scanning trajectory.During wafer scanning, the rising time should be less than equal to the steeping time of the wafer stage and the settling time is the time taken to reach constant scanning velocity. By Considering the time response requirement to scan a single die ;better performance tracking PID parameters found as

- Proportional gain ( $K_p$ )= 4.5*10$^4$
- Integral gain ($K_I$)=1.7*10$^5$
- Derivative gain ($K_D$)=1.4*10$^4$

In this paper the mass feed-forward controller is designed to approximate the inverse plant model.

$$F_s = \frac{d^2 r(t)}{dt^2} * m \quad (1\text{-}2)$$

Where r (t) is the scan trajectory and m is the gain of the feed-forward controller.The value of m found to be 0.556.

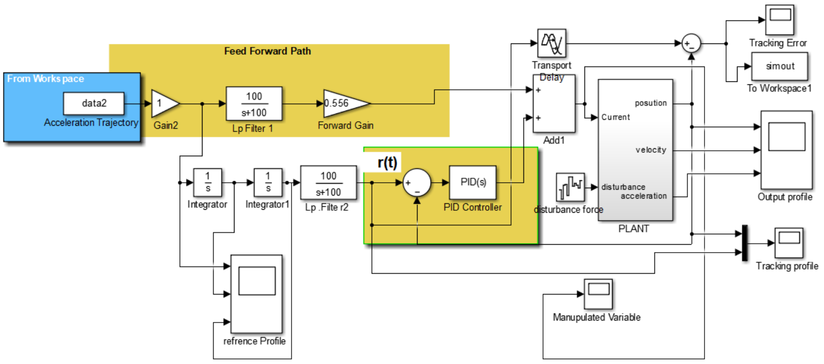

Figure 1-5 PID plus feed forward Simulation block diagram.

### Simulation results for PID plus feed forward controller

The simulation result that shows tracking of reference trajectory and its error in different wafer stage acceleration depicted in the following figures below.

I. **0.5 m/s$^2$ stage acceleration trajectory profile**

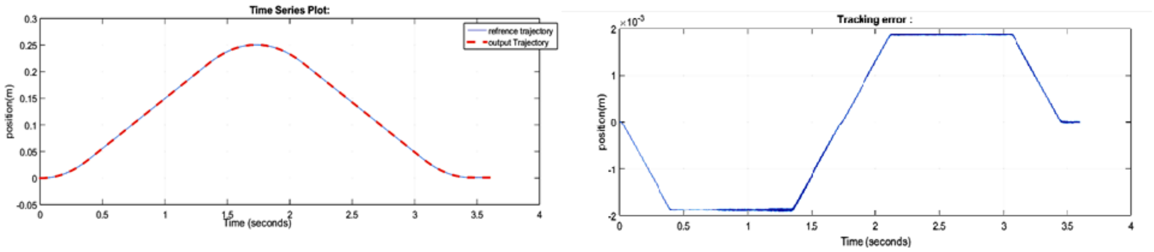

Figure 1-6 Trajectories scanning and its error for 0.5m/s2 stage acceleration respectively

### II. 2.5 $m/s^2$ wafer stage acceleration trajectory profile

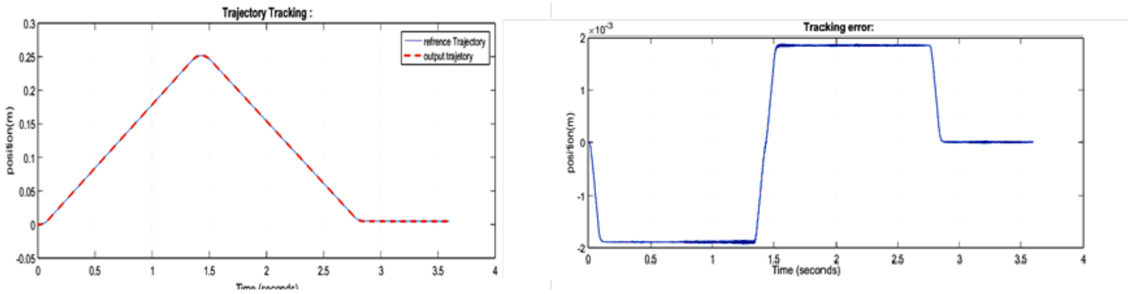

Figure 1-7 Trajectories scanning and its error for 2.5m/s2 stage acceleration respectively

### III. 5 $m/s^2$ stage acceleration trajectory profile

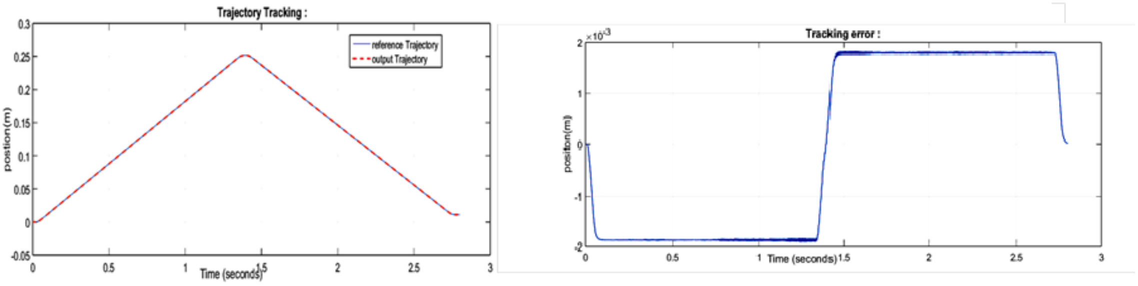

Figure 1-8 Trajectories scanning and its error for 5m/s2 stage acceleration respectively

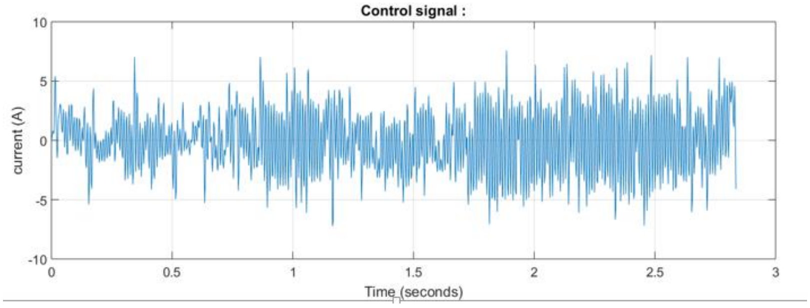

Figure 1-9 Control signal to track a trajectory of 5m/s$^2$ stage acceleration

## Generalized Model Predictive Control

Model Predictive Control (MPC) is a class of control algorithms that utilize an explicit process model to predict the future response [11]. This predictive nature of the controller helps to achieve stringent precision requirements in the ultra-precision control system. The wafer stage motion control is one kind of ultra-precision system in the IC manufacturing. The wafer stage motion during scanning follows a specific trajectory to conduct scanning. The model predictive controller takes this specific trajectory as a reference and by considering the model of the system; it provides a control variable that governs the output trajectory to follow the reference trajectory as precisely as possible. The manipulated variable is deduced from the optimized cost function; which helps to improve the performance of the manipulated variable. This portion discussed employing the generalized model predictive control (MPC) approach to the second-order wafer stage model to track the scanning trajectory. The wafer stage considered as single input single output model predictive control; the input is the reference trajectory and the output is the position of the stage; so the control objective is to find the control variable which minimize the error between the desired trajectory and reference trajectory.

### Design of discrete model for MPC

The wafer stage described by a second-order transfer function and considering the test-bed motor parameters; the plant can be described as:

$$p(s) = \frac{K_t}{Ms^2} = \frac{36}{20s^2} \quad (1\text{-}3)$$

By taking the position $(x)$ and velocity $\left(\frac{dx}{dt}\right)$as a state vector, it can describe the plant in state-space representation. The applied current (I $_q$) to the actuator is the manipulated variable in this model and the output trajectory $y$ is the controlled variable.

$$x(k+1) = \begin{pmatrix} 1 & 0 & 0 \\ 1e^{-3} & 1 & 0 \\ 1.8 * 10^{-3} & 1.8 & 1 \end{pmatrix} x(k) + \begin{bmatrix} 1e^{-3} \\ 5e^{-3} \\ 9e^{-7} \end{bmatrix} u(k) (1\text{-}4)$$

$$y(k) = [0\ ,0, 1]x(k) (1\text{-}5)$$

### Optimization objective function

For a given reference trajectory $r\ (k_i)$ at sample time, $k_i$, within a prediction horizon the objective of the predictive control system is to bring the predicted output as close as possible to the reference signal, where we assume that the set point signal remains constant in the optimization window. This objective is then translated into a design to find the 'best' control parameter vector $\Delta U$ such that an error function between the set-point and the predicted output is minimized. Assuming that the data vector that contains the set-point information is:

$$R_s^T = [1,1,1...1] r\left(k_i\right) (1\text{-}6)$$

The cost function $J$ that reflects the control objective can be defined as

$$J = (R_s - Y)^T(R_s - Y) + \Delta U^T \bar{R} \Delta U \qquad (1\text{-}7)$$

Where, the first term is linked to the objective of minimizing the errors between the predicted output and the set-point signal while the second term reflects the consideration given to the size of $\Delta U$ when the objective function $J$is made to be as small as possible. $\bar{\boldsymbol{R}}$Is a diagonal matrix in the form that $\bar{R}=\ r_w I_{Nc*Nc} (r_w \geq 0)$ where $r_w$is used as a tuning parameter for the desired closed-loop performance.

For the case that $r_w$= 0, the cost function is interpreted as the situation where we would not want to pay any attention to how large the $\boldsymbol{\Delta U}$might be and our goal would besolely to make the error $(R_s - Y)^T(R_s - Y)$ as small as possible. For the case of larger$r_w$, the cost function is interpreted as the situation where we would carefully consider how large the $\boldsymbol{\Delta} U$might be and cautiously reduce the error $(R_s - Y)^T(R_s - Y)$ to find the optimal $\boldsymbol{\Delta U}$that will minimize $\boldsymbol{J}$, $\boldsymbol{J}$is expressed as:

$$J = (R_s - Fx(k_i))^T (R_s - Fx(k_i)) - 2\square U^T \varnothing^T (R_s - Fx(k_i) + \square U^T (\varnothing^T \varnothing + \bar{R}) \square U \quad (1\text{-}8)$$

From the first derivative of the cost functions $J$: $\frac{\partial J}{\partial \square U} = 0$ (1-9) it found the optimal solution for the control signal as:

$$\square U = (\varnothing^T \varnothing + \bar{R})^{-1} \varnothing^T \left(R_s - Fx\left(k_i\right)\right) (1\text{-}10)$$

With the assumption that $(\emptyset^T \emptyset + \bar{R})^{-1}$exists. The matrix $(\emptyset^T \emptyset + \bar{R})^{-1}$ is called the Hessian matrix in the optimization literature. Note that $R_s$is a data vector that contains the set-point information expressed as:

$$R_s^T = [1,1,1...1] r\left(k_i\right) = R^{-}{}_{s}\, r\left(k_i\right) (1\text{-}11)$$

Where, $\overline{R_s} = \left[1,1,1...1\right]^T$ and the size of the matrix is $1 * N_p$

The optimal solution of the control signal is linked to the set-point signal $r(k_i)$ and the state variable $x(k_i)$ via the following equation:

$$\triangle\, U = (\emptyset^T \emptyset + R^{-})^{-1} \emptyset^T \left(\bar{R}_s \mathrm{r}(k_i) - \mathrm{Fx}(k_i)\right) \qquad (1\text{-}12)$$

### Constrained function

In PID plus feed-forward control, even if we achieve the control objective by tracking the reference trajectory in millimeter accuracy range; the control variable is exposed to huge overshot while the stage going through the acceleration phase. This was one shortcoming of the PID plus feed-forward controller. Whereas in Model predictive control controlled variable amplitude can be limited to a certain range operational interval. This feature of model predictive control prevents the control signal from being implemented to the plant when its amplitude exceeds its limit. If we do not pay attention to the saturation of the control, then in the presence of constraints, the closed-loop control performance could severely deteriorate.

This research considers the amplitude of the control variable (current) as a constraint variable. The maximum allowable current drowns by the linear motor is limited to 5.5A. This means if the model predictive controller calculated the control variable more than 5.5 A; it should prevent implementation. Mathematically it can be described as:

$$-5.5A \le u\left(k\right) \le 5.5A \text{ (1-13)}$$

**Optimization window**

Upon formulation of the mathematical model, the next step in the design of the predictive control system is to calculate the predicted plant output with the future control signal as the adjustable variables.This prediction is described within an optimization window.This section will examine in detail the optimization carried out within this window.Here, I assume that the current time is $k_i$and the length of the optimization window is $N_p$as the number of samples.

Assuming that at the sampling instant $Ki$,$Ki > 0$ the state variable vector $x(ki)$ is available through measurement, the state $x(ki)$ provides the current system information. The future control trajectory is denoted by

$$\Delta u\left(k_i\right), \Delta u\left(k_i+1\right), \ldots, \Delta u\left(k_i+Nc-1\right) \text{ (1-14)}$$

Where, $N_c$is called the control horizon dictating the number of parameters used to capture the future control trajectory. With given information $x\ (k_i)$, the future state variables are predicted for $N_p$ number of samples, where Np is called the prediction horizon. $N_p$, is also the length of the optimization window. We denote the future state variables as

$$x(k_i+1 \mid k_i, x(k_i+2 \mid k_i, \ldots, x(k_i+m \mid k_i,, \ldots, x(k_i+N_P \mid k_i) \qquad \text{(1-15)}$$

Where, $x(k_i+m|k_i)$is the predicted state variable at $K_i+m$ with given current plant information $x(k_i)$. The control horizon $Nc$ is chosen to be less than (or equal to) the prediction horizon $N_p$ .Based on the state-space model (A, B, C), the future state variables are calculated sequentially using the set of future control parameters:

$$x\left(k_i+N_p|k_i\right)=A^{N_p}x\left(k_i\right)+A^{N_p-1}B\Delta u\left(k_i\right)+A^{N_p-2}B\Delta u\left(k_i+1\right)+\ldots+A^{N_p-N_c}B\Delta u\left(k_i+N_c-1\right)$$

(1-16)

From the predicted state variables and the set point vector the predicted output variables derived as:

$$\mathrm{Y}=\mathrm{FX}\left(\mathrm{k_i}\right)+\varnothing\Delta\mathrm{U} \qquad \text{(1-17)}$$

Where

$$F=\begin{bmatrix} CA \\ CA^2 \\ CA^3 \\ . \\ . \\ . \\ CA^{N_p} \end{bmatrix} \quad \emptyset=\begin{bmatrix} CB & 0 & 0 & \ldots\ldots & 0 \\ CAB & CAB & 0 & & 0 \\ CA^2B & CAB & CB & & 0 \\ . & . & . & & \\ . & . & . & & \\ . & . & . & & \\ CA^{N_p-1}B & CA^{N_p-2}B & CA^{N_p-3}B & \ldots\ldots & CA^{N_p-N_c}B \end{bmatrix}$$

From the Augmented matrix we can determine $\emptyset$ and $F$ matrix easily and then we will find the control signal and output signal. In the concept of receding horizon principle, even if we can calculate $N_c$ amount control signal for future control action; we just apply the first element and ignore the rest. Every sampling instant we calculate the control signal in receding horizon fashion with in a given optimization window. $\emptyset$ *and* $F$ Matrix can be determine based on the given optimization window (prediction horizon) and the augmented plant parameters. Ones' we find the above matrix it is easy to find to the optimal solution of the control signal ($\Delta U$) based on the given set point signal. Then the output signal (Y) can find based on the equation.

## III. SIMULATION RESULT

This paper simulates scanning trajectories which represent the scanning of two dies. The Mat lab/ Simulink simulation to track a reference scanning trajectory of a single die using Model predictive toolbox shown in the figure below.

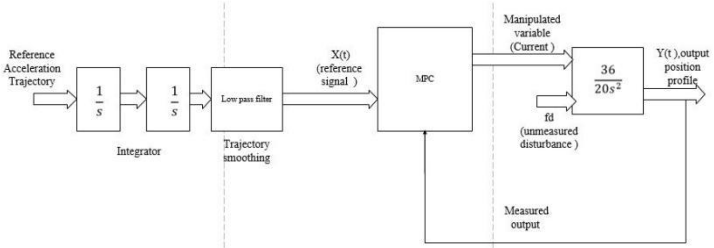

Figure 1-9 MPC simulation block diagram

**Simulation results for MPC**

Scanning trajectory tracking for different wafer stage acceleration and its tracking error discussed in figures below.

**I. <u>0.5 $m/s^2$ wafer stage acceleration trajectory profile</u>**

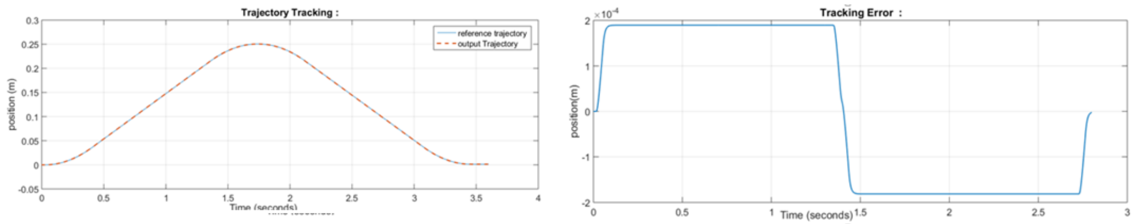

Figure 2-1 Trajectory scanning and its error for 0.5m/s2 stage acceleration respectively

**II. <u>2.5 $m/s^2$ wafer stage acceleration trajectory profile</u>**

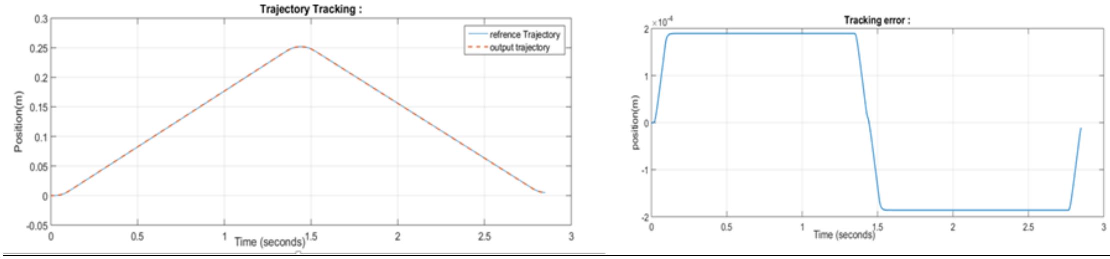

Figure 2-2 Trajectory scanning and its error for 0.5m/s2 stage acceleration respectively

**III. <u>5 $m/s^2$ stage acceleration trajectory profile</u>**

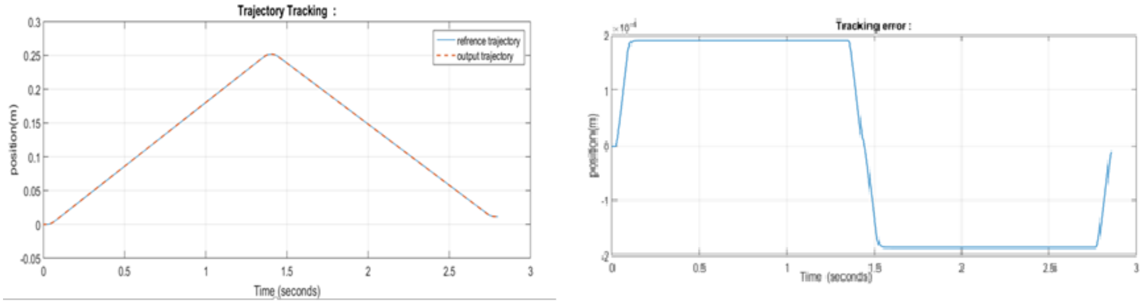

Figure 2-3 Trajectories scanning and its error for 5m/s2 stage acceleration respectively

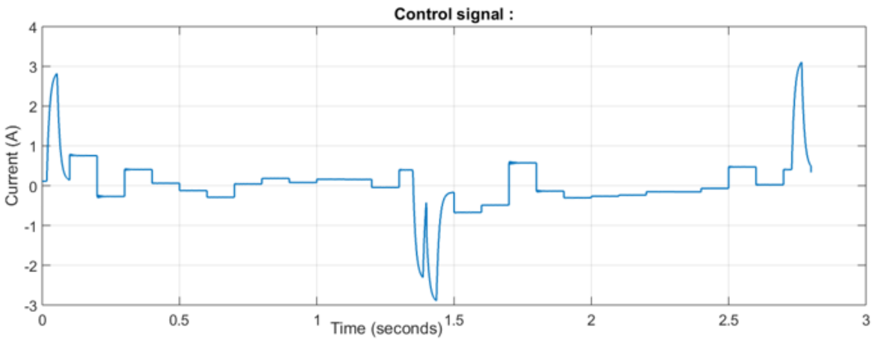

Figure 2-4 Control signal to track figure 2-3 trajectory

## IV. RESULT DISCUSSION

Figures 1-6 to 1-8 depict the performance of the PID plus feed-forward controller for different wafer stage acceleration profiles. As it is shown in the figure above the precision of the wafer stage is limited to the millimeter range and it is highly affected by vibration (it shows in the tracking error figures 1.6-1.8). And when the stage passes through acceleration or declaration the manipulated variable experience huge overshoot, this behavior is dangers for the machine safety and also has a negative impact on the accuracy of the position. Generally, PID plus feed-forward controller achieves the range of millimeter accuracy, whereas it has the following short comes.

- ✓ Have vibration
- ✓ Huge overshoot in manipulated variable (current )
- ✓ It doesn't have good capability of disturbance rejection. If the disturbance varies a little it will affect the precision of the system.

From figure 2.1 to 2.3 shows the simulation result of the model predictive controller for different wafer stage acceleration. From those above three simulation results we can conclude that trajectory tracking while scanning two wafer dies precision is about 190 micrometer and there is no vibration in the wafer stage during scanning; even if the acceleration of the wafer stage increase. Figure 2-4 below shows the control signal generated to track the scanning trajectory. As we see the control signal of the MPC controller the current signal is limited to 5 A current and the Total variation of this signal is relatively lower than PID plus feed-forward controller (compare figure 1-9 and figure 2-4 ).Which brings the advantage of reducing control effort in the controller.

**Comparison between PID plus feed forward and MPC**

Integrated absolute error (IAE), total variation (TV) and vibration reduction performance metrics analyzed to compare the controller performances.

**Integrated absolute error (IAE)**

Integrated absolute error is defined as [12]

$$IAE \square \int_0^\infty \left| r(t) - y(t) \right| dt \qquad (5\text{-}42)$$

In this thesis the time interval indicates the duration to scan the wafer $r(t)$ indicates the reference trajectory and $y(t)$ indicates the output trajectory. Table 5.1 shown below compare the IAE between PID plus feed-forward controller and MPC controller while it scan two wafer dies in different wafer stage acceleration.as we have seen the result from the tale the MPC controller has lower IAE than PID plus feed forward controller.

Table 5-1 IAE of PID plus feed forward and MPC

| IAE | | | |
|---|---|---|---|
| wafer stage acceleration | 0.5m/s$^3$ | 2.5m/s$^2$ | 5m/s$^2$ |
| PID plus feed forward | 2.232 m | 2.183m | 2.072m |
| MPC | 0.8234 m | 0.8183m | 0.8111m |

### Total Variation (TV) of Manipulated Variable

The total variation is a good measure of the "smoothness" of a signal and should be as small as possible [32].in this paper, the control signal is current applied to the plant. And the summation interval is sample time that cover two wafer dies scan. When we compare Figure 1-9 and Figure 2-4; which is the control signal of MPC and PID plus feed-forward controller. MPC control signal is smoother than PID plus feed-forward controller. From the Figure, we can conclude that MPC has a lower total variation (TV) than PID plus feed-forward controller.

**Vibration Reduction**

Another control performance compared to those controllers is the ability to reduce vibration while scanning conduct. The wafer stage hits by vibration when it accelerates to reach maximum scanning velocity. The controller should work to minimize this vibration to transfer a neat chrome pattern to the wafer. As it depicted in the error graph of both controllers; the MPC controller error graph is straight and has no oscillation than PID plus feed-forward controller. It indicates the MPC controller performs better in the reduction of vibration during scanning.

## V. CONCLUSION

The simulation results prove that MPC has lower integrated Absolute error (IAE) and lower total variation of the manipulated variable; that indicates that MPC is better in those performance Metrics. Model predictive controller (MPC) performs better performance in removing vibration than PID plus feed-forward control. MPC also prevent the control variable (current) to go beyond the maximum allowable current of the linear motor by considering the constraint nature of the MPC controller, whilst the PID plus feed-forward controller signal exhibit overshot during the stepping phase which brings deterioration in system control performance and vibration during scanning. Generally, though PID plus feed-forward controller and MPC controller can have proximate; Model predictive controller approach perform better in trajectory tracking and vibration reduction.

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