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Magnet assisted stage for vibration and heat reduction in wafer scanning

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ABSTRACT

Wafer scanning stages must deliver high accelerations/decelerations at motion reversals to achieve high productivity. The resulting inertial forces cause vibration of the machine frame and overheating of the linear motor actuators, thus diminishing the accuracy and increasing the cost of the stages. The novel stage design presented in this paper uses magnetic repulsion to provide assistive forces to the linear motors during acceleration/deceleration to reduce actuation force requirements and overheating. Vibration is reduced by transmitting the assistive forces to the ground, not the machine frame. 66% and 55% reduction in vibration and heat, respectively, are demonstrated using a prototype stage.

1. Introduction

Scanning stages are used for precise positioning in a variety of advanced manufacturing processes like laser patterning, 3-D printing, and pick-and-place type applications for hard drive manufacturing. In particular, they are used for precise positioning at various stages of silicon wafer processing, such as optical lithography and inspection [1].

In response to increased throughput demands, wafer scanning stages must deliver high accelerations/decelerations (acc/dec) at motion reversals. The resulting high inertial forces that are borne by the linear motor actuators cause Joule heating proportional to the square of the motor current, leading to increased thermal errors. Various methods such as forced cooling, thermal error compensation, light-weighting and optimal control of the motor drives can be used to mitigate thermal errors [2–5]. Forced cooling requires cooling circuits and external heat exchangers, which add to design complexities and raise costs. Effective thermal error compensation requires reliable thermal models and temperature sensor networks. Light-weighting could reduce structural stiffness and introduce unwanted vibrations. Control techniques can only offer incremental benefits for a given motor design.

In addition to generating excessive heat, the high inertial forces in scanning stages cause residual vibration of the machine frame, which adversely affects positioning speed and precision [6]. Various methods such as tuned mass dampers, input shaping and counter motion devices can be employed to mitigate residual vibration [7–10]. Tuned mass dampers and input shapers lose effectiveness when operating conditions change. Counter motion devices are bulky, expensive and energy intensive.

A passive-assist device (PAD) is a spring mounted in series or parallel with an active element (e.g., motor). A PAD consisting of a torsional spring in parallel with a rotary motor has been shown to significantly reduce motor currents and power, when properly tuned for a family of motion trajectories [11]. However, the PAD could increase motor currents/heat for operating conditions other than the ones for which it was tuned, making it limited in versatility. This paper builds on preliminary work reported by the authors in [12] by introducing a novel PAD concept that uses magnetic repulsion to simultaneously reduce vibration and heat during motion reversals in wafer scanning. A pair of repelling permanent magnets is used to store and release the stage's kinetic energy during deceleration and acceleration, respectively, to alleviate motor force requirements thus reducing heat. Residual vibrations are lessened by channeling the assistive forces provided by the magnets to the ground, instead of to the vibration-sensitive machine base [13]. The magnets can be automatically positioned to provide optimal assist for a given scan trajectory, thus enhancing the versatility of the PAD. Section 2 explains the magnet-based PAD concept in more detail, while Section 3 describes the design, sizing and control of a prototype magnet assisted stage. Experimental results obtained from the designed stage are presented and discussed in Section 4, followed by conclusions in Section 5.

2. Magnet assisted stage concept

2.1. Combined vibration and heat reduction using PADs

Fig. 1(a) shows the typical scanning profile for a silicon wafer. The *y*-axis advances in successive steps while the *x*-axis shuttles back and forth (i.e., scans) repeatedly. The scanning motion of the *x*-axis is the main focus of this paper. It consists of a constant velocity (CV) and motion reversal (MR) regions. The CV region of each scan is where the actual manufacturing process (e.g., lithography or inspection) takes place, so positioning must be extremely precise. The MR regions are not useful to the actual manufacturing process; they must therefore be executed as fast as possible (i.e., with high acc/dec) to boost throughput while ensuring that the precision of the CV regions is not compromised.

A schematic of the *x*-axis of a wafer scanning stage with PADs (denoted by dotted springs) is shown in Fig. 1(b). The scanning table,

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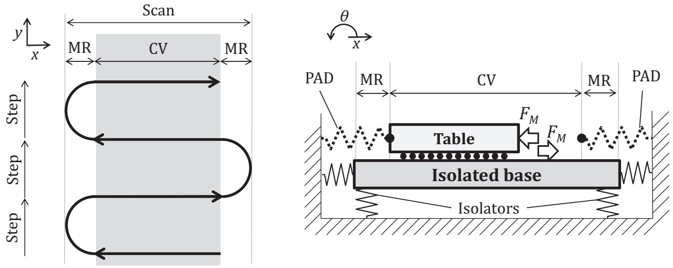


(a) (b)

Fig. 1. (a) Regions of a silicon wafer scanning profile. (b) Schematic of x-axis of silicon wafer scanning stage including PADs.

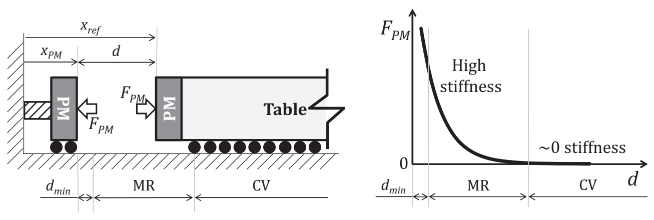
actuated by motor force F_M, is mounted on a rigid base. The base is isolated from ground vibration using very soft springs (typically pneumatic isolators) in order to achieve the desired precision in the CV regions [6]. However, when the table is in the MR regions, the presence of the soft springs causes unwanted horizontal and rocking (i.e., θ) vibration of the base due to the large inertial forces present during acc/dec [6]. Upon arriving at the next CV region, the stage must wait for the residual vibration to settle before the manufacturing process resumes, thus slowing down the process. Moreover, large inertial forces draw high electric currents from the motors, causing unwanted heat that compromises accuracy in the CV regions.

This paper proposes a novel approach for simultaneously reducing vibration and heat using PADs. As shown in Fig. 1(b), the PADs are designed to store and release some of the table's kinetic energy when the table is in the MR regions, thus reducing heat by lowering the magnitude of F_M needed for acc/dec. Vibrations are reduced by transmitting the reaction forces from the PADs directly to the ground so that they do not disturb the vibration-sensitive base of the machine [13]. An ideal PAD would store and release all of the stage's kinetic energy. Additionally, it would disengage completely from the scanning table upon entering the CV regions to stop the transmission of ground vibrations to the table, and to prevent the actuators from doing unnecessary work against the PAD to maintain the stage at constant velocity.

2.2. Approximation of ideal PAD by magnets with tunable stiffness

We propose approximating the ideal PAD described in Section 2.1 using a pair of repelling permanent magnets (PMs); one mounted to the moving table and the other fixed just outside the MR region (see Fig. 2). Magnetic repulsion provides a nonlinear stiffness relationship which is almost zero when the distance d between the magnets is large, but grows exponentially as d decreases. The effective stiffness of the device is made tunable by allowing x_{PM}, the position of the PM just outside the MR region, to be adjustable. Therefore, an optimal x_{PM} value can be determined for any desired motion profile $x_{ref}(t)$ of the stage (t denotes time). For instance, to minimize heat, x_{PM} can be selected to minimize the resistive losses in the motor, represented by the objective function f_H given by

$$f_H = \int_0^T \left(\frac{F_M(t)}{K_M}\right)^2 dt \approx \int_0^T \left(\frac{m\ddot{x}_{ref}(t) - F_{PM}(t)}{K_M}\right)^2 dt \qquad (1)$$



(a) (b)

Fig. 2. (a) Realization of a PAD using magnetic repulsion (shown for only one side of the table). (b) Characteristic force–distance curve of a pair of repelling permanent magnets.

where K_M is the motor constant and m is the moving mass of the stage. T is the time period of one scan cycle (consisting of 1 CV and 2 MR regions). $F_{PM}(t)$ can be calculated from the known $F_{PM}(d)$ curve of the PM pair making up a PAD according to the expression

$$F_{PM}(t) = F_{PM}(d(t)) = F_{PM}(x_{ref}(t) - x_{PM}) \qquad (2)$$

The minimization of residual vibration can be realized approximately by selecting x_{PM} to minimize the peak motor force represented by the objective function f_V expressed as

$$f_V = \max_{t \in [0,T]}(|F_M(t)|) \approx \max_{t \in [0,T]}(|m\ddot{x}_{ref}(t) - F_{PM}(t)|) \qquad (3)$$

Note that, with x_{PM} determined using Eq. (1) or (3), d_{min}, the minimum gap between a PM pair for a given scan trajectory, can be determined as

$$d_{\min} = \max\left[\min_{t \in [0,T]}(|x_{ref}(t) - x_{PM}|), \delta\right] \qquad (4)$$

where δ represents a safe gap between the magnets to prevent them from colliding.

3. Prototype design, sizing and control

3.1. Prototype design

A magnet assisted stage prototype is designed according to the general concept described in Section 2. Table 1 summarizes the design targets for the stage and Fig. 3 shows the CAD drawing of the prototype stage. The scanning table is guided by two sets of air bushings (New Way Air Bearings, S302502), each riding on a 25 mm precision ground shaft. A pair of linear shaft motors (Nippon Pulse, S250Q) with 600 N peak and 150 N continuous force (combined) is selected to drive the table. The table position is measured using linear encoders (Renishaw, RGSZ20) with 4.88 nm resolution post-interpolation. The scanning table sits on a 900 mm × 600 mm × 100 mm granite base suspended by four pneumatic isolators (Bilz, BiAir® 0.5-ED).

Table 1
Design targets of magnet assisted stage prototype.

Specification	Design target
Travel	300 mm
Max. acceleration	35 m/s^2 (3.5 g)
Max. scan speed	1 m/s
Table size	360 mm × 360 mm
Moving mass	~15 kg

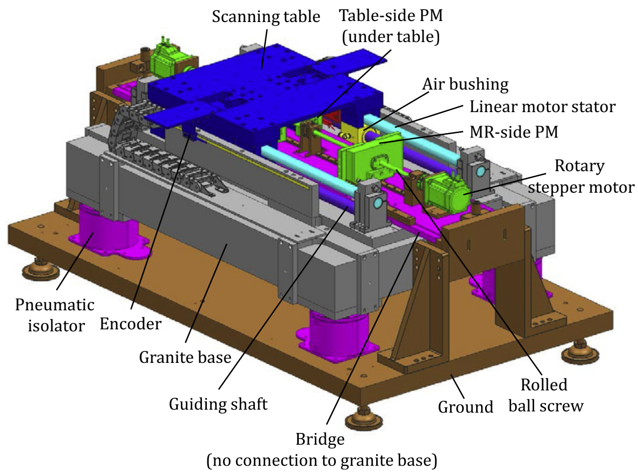


Fig. 3. CAD model of magnet assisted stage prototype.

Two pairs of permanent magnets are installed on either end of the stage (their design and sizing is discussed in the next section). An inexpensive servo comprising a single linear guide (Misumi, SSEBZ13) and a 10 mm-diameter rolled ball screw