Damping force control of frictionless MR damper associated with hysteresis modeling

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Abstract. This study presents hysteresis modelling and damping force control of the frictionless magnetorheological (MR) damper for semiconductor manufacturing stage. The vibration sources of the semiconductor stage can be classified as two. The one is environmental vibration from the floor, and the other is transient vibration occurred from the stage moving. The transient vibration has serious adverse effect to the process because the vibration scale is quite larger than other vibrations. Therefore, in this research, the semi-active MR damper which can control the transient vibration is devised. In addition, the stage needs to be isolated from tiny vibration to achieve high grade vibration level. At the high frequency range, MR damper acts like a rigid body if the dry friction exists. So the tiny vibration is transferred to the stage directly. Therefore, a dry friction of the MR damper must be removed. In order to achieve this goal, a frictionless MR damper is originally designed. After then, a designed MR damper is manufactured and its damping force characteristics and hysteresis behaviors are evaluated by experiment. The biviscous hysteresis model of MR damper is formulated and its accuracies are evaluated. Finally, damping force control performances using the hysteresis model is experimentally evaluated.

1. Introduction
The main stream of ultra-precision machining industries like semiconductor is featured by huge scale, integration and multifunction. Therefore, the accuracy limitation of machining, manufacturing and measuring systems is required to be continuously increased [1-3]. The tiny vibration from environment and transient vibration from the moving stage make noticeable problems to the accuracy. Also the transient vibration makes time problem. After a stage moving, transient vibration is occurred and process must be stopped while the vibration is reduced to suitable range. In order to resolve these problems, three types of control systems have been proposed; passive, active and semi-active. The passive system featuring rubber mount or air spring is normally used for vibration absorption. This system provides design simplicity and cost-effectiveness. However, it cannot provides sufficient performance at these days because the accuracy level of the ultra-precision system becomes more important and moving mass on the stage is operated as a huge vibration source. Also it can’t reduce the transient vibration fast. Because of the passive system has very low viscosity for vibration isolation at high frequency. On the other hand, the active control system provides high control performance at wide frequency range. However, the performance at resonance frequencies is limited and requires high

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power source and large space. It is well known that the semi-active control system offers a desirable performance without requiring large power source and space.

Recently, many research works on semi-active actuator and its vibration control strategies have been proposed and successfully implemented. Hong et al. proposed electro-rheological fluid mounts for vibration control of a frame structure [4]. They developed an ER fluid mount and controlled the vibration using optimal controller. Wang et al. developed a new magnetorheological fluid-elastomer mount [5]. They designed a new type of MR-elastomer mount and evaluated its performance. Seong et al. proposed a Preisach hysteretic compensator for the damping force control of MR damper [6]. They evaluated the hysteretic behavior of MR damper and formulated the hysteretic model and compensator using Preisach model. Choi et al. proposed magnetorheological isolators for vibration isolation [7]. They evaluated a new nonlinear hysteresis model with simplicity in form for MR isolator.

In this research, we propose the semi-active MR damper to obtain superior vibration control performance of the semiconductor equipment system. As a first step to achieve this goal, a semi-active MR damper for the stage mount is proposed and designed. The MR damper is then manufactured and its damping force characteristics are evaluated by experiment. Also the hysteretic behavior of the MR damper is evaluated and modeled using asymmetric biviscous model. Finally, the biviscous hysteretic compensator is formulated and its damping force control performance is evaluated by experiment.

2. MR Damper

The vibration sources of a semiconductor manufacturing stage can be classified as two parts: one is environmental vibration from the floor, and the other is transient vibration occurred from the stage movement. The transient vibration occurred from the stage movement affects seriously to the process because the vibration scale is quite larger than other vibrations. Thus, the use of active actuator to attenuate this vibration is not appropriate because it requires a large power source and space. Therefore, in this research, a semi-active MR damper which can control the transient vibration without requiring large power source and space is adopted. On the other hand, micro- or nano-scale tiny floor vibrations need to be isolated from the stage. If the mount has a dry-friction, tiny vibrations are transferred to the stage through friction part. So the dry-friction of the MR damper needs to be eliminated. Therefore, a new type of MR damper which can eliminate the seal friction is proposed in this study.

Figure 1 shows the configuration of the new type MR damper for the semiconductor manufacturing stage. A seal is removed from a piston head. And a gap between a piston head and a cylinder can be used as an orifice. And the silicon film is adopted for sealing between the piston and cylinder. The silicon film is fixed on the piston and the cylinder each side and crumpled according to the piston movement as shown in Figure 1. So the proposed MR damper doesn’t make any dry friction. Figure 2
shows the design and manufactured photograph of the proposed MR damper. The gap (orifice) between the piston head and cylinder is 3 mm and the silicon film is adopted. Magnetic field of the piston head is analyzed and maximized by using Ansys™. Figure 3 shows the experimental configuration for damping force measurement of the manufactured MR damper. The MR damper is excited by amplitude $\pm 4.8$ mm and frequency 3.0Hz using a electromagnetic shaker. This excitation condition is similar to the transient vibration from the stage movement. The damping force of the MR damper is measured by a loadcell and MR damper movement is measured by accelerometer. Input signal is generated from a DSP system, and this signal is fed back to the current amplifier and applied to the MR damper.
The measured damping force characteristics of MR damper are shown in Figure 4. The passive damping force range is 107.42 N and the maximum damping force range at 1.5A is 569.05 N from measured data. This damping force range obtained in this test is suitable for vibration control of the semiconductor equipment.

3. Hysteretic model

As shown in Figure 5, MR damper has two types of hysteresis. The one is velocity dependent hysteresis and the other is field dependent hysteresis. If the hysteretic behavior is compensated by model, the control accuracy can be increased. Thus, this behavior should be accommodated in order to achieve more accurate damping force control.

In this research, biviscous model is adopted and modified for represent the hysteretic behavior of the proposed MR damper. Nonlinear hysteretic biviscous model for MR damper proposed by Wereley et al. utilized a set of piecewise linear functions [8]. This nonlinear hysteretic biviscous model considers that the damping force is symmetric at jounce and rebound mode. However, as shown in Figure 5 (a), damping force is not symmetric at jounce mode and rebound mode. Therefore, asymmetric biviscous model is proposed as shown in Figure 6. Asymmetric biviscous model has 10 parameters and every parameter have different values. Also Each parameters is characterized through second- and fourth-order polynomials derived on the basis of parameters identified for each current condition [8]. Therefore, hysteretic behavior of the MR damper can be modelled as follows:
Figure 6. Asymmetric biviscous model.  

Figure 7. Model prediction.

\[
F_d = \begin{cases} 
  c_{po}\dot{x} + f_{y_n} \leq \dot{x}\leq 0 & \dot{x} > 0 \\
  c_{pr} (\dot{x} - \dot{x}_{0_p}) \leq \dot{x} \leq \dot{x}_{y1_n} & \dot{x} > 0 \\
  c_{po}\dot{x} + f_{y_p} \geq \dot{x}\geq \dot{x}_{y2_p} & \dot{x} > 0 \\
  c_{po}\dot{x} + f_{y_p} \geq \dot{x}\geq \dot{x}_{y1_p} & \dot{x} < 0 \\
  c_{pr} (\dot{x} - \dot{x}_{0_n}) \leq \dot{x}\leq \dot{x}_{y1_p} & \dot{x} < 0 \\
  c_{po}\dot{x} + f_{y_n} \leq \dot{x}\leq \dot{x}_{y2_n} & \dot{x} < 0 
\end{cases}
\]  

where \( \dot{x} \) is velocity of piston, \( c_{po}, c_{pr}, f_{y_n}, f_{y_p}, \dot{x}_{0_p}, \dot{x}_{0_n}, \dot{x}_{y1_n}, \dot{x}_{y1_p}, \dot{x}_{y2_p}, \) and \( \dot{x}_{y2_n} \) are parameters of asymmetric biviscous model. Figure 7 shows the model predicted results. As shown in Figure 8, asymmetric biviscous model is well follow the hysteretic behavior.

Figure 8. Flow chart of asymmetric biviscous compensator.

4. Damping force control

Because of the asymmetric biviscous model is nonlinear, inverse model cannot be exist. Therefore the compensation algorithm is needed for damping force control. The flow chart for implementation of asymmetric biviscous compensator is shown in Figure 8. The proposed compensation algorithm
consists of estimation and linearization of nonlinear hysteretic behavior using asymmetric biviscous model.

Figure 9 presents the damping force control results under sinusoidal decreasing desired damping force. It is seen from the control results that the asymmetric biviscous compensation has overshoot problem. This is occurred because the biviscous model has discontinuous points. This result shows that the asymmetric biviscous model is good for model prediction, but not for damping force control.

Figure 9. Damping force control.

5. Conclusion
In this work, a new type of MR damper for the semiconductor manufacturing system was proposed. The dry-frictionless MR damper was originally designed and manufactured. Then, the field-dependent damping force characteristics and hysteretic behaviors were identified. Asymmetric biviscous model was proposed for hysteresis modelling for MR damper and its performance was evaluated. After then asymmetric biviscous hysteretic compensator was formulated and its damping force control performance was evaluated. It is finally remarked that asymmetric biviscous model is good for model prediction of damping force with hysteresis. However, because of its discontinuity, damping force control performance is quite bad compared with inverse Bingham model. From now on, 4 MR dampers with air spring will be manufactured and attached to the real stage. And the vibration control algorithms will be formulated and its performances will be evaluated and compared.

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