Semi-active Vibration Control for SCARA Robot Using Magnetorheological Damper*

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Abstract—For smooth operation of SCARA robot for wafer transition, a new method using magnetorheological damper for vibration suppression is proposed. Vibration often occurs when the acceleration decrease or increase abruptly. Especially in the end of an operation period, the residual vibration decreases the safety of wafer operation and extends settling time. Firstly, Vibration sources are analyzed. And dynamics model of robot joint considering elasticity is established. Magnetorheological damper is introduced into joint structure to realize vibration suppression by physical mean. It could provide a reliable suppression effectiveness. Control structure of joint with elasticity and MR damper is discussed. A PD controller is applied into joint motion control to a desired movement. Frequency characteristics of the joint with MR damper are analyzed. Finally, a simulation is implemented to verify the effectiveness of the proposed method.

I. INTRODUCTION

SCARA robots have been developed as essential necessity in operation automation, manufacturing to improve the productivity and quality. They are well-known in light duty applications such as electronics manufacturing, assembly[1,2]. The wafer manipulation robot is a type of SCARA robot which require high accuracy and repeatability[3-8]. But in operation of SCARA wafer transfer robot, the abrupt changes in acceleration or deceleration often result in residual vibration. The vibration of the robot end effector may cause wafer damage and extend the settling time of the operation cycle[9]. Vibration control of the SCARA robot has become a key problem in the robot operation[10].

Vibration of the robot is partially caused by elasticity of transmission mechanism. Driving of SCARA robot always uses servo motors and transmission mechanism including harmonic reducer, pulleys and timing belt. This configuration could isolate the payload variation effect acting on the actuator[9]. But it results in another disadvantage that the elasticity of the transmission mechanism increases the flexibility of the robot arm. And the elasticity worsens the stability of the robot operation, especially introduces the residual vibration.

There are some vibration control methods developed, to suppress the vibration in the SCARA robot operation. Liu et al. proposed a trajectory optimizing method to smooth the motion profile in transitional period[10]. Tao et al. analyzes the dynamic influence of joint elasticity, and implements a acceleration smoother to reduce the residual vibration in end motion of SCARA robot[9]. Hessan et al. promotes a active force control method by applying a force to robot joint refers to vibration state to suppress vibration for a handhold tool[11]. Input reshaping control based on impulse response is used to suppress vibration at the start and the end position of manipulators by preshaping the joint trajectory[12]. The above methods are aimed to adjust the motion input of robot joint to reduce vibration. But the vibration cannot be avoid by utilizing these optimal profile input due to the compliance of the mechanical transmissions in practice. So there needs other methods for residual vibration suppressing after the vibration occurring.

Application of the active vibration control is restricted by the limit in time delay and reliable safety of electrical components. And the active control algorithms need high response bandwidth. While, passive vibration control which is realized by implementing passive damper could realize more stable suppress effect. Meanwhile, passive vibration couldn’t guarantee stable suppressing effect in time varying system like SCARA robot. So that semi-active/passive vibration control method is a new way to settle this problem[13,15]. Electrorheological damper is studied to be utilized in robot joint vibration suppression, but it needs high voltage for electric field[14], which limit its application. Magnetorheological(MR) damper is a new type of variable viscous damper[15]. It has been used as passive damper component in the mechanical design of manipulators[15]. But there is less proper model established for the robot arm for residual vibration suppression control. MR damper cannot be modeled exactly by Bingham model in residual vibration period.

In this paper, an effective residual vibration suppressing method is proposed for the SCARA robot to improve its locomotion smoothness. Vibration source of robot in operation both at the start and stop periods is analyzed. By applying MR damper into the robot joint mechanism design, a proper damping force is produced to suppress the residual vibration. A control strategy using PD controller is implemented to the joint position control. MR damper increases the joint vibration resistance ability, meanwhile guarantees a proper bandwidth of the control loop.

In section II, configuration of a typical SCARA robot is described. In section III, vibration source of the robot is analyzed. And the joint control model is disused in section IV.

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Then simulation is conducted and results are analyzed in section V. Conclusions and future work is stated in section VI.

II. MODEL OF THE SCARA ROBOT

Structure of the SCARA robot used in the wafer transfer is illustrated in Fig. 1. It includes three rotational joints and one translational joint. The robot has four DOFs (including R, T and Z). Pulleys and timing belts are used in the transfer mechanism to drive the joints to desired position.

![Fig. 1. Structure of SCARA robot](image)

The robot is driving by DC motors. There is high gear ratio in the power transmission. This structure has an advantage that the change of payload has little effect on actuator due to the high reduction ratio. But introduction of elasticity including harmonic reducer, timing belts reduces joint stiffness and makes the robot work like a flexible manipulator [9].

Wafer transfer operation needs high precision and high speed. But in the start point and end point, the acceleration or deceleration could result in residual vibration. Coordinate frames of the robot is established as shown in Fig. 2. Coordinate frames of each link are expressed by \{x_i, y_i, z_i\}, i = 1,2,3,4. \{x_0, y_0, z_0\} refers to the frame of fixed base.

III. VIBRATION ANALYSIS AND MODEL

Vibration often occurred when the robot reached the destination position, or abrupt shock in accident. High joint stiffness could isolate vibration. But the timing belt, harmonic reducer introduce elasticity into joint so that the stiffness decrease. And response frequency of the joint reduces.

For the SCARA type wafer robot, vibration mainly occurs in the joint 2 and joint 3. So the vibration suppression methods always focus on the trajectory optimizing or acceleration reshaping [9,10].

Fig. 3 illustrates the model of robot joints including elasticity. Joint 2 is driven by harmonic reducer. Joint 3 and 4 are driven through timing belts. Each elastic joint is indicated by spring-damper model. The elasticity leads to an angle increment for the three joint.

Dynamics of joint with elasticity could be expressed as

\[ I \ddot{\theta} + b \dot{\gamma} + k \gamma = T \]

\[ q = \theta + \gamma \]

(1)

Where, \( q \) refers to joint angle; \( \gamma \) refers to angle increment generated by elasticity; \( \theta \) refers to joint angle without joint elastic deformation; \( k \) is rotational stiffness of joint; \( b \) is the damping coefficient.

![Fig. 2. Coordinate frames of the SCARA robot](image)

![Fig. 3 Model of robot including joint elasticity](image)

To suppress the vibration, a magnetorheological (MR) damper is designed to use in the SCARA robot joint. As shown in Fig. 4, the damper is with cylinder structure. It is composed of rotor, stator, coil, sealing, bearing and MR fluid. The viscous characteristics of MR fluid could be controlled by current in the coil.

The developed MR damper for SCARA robot is shown as Fig. 5. The damper is equipped between the \( i \)th link and \((i+1)\)th link, so it is parallel to the motor and reducer package. In the end point of operation, the damper putout resistant torque onto joint to suppress mechanical vibration.

In residual vibration period, there is no driving torque in the joint. Only the MR damper torque \( T_d \) exerts on joints. So dynamic model of robot joint with MR damper in residual vibration period is given as

\[ I \ddot{\gamma} + b \dot{\gamma} + k \gamma + T_d = 0 \]

(2)

A desired torque generated by MR damper denoted by \( T_d \) is expressed as.
Substituting (3) into (2), we get

\[ I \ddot{\gamma} + (b + b_d) \dot{\gamma} + k \gamma = 0 \]  

(4)

To investigate effect of MR damper, a model of robot joint with MR damper is expressed as Fig. 6. The elasticity component of joint could be expressed by a spring and damper. MR Damper acts as an adjustable damper according to vibration conditions, which could vary according vibration conditions.

To simply the dynamic model, the viscous coefficient \( b \) is ignored. So (4) is transformed to

\[ I \ddot{\theta} + b_d \dot{\theta} + k \theta = 0 \]

(5)

express the hysteretic curve around zero point. [16] uses a simple Bingham model for MR damper, but the model does not give a proper damper torque when angle velocity approaching zero. Other models such as Bouc-Wen model and modified Bouc-Wen model have complex equations that are difficult to be used in vibration control.

So an improved Bingham model is proposed. For simplifying the hysteretic loop of the MR damper, there is an assumption that the damper torque is linear scaling round zero point. The proposed model for the MR damper could cover the shortage of the traditional Bingham model. The improved Bingham model is as shown in (5).

\[
\tau = \begin{cases} 
\tau_s(B) \cdot \text{sign}(\dot{\gamma}) + \eta \dot{\gamma}, & \dot{\gamma} < -w_i \text{ or } w_i < \dot{\gamma} \\
\tau_s(B) \cdot \frac{\dot{\gamma}}{w_i} + \eta \dot{\gamma}, & -w_i < \dot{\gamma} < w_i 
\end{cases}
\]

(5)

Where, \( \tau \) refers to shear stress of MR damper; \( \tau_s(B) \) refers to shear stress of plastics model; \( \eta \) denotes viscous damping coefficient; and \( \gamma \) refers to the relative angle between rotor and stator; \( w_i \) refers to a angle velocity node.

When \(-w_i < \dot{\gamma} < w_i\), shear stress of plastics model performances linear scale characteristics. But out of the area \([-w_i, w_i]\), the model performances saturation characteristics.

The improved Bingham model aim to simplify the model of MR damper so as to be implemented in vibration control system. And it could approximate the actual torque in the hysteretic loop around zero point more accurately.
From (5), damper torque is obtained as

$$T_d = L \int_{\tau}^{\tau} 2\pi \tau d\tau = 2\pi L \int_{\tau}^{\tau} \tau d\tau$$  \hspace{1cm} (6)$$

The used MR damper is with cylinder type structure. So the output torque could be simplified from (5) and (6)

$$T_d = 2\pi L r_i^2 \dot{\theta} \sin \alpha + \eta_i$$  \hspace{1cm} (7)$$

Where, $$\alpha = \begin{cases} \text{sign}(\dot{\gamma}), & \dot{\gamma} < -w_i \text{ or } w_i < \dot{\gamma} \\ \dot{\gamma}, & -w_i < \dot{\gamma} < w_i \end{cases}$$

Substituting (7) into (2), we get

$$I \dot{\theta} + (C - 2\pi L r_i^2 h\eta) \dot{\gamma} + K \gamma = 2\pi L r_i^2 \alpha \tau_i(B)$$ \hspace{1cm} (8)$$

The stress of MR damper is controlled by current in coil, so it could be expressed as a function of current

$$\tau_i(B) = f(I)$$ \hspace{1cm} (9)$$

Where, $$I$$ refers to the coil current inner the damper.

The joint model with MR damper is illustrated in Fig. 7. The model of MR damper uses the improved Bingham model. 

Control of the robot arm using MR damper is demonstrated by the block diagram shown in Fig. 8[11]. $$T_m$$ is the driving torque from DC motor, and $$\theta_i$$ is the motor angle. Damper model in Fig.8 represents the block diagram shown in Fig. 7.

Position control of the joint motor adopt PD algorithm. It controls the output angle from the motor and reducer. Damping coefficient of the MR damper is adjustable according to joint acceleration.

The MR damper influences the output joint angle.

IV. SIMULATION AND EXPERIMENT

When coil current of the MR damper circuit electric is zero, the frequency characteristic from $$T_m$$ to $$\theta$$ is as shown in Fig. 9(a). The magnitude characteristic has a peak. The system has resonant trend near the cross-over frequency corresponding to the peak.

When the electric current is applied into the MR damper coil, viscous coefficient of the driving system increases. So resistance torque from MR damper increases antiresonant ability. From the magnitude characteristic shown in Fig. 9(b), the peak is weakened substantially.

The zero and pole location of $$\theta/T_m$$ is shown in Fig. 10. The small crosses are the poles and zeros. It is apparent that the poles and zeros are located in left part of complex plane.

From Fig. 10, it is shown that position control system from $$\theta$$ to $$\theta_m$$ is steady. Position offset and its derivative is substituted into PD controller.

To investigate the effect of residual vibration suppression, trapezoidal curve signal response of the control system is simulated. Simulation parameters are listed in Table 1. The elastic coefficient $$k$$ is identified from one of the SCARA robot[9]. Rotational inertia $$J_1$$ and $$J_d$$ are calculated.
from material and geometry of the robot mechanical model. Simulation results are shown in Fig. 11.

![Frequency response of robot joint](image1)

**Fig. 10. Frequency response of robot joint**

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>PARAMETERS OF THE SYSTEM</th>
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<tbody>
<tr>
<td>$k_p$</td>
<td>0.580</td>
</tr>
<tr>
<td>$k_v$</td>
<td>0.0047</td>
</tr>
<tr>
<td>$J_1$</td>
<td>$0.35\times10^{-5}$ $kg \cdot m^2$</td>
</tr>
<tr>
<td>$k$</td>
<td>439 $Nm/rad$</td>
</tr>
<tr>
<td>$J_d$</td>
<td>0.0384 $kg \cdot m^2$</td>
</tr>
</tbody>
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**Fig. 11 a) is the joint angle without MR damper, From Fig. 11 a) and c), it is obviously that vibration occurs in the step input, overshoot is about 20%, and the settling time is long. Fig. 11 b) is the joint angle response with MR damper. Apparently the vibration amplitude is weakened after the MR damper is enabled. Fig. 11 c) and d) show the joint angle acceleration before and after MR damper enabled respectively. The residual vibration occurring during abrupt accelerating is substantially decreased after the MR damper working. And the settling time is shorten obviously. The output converges to zero after a short time shock. To not influence the steady state output of joint angle, MR damper should provide lower damping force along with the vibration magnitude decreasing. So coil current should be reduced accordingly.**

The above results show that the method by introducing a physical damper into joint design suppresses residual vibration effectively, and shorten the settling time substantially.

V. CONCLUSION

Vibration is an important issue which influence the motion stability and position precision of SCARA type wafer transfer robot. The paper gives an effective method to suppress vibration among robot operation or residual vibration in the start or end position. Control structure of the robot with MR damper is established, and its frequency characteristics are discussed. Experiments results show that vibration magnitude decrease abruptly with MR damper working. The
The proposed method gives a new way to guarantee stability, safety of SCARA robot, as well as shorten settling time for robot operation to improve working efficiency. The next step is to implement the method into physical robot model.

REFERENCES


