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Vibration Suppression for SCARA Robot with Magnetorhelogical Damper by Using Switching control*

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***Abstract* –A vibration suppression method using switching control is proposed for smooth motion control of SCARA robot in wafer transition. The wafer robot is composed of joints integrated with magenetorhelogical damper. Vibration often occurs when acceleration jump abruptly, especially in the end of operation period. The residual vibration decreases the safety of wafer operation and extends the settling time. Firstly, Vibration sources of the driving joints are analyzed. Strategy by using switching control is analyzed. And dynamics model of robot joint with elasticity element is established. Magenetorhelogical damper is introduced into the design of joint structure to suppress vibration. It could provide reliable suppression effectiveness. Control structure of joint with elasticity and MR damper is discussed. And a PD controller is applied into joint motion control. Frequency characteristic of the joint demonstrates the stability of the control loop. Finally, simulation is implemented to verify the effectiveness of the proposed method.**

Index Terms* – *vibration suppression; SCARA robot; magnetorhelogical damper; switching control.

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 effecter 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*. proposes 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]. Electrorhelogical damper is studied to be utilized in robot joint vibration suppression, but it needs high voltage for electric field[14], which limit its application. Magnetorhelogical(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 modelled exactly by Bingham model in residual vibration period.

In this paper, an effective residual vibration suppressing method using switching control 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

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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.

II. Vibration Analysis and Model of 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.

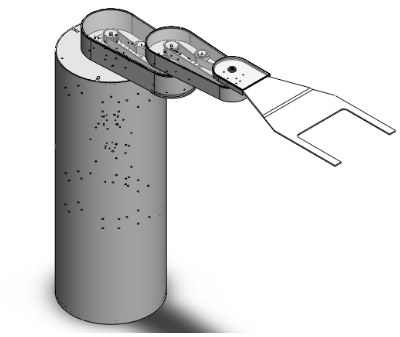


Fig. 1. Structure of SCARA robot

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.

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.

Coordinate frames of the robot is established as shown in Fig. 3. 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.

Dynamics of joint with elasticity could be expressed as

$$\begin{aligned} I\ddot{\theta} + b\dot{\gamma} + k\gamma &= T \\ q &= \theta + \gamma \end{aligned} \tag{1}$$

Where, q refers to joint angle; γ refers to angle increment generated by elasticity; θ refers to joint angle without joint elastic deformation; k is rotational stiffness of joint; b is the damping coefficient.

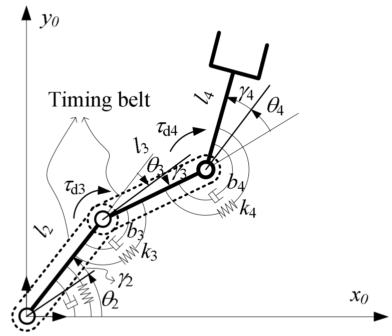


Fig. 2 Model of robot including joint elasticity

III. Switching Control

When the robot arrives the destination, the residual vibration need to be suppressed by proper method to guarantee the stability and shorten the settling time. Here, a vibration suppression method by using MR damper is used. But the MR damper could increase the driving torque of robot joint, meanwhile it increase the response time of control system. To acquire proper vibration suppression effectiveness and not lower the performance index of robot controller, a switching control strategy is established.

Switching control strategy for the SCARA robot is shown as Fig. 3. Position control is implemented to control robot trajectory from initial position and destination. And position control is used in stable stated among the robot motion. On the other hand, damping control is used to realize vibration suppression, such as residual vibration in the end period of motion. Damping control is actually as vibration control for the unsmooth motion state.

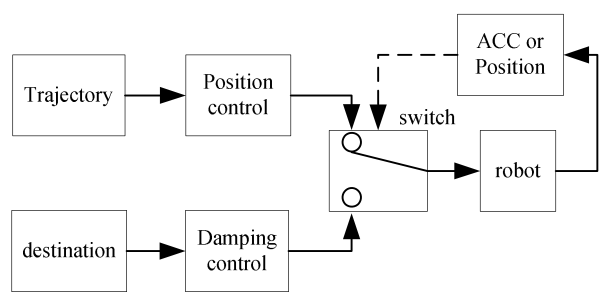


Fig. 3 Switching control system

Position control and damping control are switched according to motion period and acceleration of robot.

In actual motion control, chattering of switching controller may occur if the switching terms are improper. Switching terms play an important role.

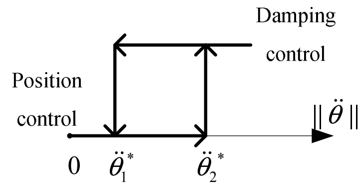


Fig. 4. Switching sketch with hysteresis of joint control between low damping state and high damping state

So a switching term including hysteresis is proposed. As shown in Fig. 4, the controller is switched from position control to damping control as following

$$\|\ddot{\theta}\| > \ddot{\theta}_2^* \tag{2}$$

Where, $\|\ddot{\theta}\|$ is the absolute value of angular acceleration, and $\ddot{\theta}_2^*$ is the upper limit value of acceleration.

The controller is switched from damping control to position control is as following

$$\|\ddot{\theta}\| < \ddot{\theta}_1^* \tag{3}$$

Where, $\ddot{\theta}_1^*$ is the lower limit value of acceleration. And $\ddot{\theta}_1^* < \ddot{\theta}_2^*$.

Besides the acceleration term, motion period of robot is also used to switch motion. In the beginning and intermediate point, the controller switched to position control. In the destination point, the controller is switched to damping control. The motion period term is switched without hysteresis.

IV. Vibration Control of Robot Joint

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 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

$$I\ddot{\gamma} + b\dot{\gamma} + k\gamma + T_d = 0 \tag{4}$$

A desired torque generated by MR damper denoted by T_d is expressed as

$$T_d = b_d\dot{\theta} \tag{5}$$

Substituting (5) into (4), we get

$$I\ddot{\gamma} + (b + b_d)\dot{\gamma} + k\gamma = 0 \tag{6}$$

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 (6) is transformed to

$$\begin{aligned} &I\ddot{\theta} + b_d\dot{\gamma} + k\gamma = 0 \\ &q = \theta + \gamma \end{aligned} \tag{7}$$

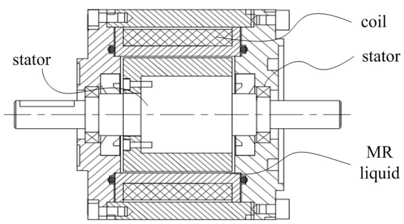


Fig. 5. Structure of variable viscous rotational MR damper

Bingham model is a commonly used model for MR dampers. But in residual vibration control of the MR damper, Bingham model has some shortcomings. The dampers using MR/ER fluid has saturation characteristics in time response. Bingham model for MR damper could not settle the saturation. It cannot describe torque exactly in low rotational speed or 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 (8).

$$\tau = \begin{cases} \tau_y(B)\cdot sign(\dot{\gamma}) + \eta\dot{\gamma} & ,\dot{\gamma} < -w_1 \quad or \quad w_1 < \dot{\gamma} \\ \tau_y(B)\cdot \dfrac{\dot{\gamma}}{w_1} + \eta\dot{\gamma} & ,-w_1 < \dot{\gamma} < w_1 \end{cases} \tag{8}$$

Where, τ refers to shear stress of MR damper; $\tau_y(B)$ refers to shear stress of plastics model; η denotes viscous damping coefficient; and γ refers to the relative angle between rotor and stator; w_1 refers to a angle velocity node.

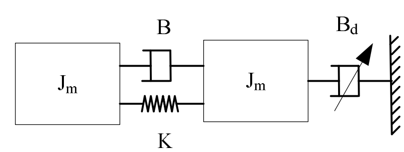


Fig. 6. Mass-spring-damper model of robot joint with MR damper

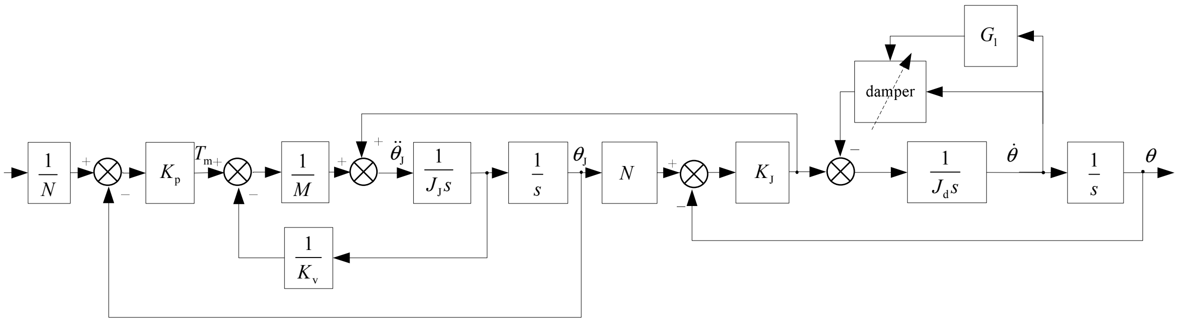


Fig. 7. Block diagram of robot joint transfer function

When $-w_1 < \dot{\gamma} < w_1$, shear stress of plastics model performances linear scale characteristics. But out of the area $[-w_1, w_1]$, 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 (8), damper torque is obtained as

$$T_d = L\int_{r_i}^{r_o} 2\pi r\tau dr = 2\pi L\int_{r_i}^{r_o} r\tau dr \qquad (9)$$

The used MR damper is with cylinder type structure. So the output torque could be simplified from (8) and (9)

$$T_d \approx 2\pi L r_i^2 \tau h = 2\pi L h r_i^2 (\alpha\tau_y(B) + \eta\dot{r}_i) \qquad (10)$$

Where, $\alpha = \begin{cases} sign(\dot{\gamma}), \dot{\gamma} < -w_1 \quad or \quad w_1 < \dot{\gamma} \\ \dfrac{\dot{\gamma}}{w_1} \qquad , -w_1 < \dot{\gamma} < w_1 \end{cases}$

Substituting (10) into (4), we get

$$I\ddot{\theta} + (C - 2\pi L r_i^2 h\eta)\dot{\gamma} + K\gamma = 2\pi L r_i^2 h\alpha\tau_y(B) \qquad (11)$$

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

$$\tau_y(B) = f(I) \qquad (12)$$

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. J_d denotes the inertia of damper rotor. Output torque of damper is denoted by T_d, it is relative to joint angler velocity. The block diagram is corresponding to (8) and (10).

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 θ_J is the motor angle. Damper model in Fig.8 represents the block diagram shown in Fig. 7.

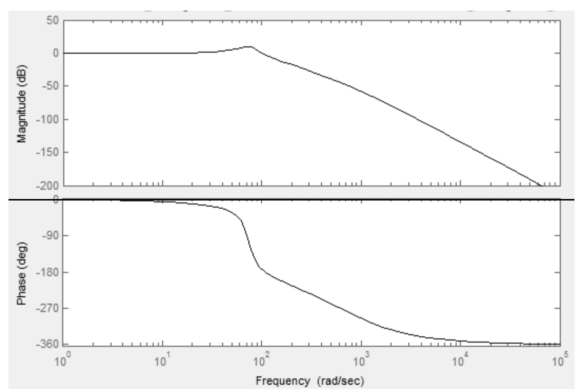
Position control of the joint motor adopt PD algorithm. It controls the output angle from the motor and reducer. Damping coefficient of the MR damper is adjustable according to joint acceleration.

The MR damper influences the output joint angle.

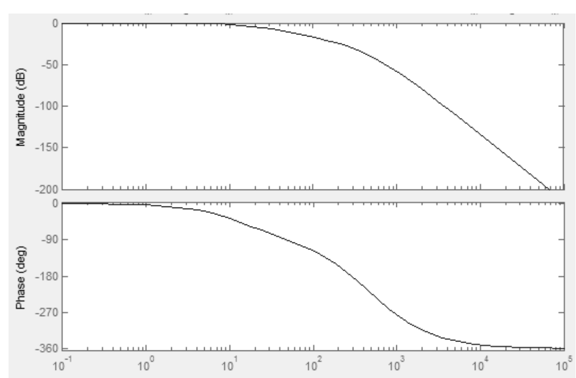
V. Simulation and Experiment

When coil current of the MR damper circuit electric is zero, the frequency characteristic from T_m to θ is as shown in Fig. 8(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 antresonant ability. From the magnitude characteristic shown in Fig. 8(b), the peak is weakened substantially.



a) without MR damper



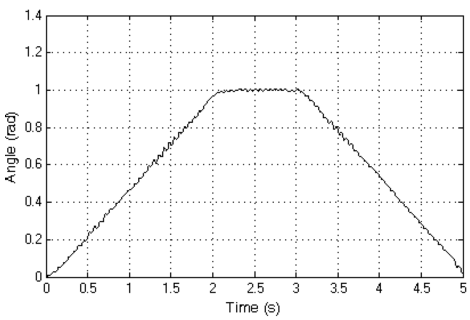
b) with MR damper

Fig. 8. Frequency response of robot joint

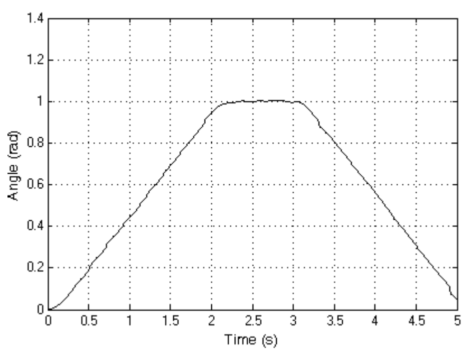
To investigate the effect of residual vibration suppression, trapezoidal curve signal response of the control system is simulated. Simulation parameters are listed in Table 1. The elastic coefficient k is identified from one of the SCARA robot[9]. Rotational inertia J_1 and J_d are calculated from material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

TABLE I
PARAMETERS OF THE SYSTEM

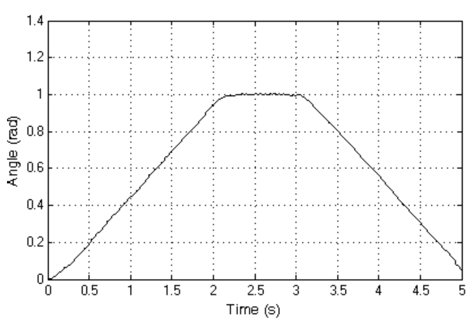
k_p	0.580
k_v	0.0047
$J_l(kg\ m^2)$	0.35e-5
$k(Nm/\text{rad})$	439
$J_d(kg\ m^2)$	0.0384



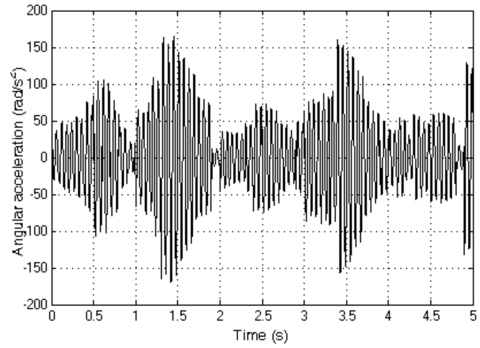
a) Without MR damper



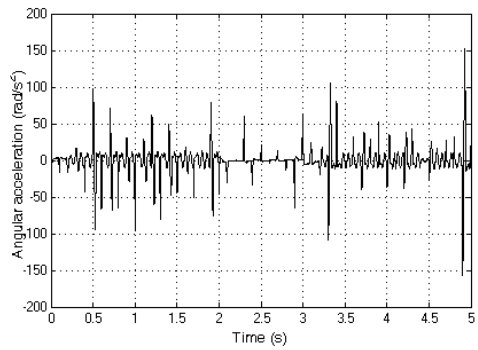
b) With MR damper



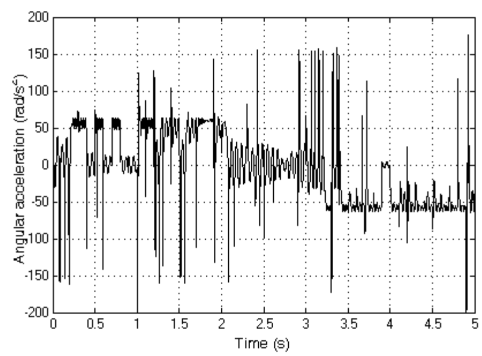
c) With switching control
Fig. 9. Time response of robot joint angle



a) Without MR damper

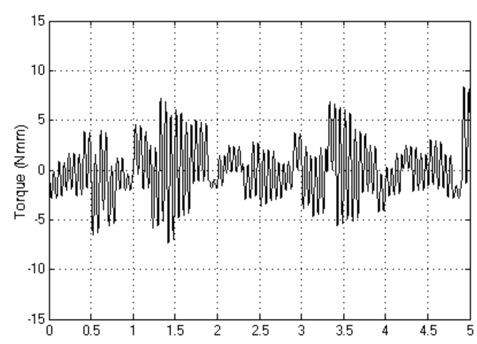


b) With MR damper

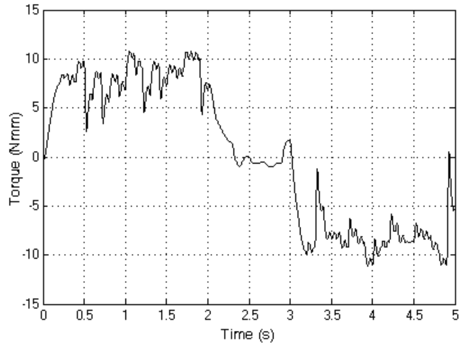


c) With switching control

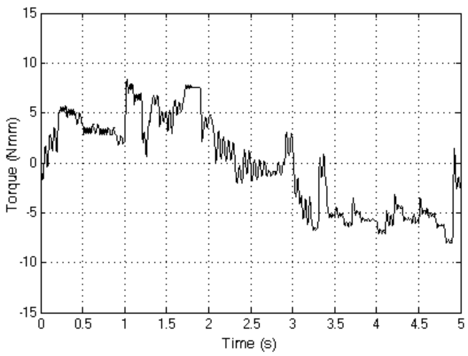
Fig. 10. Frequency response of robot joint acceleration



a) Without MR damper



b) With MR damper



c) With switching control

Fig. 11. Time response of robot joint torque

Fig. 9 a) is the joint angle without MR damper, From Fig. 9 a) and c), it is obviously that vibration occurs in the step input, overshoot is about 20%, and the settling time is long. Fig. 9 b) is the joint angle response with MR damper. Apparently the vibration amplitude is weakened after the MR damper is enabled. Fig. 10 a) and b) show the joint angle acceleration before and after MR damper enabled respectively. c) shows the results by using switching control. in the three condition are illustrated. In Fig.11, joint torques 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. From the torque curves, it is obvious that joint torque in the switching control is lower than damping control. The switching control has less influence than the simple damping control.

The above results show that the method by using switching control has effective vibration suppression. And Introducing of the physical damper in joint design suppresses residual vibration effectively, and shorten the settling time substantially.

VI. Conclusion

Vibration is an important issue which influence the motion stability and position precision of SCARA type wafer transfer robot. The paper gives an vibration suppression method by using switching control 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 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 damping controller guarantee the bandwidth of the position control loop, and have enough vibration suppression ability.

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