Optimization of Active Vibration Control of a Laser Pattern Generator in Micro Lithography

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Abstract

The extreme precision requirements in semiconductor manufacturing drive the need for an active vibration isolation system in a laser pattern generator. Optimization has been performed and evaluated in a model using a high level programming tool [1]. The areas of optimization were 1) Decoupling strategies for decentralized control and 2) Improved feed forward control. Only a limited description of the model itself is given here. More about the model is presented in [2] and [3].

1 Objective

This study evaluates if optimization of the controller of a vibration isolating system could improve performance of disturbance rejection and thereby reduce cost of ownership by extended lifetime of consumables and stretched service intervals. A secondary effect could be to improve isolation performance.

1 Decoupling strategies

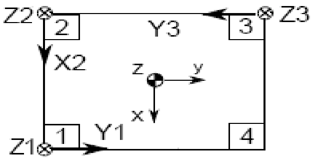
A system with multiple inputs and multiple outputs (MIMO), as the Active vibration control, can be controlled with a set of single input and single output (SISO) regulators, so called decentralized control. This can be done by combining sensors to a set of regulator inputs and applying the output signal from each regulator on a combination of actuators, using matrices M_S and M_M as pre- and post compensators respectively. The choice of strategy for creating these matrices will strongly affect the performance of the control system. Good performance is achieved when the regulators are well decoupled, i.e. minimizing the cross coupling between regulators.

1.1 Geometric decoupling

The original decoupling strategy is using the geometrical center of the sensors and actuators as reference point and applies a coordinate system with three translation and three rotation axes, parallel to the geometrical axes. This simple strategy does not attempt to compensate for cross coupling between translation and rotation axes.

1.2 Center of gravity decoupling

In an attempt to improve decoupling, the true motion of the center of gravity (COG) of the vibration isolated unit is controlled in three translation and three rotation axes. The inherent cross coupling between rotation and translation axes, due to sensor and actuator offset from COG, is compensated for. To preserve the intuitive understanding of the system the axes are still parallel to the geometrical axes.



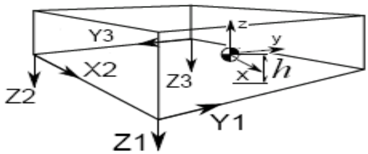


Figure 1: Sensors, actuators and control axes for geometric- and COG-decoupling

1.3 Modal decoupling

Because the rigid body vibration modes of the isolated unit do not correspond to the geometrical axes of the system, cross coupling between the regulators will occur as long as the geometrical axes are used as base for the decoupling. If instead a modal decoupling strategy is used, i.e. using the eigenvectors of the system and transform the geometrical coordinates into modal coordinates, each resonance mode is controlled independently and thus the decoupling is theoretically complete.

The equations of motion in the state-space form is given by

$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t)$$

A matrix E containing the eigenvectors of A can be used to transform the physical coordinates into modal coordinates. According to [4] the pre- and post compensation matrices for the modal decoupling are given by

$$M_S = (C^{-1}E^{-1})^T$$
$$M_M = B^{-1}E$$

1.4 Effects of different decoupling

Evaluation of the different decoupling strategies is done by comparing the transfer functions of the open loop regulators in the computational model of the system. If each transfer function shows only one resonance peek the decoupling is successful. In Figure 2 the three methods described above are compared. The cross coupling between the X-translation at 0.9 Hz and the Y-rotation at 2.1 Hz is obvious for the original (geometric) and the COG decoupling, whereas the modal decoupling shows only one mode in each graph. Figure 3 shows that the transmissibility of floor vibrations is not affected by changing the decoupling strategy.

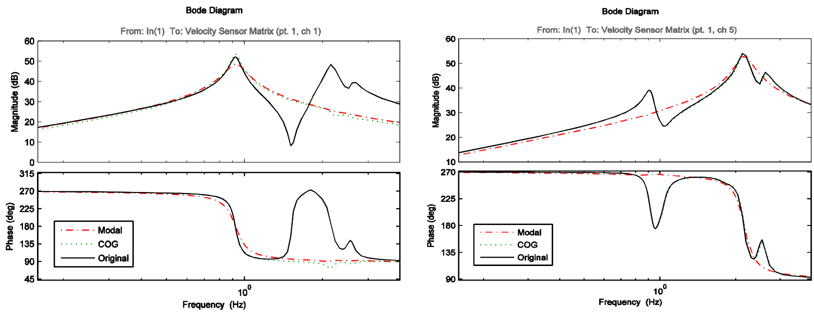


Figure 2: Transfer functions X-translation and Y-rotation with different decoupling

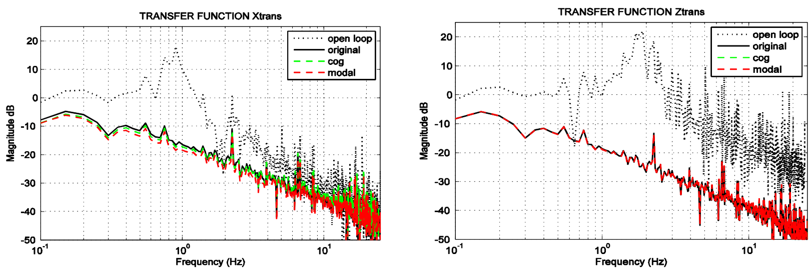


Figure 3: Transmissibility of floor vibr. X- and Z-direction with different decoupling

2 Feed forward optimization

The stage feed-forward compensation shall counteract forces created by movements of the X/Y-stage. Using the computational model it is possible to calculate theoretically optimal values of the feed-forward matrix, H_{ff} as shown in Figure 4.

2.1 Invers matrix method

In order to cancel out the disturbance from X/Y-stage movements, the control unit needs to calculate appropriate control signals to the force actuators based on the four signals. With perfect disturbance rejection achieved by the feed-forward controller, the isolated unit would stand still ($y = 0$, the setpoint is zero, $r = 0$), output is given by

$$y = (H_{ff} M_M K_M G_O(s) d_m + G'_d(s) d) M_S = 0$$

Where d_m is the measured disturbance, H_{ff} the feed-forward controller, and G_O the mobility of the isolated unit. Furthermore, G'_d denotes the mobility of the isolated unit through the disturbance path i.e. from the true disturbance d to output y. M_M and M_S are the motor and sensor steering matrices, as described in the previous chapter. If the reshaped plant $G(s)$ is used and assuming the measured disturbance be equal to the real disturbance the feed forward controller should be designed according to

$$H_{ff} = -G_d(s)G(s)^{-1}$$

So regardless of how M_M and M_S are chosen according to the decoupling strategy, as long as $G(s)^{-1}$ exists it is possible to calculate the appropriate H_{ff}.
The feed forward control is inherently sensitive to model errors, so in a real system some final tuning may be required. Experiments have proven that the method supplies a very close match and only limited tuning needed to achieve good performance.

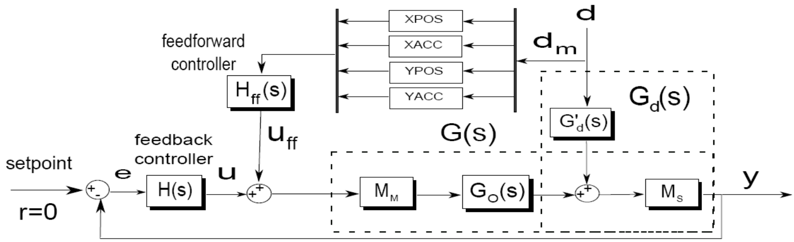


Figure 4: Model overview

3 Conclusion

The study has shown: 1) Modal decoupling minimizes the cross coupling between modes, resulting in a better stability margin for the control loops.
2) The inverse matrix method can find the optimum feed-forward matrix, regardless of decoupling strategy.
However experiments in the real system have proven that neither the decoupling strategy or the feed-forward matrix are limiting performance of this particular system – instead it is limited by non-linear effects of the feed-forward control.

References:

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