Multi-Axis Resonant Filter Design using Frequency Response Data applied to Industrial Scan Stage

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***Abstract*—Disturbance rejection of the high-precision scan stages is important in industrial lithography equipment. The aim of this paper is to develop an optimization method for designing multi-axis resonant filters, that enhance the disturbance rejection performance in scanning motion. The developed optimization method explicitly defines resonant filters in structured representation and formulates the data-driven convex optimization problem. The method enables the multi-axis resonant filter design with iterative convex optimization using the frequency response data of the six-degree-of-freedom experimental setup. Experimental results on the industrial large-scale high-precision scan stage demonstrate the performance improvement of the disturbance rejection in the scanning motion using the optimized resonant filters.**

***Index Terms*—Disturbance rejection, Loop shaping, Resonant filter, MIMO system, Frequency response, Data-driven design, Convex optimization**

I. Approach

Fig. 1 shows the experimental setup of the industrial FPD lithography system which is used for the production of flat panel displays. In the setup, the MIMO large-scale high-precision scan stage is implemented and it has 6-DOFs $(x, y, \theta_z, z, \theta_x, \theta_y)$. The main scan stroke is the translation along the x-axis.

The resonant filter has high-gained characteristics at the designed resonance frequency and effectively rejects the disturbance at the same frequency. In the decentralized resonant filter for the MIMO controlled system, resonant filters in each axis are shown in Fig. 2 and are defined as

$$F_{k_y}(\mathrm{j}\omega_{k_f}, \boldsymbol{\rho}_{k_y}) = 1 + \sum_{k_r=1}^{n_{r,k_y}} \frac{\rho_{k_y,(k_r,2)}(\mathrm{j}\omega_{k_f})^2 + \rho_{k_y,(k_r,1)}(\mathrm{j}\omega_{k_f})}{(\mathrm{j}\omega_{k_f})^2 + 2\zeta_{r,k_y,k_r}\omega_{r,k_y,k_r}(\mathrm{j}\omega_{k_f}) + \omega_{r,k_y,k_r}^2}. \quad (1)$$

The tuning parameters, the resonance frequency, and the damping coefficient in each axis are $\rho_{k_y,(k_r,:)}$, ω_{r,k_y,k_r}, and ζ_{r,k_y,k_r}. The initial resonant filters are designed as K times larger gain at the resonance frequency ω_r and the vector locus recedes from $(-1, \mathrm{j}0)$ with a resonance circle as shown in Fig. 3. The optimized resonant filters are designed with optimization for the gain and phase of the resonant filters to improve the MIMO performance. The MIMO performance is evaluated by the Frobenius norm of the normalized error frequency spectrum matrix. The original non-convex optimization problem is reformulated to the iterative convex optimization problem by the Moore-Penrose inverse and sequential linearization.

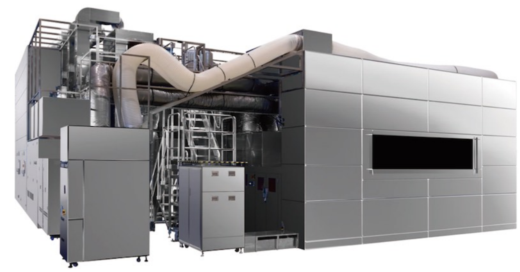

Fig. 1. Experimental setup of FPD lithography system [1].

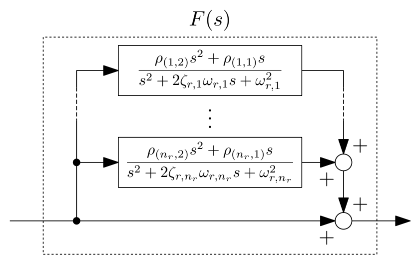

Fig. 2. Block diagram of resonant filters in each axis.

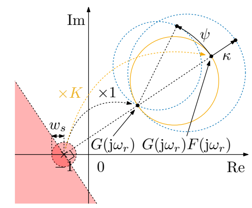

Fig. 3. Vector locus with resonant filter and robust stability condition.

TABLE I
Experimental root mean square errors of 8 scan regions in 6-DOFs without resonant filters (w/o), with initial resonant filters (ini), and with optimized resonant filters (opt).

[count]	e_x	e_y	e_{θ_z}	e_z	e_{θ_x}	e_{θ_y}	$\int_t \lVert \boldsymbol{W}^{-1}\boldsymbol{E} \rVert_F$
w/o	49	120	28	116	61	75	100 %
ini	88	88	41	111	60	108	104 %
opt	59	65	34	107	48	116	87 %

II. Result

The stage is moving along the main stroke x-axis with constant velocity $0.5\,\mathrm{m/s}$. From TABLE I, the experimental results show that the MIMO performance with optimized resonant filters outperforms that without resonant filters in $13\,\%$ and that with initial resonant filters in $17\,\%$. Experiments on the industrial MIMO large-scale high-precision scan stage demonstrate effective disturbance rejection performance with the optimized resonant filters.

References

[1] Nikon, "FPD Lithography Systems Lineup," https://www.nikon.com/business/fpd/lineup/, 2024.