MECHATRONICS CONCEPTS FOR THE NEW HIGH DYNAMICS DCM FOR SIRIUS

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Abstract

The monochromator is known to be one of the most critical optical elements of a synchrotron beamline, since it directly affects the beam quality with respect to energy and position. Naturally, the new 4th generation machines, with emittances in the range of order of 100 pm rad, require even higher stability performances, in spite of the still conflicting factors such as high power loads, power load variation, and vibration sources. A new high-dynamics DCM (Double Crystal Monochromator) is under development at the Brazilian Synchrotron Light Laboratory for the future X-ray undulator and superbend beamlines of Sirius, the new Brazilian 4th generation synchrotron [1, 2]. Aiming at an inter-crystal stability of a few tens of nrad (even during the Bragg angle motion for flyscans) and considering the limitations of the current DCM implementations, several aspects of the DCM engineering are being revisited. The system concept is chosen such that a control bandwidth in the order of 200 to 300 Hz can be achieved. This requires well-designed system dynamics, which can be realized by applying a fundamentally different architecture than that used in common DCM designs, based on the principles used in ultra-precision systems for semiconductor manufacturing. As a result, a lot of the known disturbances can be attenuated or suppressed, and internally excited modes can be effectively handled. The mechatronics concepts and analyses, including the metrological details, are shown.

INTRODUCTION

In the recent years it has become clear to the synchrotron community that the stability performance of DCMs would turn out to be one of the main bottlenecks in the overall performance of many X-ray beamlines, particularly for the new 4th generation machines, the so called Diffraction Limited Storage Rings (DLSR). Indeed, their performance is typically affected by well-known vibration sources, as the cooling system, the experimental floor and vacuum pumps in the surroundings. In addition, the self-induced disturbances, caused by servo and piezo actuators, for instance, have recently been more carefully investigated [3, 4].

Even though some incremental progress has been achieved in mitigating such disturbances, examples from applications in other industries show that the required stability could not be achieved by these incremental changes, based on the common architecture. A fundamentally different overall system approach is necessary to successfully design and realize such ultra-precision system. This work shows the mechatronics concepts used at the new high-stability DCM for Sirius [5]. More details about the full system and its specifications can be found in [6].

CONCEPTUAL DESIGN

The concepts applied in the present design aim at a high-bandwidth closed-loop control, in which the main target is a control bandwidth of the inter-crystal parallelism in the order of 200 to 300 Hz. Thus, the disturbance rejection capacity of the control loop can suppress errors to the required nm levels, both in stand-still and during flyscan. By a proper design of the mechanics, the internal errors (noise sources) are minimized.

To achieve such a high closed-loop control bandwidth, a very well designed mechanical system, based on a fundamentally different dynamic architecture, is applied, and the use of voice-coil (VC) actuators is crucial. Whereas common DCM systems typically use piezo actuators or other inherently stiff actuators systems (like spindle drives), the use of inherently compliant actuators, as VCs, allows for another dynamic architecture. By this principle, the dynamics of the system can be designed to reach a significant higher closed-loop bandwidth, as only the essential mechanical components will act in the control loop. Namely, by means of a mechanical filter, established by a so-called reaction mass, or balance mass, the non-essential so-called reaction path dynamics can be filtered and, as such, be eliminated from the close-loop dynamics in the sense of control stability and disturbance amplification.

Essential for a successful design of such high-end system is predictive modelling, not only with respect to dynamics, but also thermal and other physical and mechanical aspects. Starting with the right overall architecture and taking all the essential requirements into account, predictive modelling, error-budgeting and proper design principles based on experience are crucial to design such complex high-end system. With respect to dynamics, dynamic system models, lumped-mass as well as FE-models are made. From these models, transfer functions are derived and evaluated to guide the conceptual choices and mechanical design to finally reach the required performance. Based on PSD analysis quantitative error budgeting is applied to finally predict the expected performance.

Dynamic Model and Control Tools

Figure 1 shows a schematic drawing of the DCM, which was used as the basis for a 1D-lumped-mass dynamic model of the system. The chosen degree of freedom to be used in this model was Rx, since pitch requirements are the most critical in terms of stability. Starting with such relative simple lumped-mass model, several

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concepts can be evaluated and the feasibility can be proven quickly. Of course, the outcome of such model and the reliability of the results is not trivial, but requires experience in predictive modelling and designing high-end systems. By means of transfer functions, the system was evaluated and adaptions to the concepts were made. In parallel, the mechanical design was built and continuously updated, from rough to more detailed versions, whilst more detailed analysis, like simple hand calculations or FE analyses, provided more realistic numbers, so that masses and compliances/stiffness numbers could be refined to improve the dynamic model.

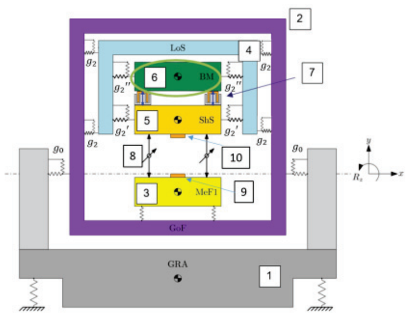

Figure 1: DCM schematic: (1) inertial reference; (2) rotating subsystem; (3) first crystal metrological frame and fixation base; (4) first level translational structure; (5) Second crystal metrological frame and fixation base; (6) reaction mass; (7) VCs; (8) optical interferometers; (9) First crystal; (10) second crystal.

The dynamic model allows for the convenient representation of the system in Bode plots, which reveal the mechanical performance of the system in the frequency domain. It can also be used to verify the control sensitivity of a given input, whether a control input or a disturbance source. Regarding control, the model is also used in analyses of Nyquist plots and phase margin for system stability. By varying specific system parameters, the impact of stiffness, misalignments, imbalance and construction tolerances, for example, can be analyzed, conferring robustness for the control project.

Actuator Concept

Piezoelectric actuators are extensively used in high-precision positioning systems, including the precise adjustment of parallelism between crystals in DCMs. However, as spindle drives with stepper motors, they are position based actuators and stiff by definition. Depending on the control loop and relative positioning of the mechanical parts in a given system, this inherent stiffness can be beneficial. However, in more complex systems, like the DCM, this inherent stiffness also creates a dynamic link that significantly limits the overall dynamic performance. Especially in scanning systems, as the DCM in flyscan, such mechanically stiff connection would couple the motion errors of a guiding system directly to the final positioning performance of the system. Thus, in the case of such an inherently stiff actuation principle (as in piezos) the control loop has to fight against its own inherent stiffness, since the noise in the guiding system becomes visible in the relative position of the crystals during the flyscan motion. Considering the required nm performance, a lean and predictable system, without these unwanted interactions, is clearly needed. Some first-order simulations of the closed-loop bandwidth of the DCM were made for piezo and VC actuators (see Table 1). For the first, due to the mechanical and dynamic interaction of the inherently stiff piezos, the control gain is relatively limited, with a bandwidth in the order of a few tens of Hz. The VCs, on the other hand, without the unwanted mechanical and dynamic coupling, allow for a more robust control, with closed-loop bandwidth that may reach a few hundreds of Hz.

Reaction Mass Concept

The attainable bandwidth will be limited by resonances in the system to be controlled, which can be in the forward-path (ShS), or in the backward-path, i.e., in the structure dynamics. Both the forward and backward path Bode plots for pitch control are depicted in Fig. 2, with and without a reaction mass. It can be seen in the forward-path the intentional decoupling of ShS at low frequencies and the internal resonances above 1 kHz. Indeed, the forward-path has been carefully designed, such that the first internal resonances are above 1.5 kHz. The backward-path, on the other hand, is much more complicate and involves many bodies with internal resonance far below 1 kHz (typically a few hundred Hz), which are back excited by the reaction forces of the actuator, so that they become visible in the control loop and can limit the close-loop bandwidth due stability reasons. Without a reaction mass, Fig. 2(a), the backward-path peaks overcome the forward-path control and limit the closed-loop bandwidth well below 100 Hz. On the other hand, with the reaction mass, Fig. 2(b), the reaction forces act directly against it, which is also decoupled at low-frequencies. Thus, it effectively filters the reaction forces of the actuator with respect to the overall structure, attenuating the backward-path dynamics, so that it does not limit the achievable bandwidth anymore.

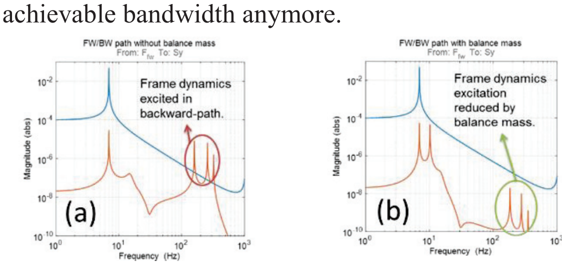

Figure 2: Transfer function for pitch correction in the 2^{nd} crystal of the DMC: forward path in blue and backward path in red. In (a) the reaction force acts against the long stroke frame, whereas in (b), against the balance mass.

Feedback

In order to achieve the high-bandwidth control, the sensor system becomes crucial in the feedback performance. The noise level should be low enough, whereas the sample rate, high enough to achieve the nm performance and the high close-loop bandwidth. Considering the nm performance and the several mm of stroke that we need, an incremental optical measurement system is an obvious choice. Moreover, considering not only the gap variation of several mm but also the angular motions (pitch and roll), an optical distance measurement interferometers (DMI) seems to be the most elegant solution in this application. By the DMI, subnanometer resolution and stability can be provided at 10 kHz sampling time. Thus, three optical interferometers are combined to measure the gap and the two angles (pitch and roll) between the two metrology frames that support the crystals.

RESULTS

In order to analyze the contribution of various error sources, an error budgeting approach is used, allowing for a complete understanding of the system and identification of the main players, which aids in concept and design choices. For the DCM this approach has been applied for manufacturing tolerances, metrology, alignment and dynamics. All error sources must be considered to predict the final performance of the monochromator.

Table 1 shows a preliminary dynamic error budget for the 1D model (Rx) for different actuator types. Even though it is incomplete, because not all error sources were known, it is very instructive since it shows significant figures that compare the performance of the DCM with the proposed technology to that with the most standard piezo solution, as well as piezo walker actuators.

Table 1: Rx Error Budget for Different Actuators

	Lorenz (VC) [nrad] 3σ	**Piezo Stack** [nrad] 3σ	**Piezo walker** [nrad] 3σ
Bandwidth	200Hz	20Hz	20Hz
Floor vibrations	0.8	2.5	0.9
Amplifier noise	1.4	44.1	2.9
Amplifier DAC quantization	0.2	0.2	0.2
DMI quantization errors	0.2	0.1	0.1
Quadratic sum [nrad] 3σ	1.6	44.1	3.1

Figure 3(a) depicts another interesting analysis tool for the error budget, namely, the cumulative power spectrum. Figure 3(b), on the other hand, shows a stability analysis via Nyquist plots. Both results already belong to the full 6D dynamic model of the system, which was developed in parallel with the mechanical design in order to guide and feedback the development of the conceptual design (conceptual design phase was finished just a few weeks ago). Figure 3(b) shows the open loop Nyquist plot with the system tilted in its outer range and taking misalignments into account. Extensive modelling and error budgeting has been done with respect to alignment and assembly strategy of the system, since assembly and alignment tooling, and interfaces were also part of the conceptual design phase. Simply ignoring them and trying to add them later would never succeed in such complex system design. Finally, to reach the required closed-loop bandwidth in the order of 200 to 300 Hz, the phase loss in the feedback loop is analyzed to define the necessary sample rate of the MIMO controller. As it can be seen in Table 2, by looking at sampling frequency, desired bandwidth and system latency, the phase loss can be calculated and the minimum sampling frequency for a certain system robustness requirement can be determined. For the first prototype of the DCM the MIMO controller will be realized in a real-time XPC target, whereas a high-end motion controller is under evaluation for the final solution.

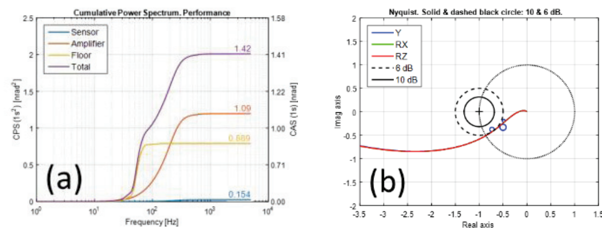

Figure 3: (a) Cumulative Power Spectrum Performance, analysing disturbances individual contributions. (b) Nyquist plot example, with analysis made for misaligment impacts on stability.

Table 2: Phase Loss vs. Sample Frequency

Sampling frequency	**5 kHz**	**10 kHz**	**20 kHz**
Zero-order holder	-5.40º	-2.70º	-1.35º
General delay	-10.80º	-5.40º	-2.70º
Interferometer latency	-0.11º	-0.11º	-0.11º
Total	-16.31º	-8.21º	-4.16º
Spec < -10º	Not Ok	Ok	Ok

CONCLUSION

In this paper a proven dynamic architecture of high-end equipment, as commonly used in semiconductor manufacturing equipment, is applied for a DCM. With a solution based on VC actuators and a balance mass, the present dynamic model predicts that a closed-loop bandwidth above 200 Hz will be achieved in this prototype. This is necessary to reach high disturbance rejection and tracking performance, and thus attain to a few nrad also during flyscan, as required in next generation DCMs. The development of the dynamic model and the use of a set of analysis tools has proven to be essential to accomplish the predictive modelling that such high performance system demands. In conclusion, these concepts and this approach have already started to be applied in other mechanisms of the Sirius beamlines, including mirror systems and sample stages.

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