STUDIES ON FLOW-INDUCED VIBRATIONS 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]. The disturbances induced by the coolant flows are known to be among the most detrimental influences to a DCM performance, however, quantitative force numbers are not commonly investigated. According to the novel dynamic concept, these forces should be predictably translated into stability performance. Therefore, experimental setups that allow the indirect measurement of such forces in conditions close to those of operation were designed. The results comparing different indirect cooling profiles and manufacturing processes (brazing and additive manufacturing) are shown.

INTRODUCTION

The goal of this work is to present the flow-induced vibrations experiments, an indirect measurement of the force frequency spectrum for the cooling vibrations disturbances at the new high stability monochromator for Sirius [1]. Details about the full system can be found in [3].

DCM CLOSED LOOP CONTROL

The new high-dynamics monochromator introduced in the present conference is a high ending mechatronics system [4], in which the system stability, in particular, is only possible because of a high-bandwidth closed loop control. As it is highlighted in Fig. 1, in order to achieve a nanometric positioning resolution and stability it is essential to understand the disturbances actuating on each element of the closed loop control, so that the effects of each disturbance can be analysed already at project level. Therefore, one must know the frequency domain characteristics and energy content of each component.

A preliminary work has already been dedicated to floor vibration characterization at Sirius [5], whereas amplifier and quantization noise, delays, non-linearities and other disturbances from the chosen equipment are well-known (see [6]). Flow-induced vibrations, on the other hand, are a more difficult subject, to which this work is dedicated.

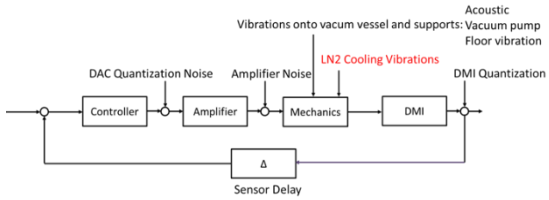

Figure 1: Block diagram of a generic representation of the main disturbances of the closed loop control.

LIQUID NITROGEN COOLING

Due to the high power load that reaches the first crystal in the DCM, liquid nitrogen (LN_2) or water-cooling is generally necessary. An important development front was conducted in this subject to match the LN_2 cooling requirements with the high-dynamics and metrology methods [7].

The problems associated with flow-induced vibrations are known since very long [8], and their negative influence in the performance of monochromators has already been identified and characterized [8, 9]. Indeed, previous works presented vibration results as position vs. frequency plots [10] or acceleration levels (or arbitrary units) in time plots [11, 12]. The state-of-the-art DCMs typically live under given conditions, passively dealing with them by means of mechanical improvements to damp the vibrations and tuning flow and working pressure for each system.

However, in order to guarantee higher bandwidth dynamic control and set the appropriate designing targets for the project, quantitative data of disturbance forces in conditions close to that of real operation should be available. Thus, the force Power Spectral Density (PSD) from the flow-induced vibrations should be characterized.

DYNAMIC MODEL

Discrete structure model

The first step was the development of a 1D lumped-mass model, as depicted in Fig. 2(a). The purpose was to design an experimental setup that would be sensitive enough to the expected small force levels. The first approximation was that the flow-induced disturbance forces would be in the range of 1 to 10 mN. These values guided the definition of masses and stiffness for the setups. It was soon realized that the PSD noise floor of the metrology instruments together with parasitic disturbances, such as floor vibrations, would prevent the full frequency range of interest (from about out 5 Hz to 2 kHz), from being evaluated with a single setup.

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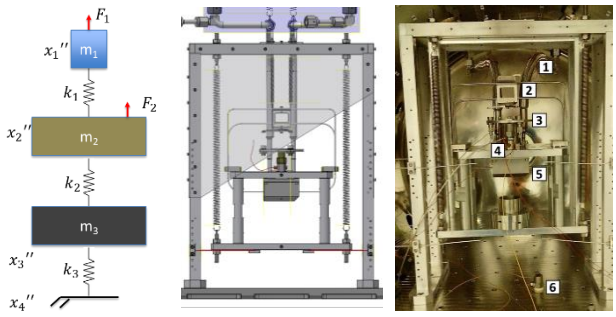


(a) (b) (c)

Figure 2: Dynamic project phases: (a) 1D lumped-mass model; (b) 3D CAD model, with dynamic simulations and model validation; (c) full instrumented setup, assembled on a UHV chamber, where: 1: LN_2 lines, 2: cooling block, 3: interferometer, 4 and 6: accelerometers, 5: manifold.

Therefore, this evaluation would need to be done with different sensors in different setups for two separate frequency regions. In the DCM the low-stiffness pipes that are used prevent the cooling system from fighting against the metrology architecture. In this case, this mechanical property of the pipes allowed for the design of the experiment in those two regions, namely, before and after the mechanical decoupling of the mass of interest, which could be the copper cooling blocks (m1) or the LN_2 manifold (m2) of the DCM, from the rest of the structure. Indeed, by using the assembly stiffness and measuring displacement, vibration forces in the low frequency range (before decoupling) could be found. Likewise, by using the mass and measuring acceleration, vibration forces in the high frequency range (after decoupling) can be obtained. Fig. 3 depicts the basic dynamics of a second order system, showing the dominant regions of stiffness and mass, which defines the concept that has been used.

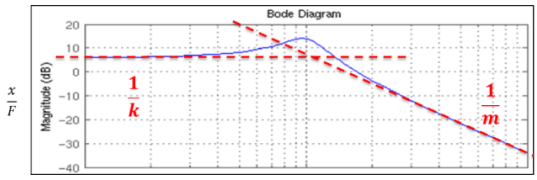


Figure 3: Bode Diagram for a second order system, showing the frequency range proportional to the stiffness (1/k) and the one proportional to the mass (1/m).

Dynamic Simulation and Previous Evaluation

As mentioned, two force PSD levels are of interest, namely, F1, the vibration disturbance force in the cooling blocks, and F2, the force in the LN_2 manifold. Fig. 4 shows MIMO Frequency Response Functions for this system, through which an iterative method was applied, in order to achieve the ideal setup configurations, namely, convenient attenuation of the parasitic disturbances to assure reliable quantitative data in the measurements. It also shows the progress of the model: "First model" represents the initial target values, "Updated model" uses the values after final mechanical design and FEA analysis, and "Measured parameters model" uses the measured stiffness and mass for each body. It can be seen that the real setup is in very good agreement with the designed model. Finally, it represents the MIMO FRF for case 1 at Table 1, where the working cases are summarized. Looking at the first output in Fig. 5, i.e. the first row with the sensitivity of the displacement measurements by the interferometer, one can see that, in the frequency range of interest, the inputs from Acc1 (floor acceleration) and F2 are attenuated, whereas F1 is not.

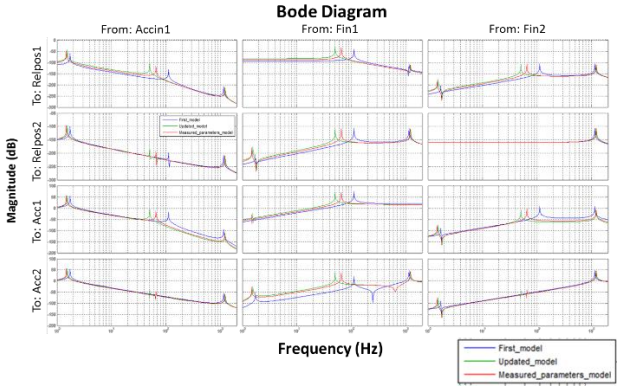
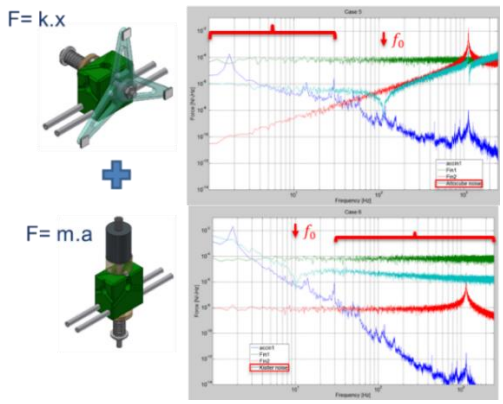


Figure 4: MIMO System FRF. Inputs: Acc1, floor acceleration; F1, forces at the cooling block; and F2 forces at the manifold. Outputs: displacement 1 (w.r.t m2) and 2 (w.r.t m3) and accelerations at m1 and m2.

Table 1: Setup matrix information

Case	Measured output	Measured force	Frequency range
1	Relpos1	F1	5 – 40 Hz
2	Acc1	F1	70 – 2 kHz
3	Relpos2	F2	5 – 40 Hz
4	Acc2	F2	10 – 2 kHz



(a)

(b)

Figure 5: Force measurement, using stiffness and position in (a) and acceleration and mass in (b).

In Fig. 5, from the transfer functions, the disturbances and instruments characteristics, a final dynamic analysis was made, in which can be seen the simulated force level of each disturbance or force, as well as the sensor noise level. The goal of this analysis was to ensure that the force magnitude of interest was at least one order of magnitude higher than all other values, in order to take the values as reliable data, as already mentioned.

EXPERIMENT

Instrumentation Description

The previous dynamic analysis showed that the selection of the appropriate sensor or instrument is essential to have the reliable force results. The Fabry-Perot interferometer from AttoCube was used to measure displacement, with resolution of 1 pm and acquisition bandwidth of 10 MHz [6]. The operational conditions, cryogenic temperatures and UHV, were the most critical obstacles. As a complementary measurement instrument, Kistler 8786A5 accelerometer sensors were used. They were chosen for their relative small mass and low noise floor at the required frequency range. The operational conditions were a problem once again, since these sensors have nonlinear behaviours with temperature and are definitely not cryogenic compatible. Thus, cartridge resistances and thermocouples were used to make localized closed-loop temperature control, keeping them at room temperature, despite the cryogenic conditions of the setup.

The experiment automation was designed in a National Instruments cRIO platform. The FPGA was essential to read the interferometer's HSSL protocol [13]. A NI USB-4431 24 bit ADC was preferred to read the accelerometer signals and ensure a lower digitizer influence. Finally, FMB Oxford Series F Cryocooler was chosen because of its proven dynamic stability. The auxiliary vacuum vessel and its instrumentation, which were needed due to the low temperatures, is a fully automated system that was recently developed in-house exactly for this sort of application. It is called Multipurpose Vacuum Chamber.

Setup validation and calibration

Before the final assembly of the parts, it was necessary to measure the real parameters to validate and calibrate the dynamic model. The mass of each part was measured in a precision weighing scale, whereas the stiffness values were indirectly determined in auxiliary tests in which the displacement caused by known masses was measured. Then, the final alignment of the setup was made using auxiliary level sensors, what was necessary because of the flexible extension springs used to decouple the system from the outside vibrations influences, as shown in Fig. 2. Finally, after the final assembly, the background signal levels of the sensors were measured to ensure the reliability of the collected data and proper post-processing analyses.

PARALLEL DEVELOPMENT

To achieve the right vibration and thermal performances in the DCM. The well-known brazing of OFHC Copper and 316L Stainless Steel, using Palcusil-10 are the first production approaches. Nevertheless, 3D printing technology is also under validation, to make the optimal cooling design possible. The first leak test results of the 3D parts are showed on Table 2. Unfortunately, the only process with a successful prototype regarding UHV application (target leak: $\leq 1.0 \cdot 10^{-11}$ mbar.l/s) has failed in producing the final design. However, this is still work in-progress.

Table 2: Leak test results of 3D-printed prototypes

Material	Supplier	Leak test result [mbar.l/s]	Approved
CoCr	UNICAMP	$1.0 \cdot 10^{-4}$	Not OK
SS – PH1	UNICAMP	$1.0 \cdot 10^{-1}$	Not OK
SS – 316L	Höganäs	$1.0 \cdot 10^{-11}$	OK

In addition, the development of a low-vibration flexible hose with an internal mesh is under evaluation (Fig. 6). Since F2 also includes the contribution of the vibrations from the hoses, their design should be optimized. This development based on the results shown on [10].

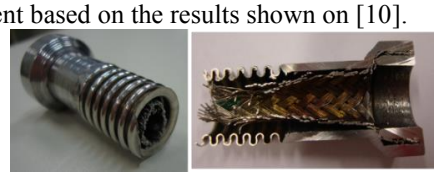


Figure 6: Flexible hose with internal mesh to reduce turbulence and vibration levels in the cooling lines.

RESULTS

The experiments are still in progress and the first results are according to the initial force estimates, i.e., in the mN range in the PSD plot, as shown in Fig. 7. Considering Fig. 4, the first low-frequency peak, at about 7 Hz, should come from input1-output1 and the last peak, at about 80 Hz, should be the first resonance frequency of input1-output2.

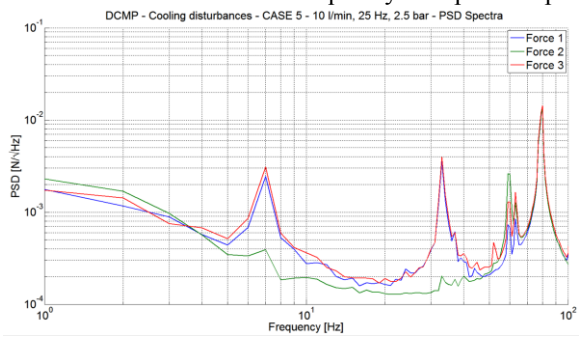


Figure 7: First results for case 1. Forces 1, 2 and 3 come from three simultaneous interferometer readings that measure the displacement of the cooling block. The correlated data provide distance, pith and roll data.

CONCLUSIONS

The proposed approach has been successfully validated and the forces actuating on the first crystal of the high-dynamics DCM for Sirius can be extracted from the PSD measurements and feed back into the dynamic model of the DCM. Simultaneously, different cooling designs are being evaluated to guide the design targets for the final DCM system.

ACKNOWLEDGEMENT

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