MECHATRONICS APPROACH FOR THE DEVELOPMENT OF A NANO-ACTIVE-STABILIZATION-SYSTEM

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Abstract

With the growing number of fourth generation light sources, there is an increased need of fast positioning end-stations with nanometric precision. Such systems are usually including dedicated control strategies, and many factors may limit their performances. In order to design such complex systems in a predictive way, a mechatronic design approach also known as "model based design", may be utilized. In this paper, we present how this mechatronic design approach was used for the development of a nano-hexapod for the ESRF ID31 beamline. The chosen design approach consists of using models of the mechatronic system (including sensors, actuators and control strategies) to predict its behavior. Based on this behavior and closed-loop simulations, the elements that are limiting the performances can be identified and re-designed accordingly. This allows to make adequate choices concerning the design of the nano-hexapod and the overall mechatronic architecture early in the project and save precious time and resources. Several test benches were used to validate the models and to gain confidence on the predictability of the final system's performances. Measured nano-hexapod's dynamics was shown to be in very good agreement with the models. Further tests should be done in order to confirm that the performances of the system match the predicted one. The presented development approach is foreseen to be applied more frequently to future mechatronic system design at the ESRF.

INTRODUCTION

With the new 4th generation machines, there is an increasing need of fast and accurate positioning systems [1].

These systems are usually including feedback control loops and therefore their performances are not depending on the mechanical system alone, but also on its interaction with the actuators, sensors and control electronics.

In order to optimize the performances of such system, it is essential to consider a design approach in which the structural design and the control design are integrated. This approach is called the "mechatronic approach" and was shown to be very effective for the design many complex systems [2, 3]. Such design methodology was recently used for the development of several systems used by the synchrotron community [4–6].

In this paper, such approach is described for the design of a Nano Active Stabilization System (NASS).

NASS - MECHATRONIC APPROACH

The ID31 Micro-Station

The ID31 micro-station is used to position samples along complex trajectories [7]. It is composed of several stacked stages (represented in yellow in Fig. 1). Such architecture allows to obtain high mobility, however, this however limits the position accuracy to tens of μm.

The Nano Active Stabilization System

The NASS is a system whose goal is to improve the positioning accuracy of the micro-station. It is represented in Fig. 1 and consists of three main elements:

- A nano-hexapod located between the sample to be positioned and the micro-station
- An interferometric metrology system measuring the sample's position with respect to the focusing optics
- A control system (not represented), which based on the measured position, properly actuates the nano-hexapod in order to stabilize the sample's position.

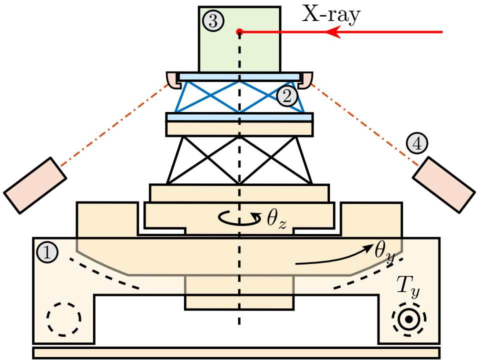

Figure 1: NASS - Schematic representation. 1) Micro-station, 2) Nano-hexapod, 3) Sample, 4) Metrology system

Mechatronic Approach - Overview

In order to design the NASS in a predictive way, a mechatronic approach, schematically represented in Fig. 2, is used. It consists of three main phases:

1. Conceptual phase: Simple models of both the micro-station and the nano-hexapod are used to first evaluate the performances of several concepts. During this phase, the type of sensors to use and the approximate required dynamical characteristics of the nano-hexapod are determined.

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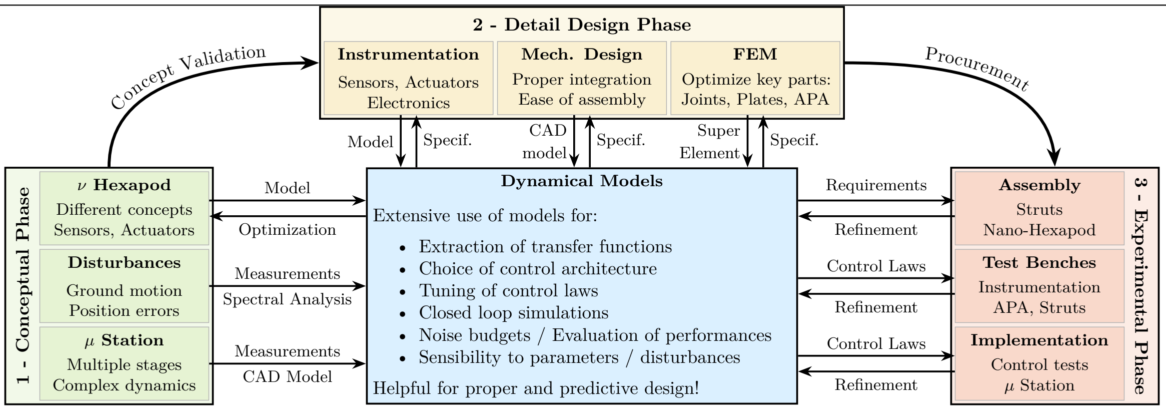


Figure 2: Overview of the mechatronic approach

2. Detail design phase: Once the concept is validated, the models are used to list specifications both for the mechanics and the instrumentation. Each critical elements can then be properly designed. The models are updated as the design progresses.

3. Experimental phase: Once the design is completed and the parts received, several test benches are used to verify the properties of the key elements. Then the hexapod can be mounted and fully tested with the instrumentation and the control system.

Models

As shown in Fig. 2, the models are at the core of the mechatronic approach. Indeed, several models are used throughout the design with increasing level of complexity (Fig. 3).

At the beginning of the conceptual phase, simple "mass-spring-dampers" models (Fig. 3a) are used in order to easily study different concepts. Noise budgeting and closed-loop simulations were performed, and it was concluded that a nano-hexapod with low frequency "suspension" modes would help both for the reduction of the effects of disturbances and for the decoupling between the nano-hexapod dynamics and the complex micro-station dynamics. Also, including a force sensor in series with the nano-hexapod's actuators can be used to actively damp the resonances using the "Integral Force Feedback" (IFF) strategy. The goal is to obtain a "plant" dynamics which is easy to control in a robust way.

Rapidly, a more sophisticated and more realistic multi-body model (Fig. 3b) was used. This model is based on the 3D representation of the micro-station as well as on extensive dynamical measurements. Time domain simulations can then be performed with each stage moving with the associated positioning errors and disturbances. Such model permits to study effects such as the coupling between the actuators and the sensors as well as the effect of the spindle's rotational speed on the nano-hexapod's dynamics [8]. The multi-input multi-output control strategy can be developed and tested.

During the detail design phase, the nano-hexapod model is updated using 3D parts exported from the CAD software as the mechanical design progresses. The key elements of the nano-hexapod such as the flexible joints and the APA are optimized using a Finite Element Analysis (FEA) Software. As the flexible modes of the mechanics are what generally limit the controller bandwidth, they are important to model in order to understand which ones are problematic and should be maximized. To do so, a "super-element" can be exported using a FEA software and then imported in Simscape (Fig. 3c). Such process is described in [9]. The multi-body model with included flexible elements can be used to very accurately estimate the dynamics of the system. However due to the large number of states included, it becomes non practical to perform time domain simulations.

Finally, during the experimental phase, the models are refined using experimental system identification data. These models can be used to understand the measurements, the associated performance limitations and to gain insight on which measures to take in order to overcome these limitations.

For instance, it has been found that when fixing the encoders to the struts (Fig. 4), several flexible modes of the APA were appearing in the dynamics which render the control using the encoders very complex. Therefore, an alternative configuration with the encoders fixed to the plates was used instead.

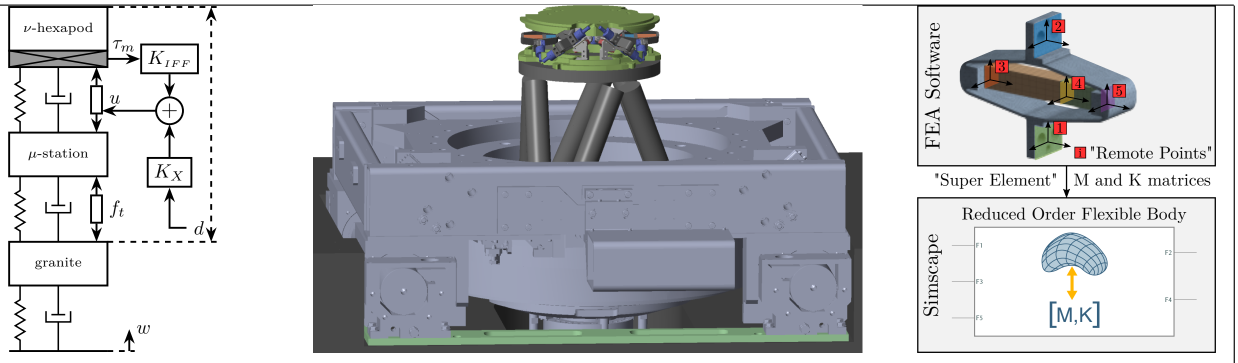
NANO-HEXAPOD DESIGN

Nano-Hexapod Specifications

The nano-hexapod should have a maximum height of $95\,mm$, support samples up to $50\,kg$ and have a stroke of $\approx 100\,\mu m$. Has shown in Fig. 4, it only has few parts: two plates and 6 active struts in between. Each strut is composed of one flexible joint at each end, and one actuator in between (Fig. 5).

Based on the models used throughout the mechatronic approach, several specifications was obtained in order to maximize the performances of the system:

- Actuator: axial stiffness $\approx 2\,\mathrm{N}/\mu\mathrm{m}$.



(a) Mass Spring Damper Model (b) Multi Body Model (c) Finite Element Model

Figure 3: Schematic of several models used during all the mechatronic design process.

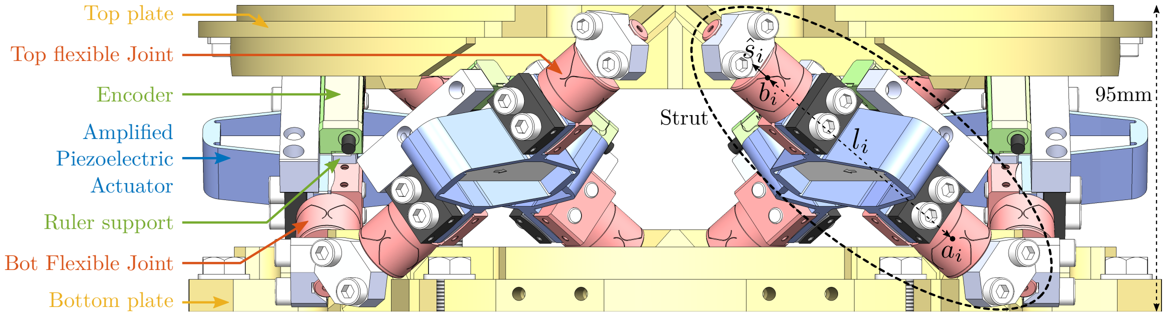


Figure 4: CAD view of the nano-hexapod with key elements

- Flexible joints: bending stiffness $< 100\,\mathrm{Nm/rad}$ and axial stiffness $> 100\,\mathrm{N/\mu m}$.
- Precise positioning of the b_i and $\hat{s}_i$ to accurately determine the hexapod's kinematics.
- Flexible modes of the top-plate as high as possible to increase the control robustness.
- Integration of a force sensor in each strut for active damping purposes.

Parts' Optimization

The geometry of the flexible joint could be optimized using a finite element software. The obtained stiffnesses are compliance with the requirements and the model was updated.

The top plate geometry was manually optimized to maximize its flexible modes. First flexible modes at around 700 Hz could be obtained.

Amplified Piezoelectric Actuators (APA) were found to be the most suitable actuator for the nano-hexapod due to its compact size, large stroke and adequate stiffness. The chosen model was the APA300ML from Cedrat Technologies (shown in Fig. 5). It is composed of three piezoelectric stacks, a lever mechanism increasing the stroke up to $\approx 300\,\mu\mathrm{m}$ and decreasing the axial stiffness down to $\approx 1.8\,\mu\mathrm{m}$. One of the three stacks can be used as a force sensor, at the price of loosing 1/3 of the stroke. This has the benefits providing good "collocation" between the sensor stack and the actuator stacks, meaning that the active damping controller will easily be made robust [10].

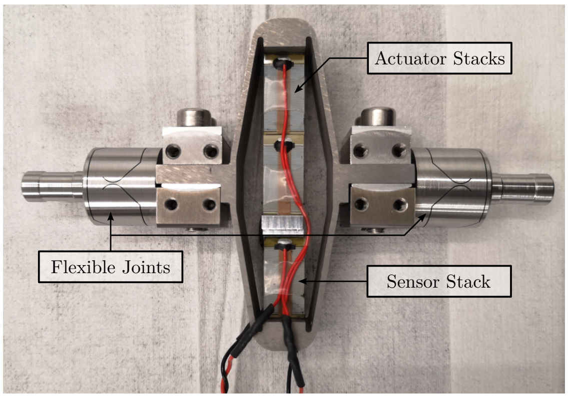


Figure 5: Picture of a nano-hexapod's strut

Nano-Hexapod Mounting

A bench were developed to help the mounting of the struts such that the APA and the two flexible joints are well aligned. This helped reducing the effects of flexible modes of the APA.

A second mounting tool were used to fix the six struts to the two plates without inducing too much strain in the flexible joints.

The nano-hexapod fixed on top of the micro-station is shown in Fig. 6.

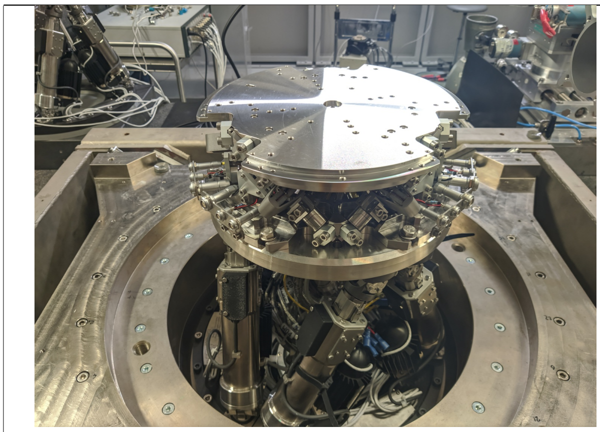


Figure 6: Nano-hexapod on top of the ID31 micro-station

TEST-BENCHES

Flexible Joints and Instrumentation

Before adding the NASS to the micro-station, several test benches were used to characterize the individual elements of the NASS.

The bending stiffness of the flexible joints was measured by applying a controlled force to one end of the joint while measuring its deflection at the same time. This helped exclude the ones not compliant with the requirement and pair the remaining ones.

The transfer function from input to output voltage of the voltage amplifier[1] as well as its output noise was measured. Similarly, the measurement noise of the encoders[2] was also measured.

These simple measurements on individual elements are useful to refine their models, to found any problem as early as possible, and to help analyzing the results obtained with the nano-hexapod mounted and all elements combined.

APA and Struts Dynamics

An other test bench schematically shown in Fig. 7 was used to identify the dynamics of the APA. It consist of a 5 kg granite fixed on top of the APA and vertical guided with an air bearing. An excitation signal (low pass filtered white noise) is generated and applied to two of the piezoelectric stacks. Both the voltage generated by the third piezoelectric stack and the displacement measured by the encoder are recorded. The two obtained frequency response functions (FRF) are compared with the model in Fig. 8.

The piezoelectric constants describing the conversion from the mechanical domain (force, strain) easily accessible on the model to the electrical domain (voltages, charges) easily measured can be estimated. With these constants, the match between the measured FRF and the model dynamics is very good (Fig. 8).

The same bench was also used with the struts in order to study the added effects of the flexible joints.

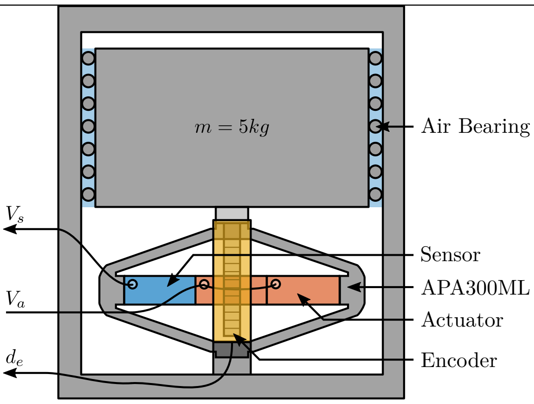
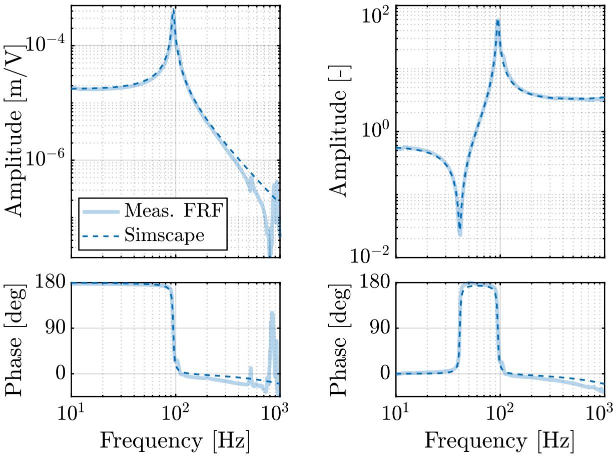


Figure 7: Schematic of the bench used to identify the APA dynamics



(a) Encoder d_e/V_a

(b) Force Sensor V_s/V_a

Figure 8: Measured Frequency Response functions compared with the Simscape model. From the actuator stacks voltage to the encoder (a) and to the force sensor stack (b).

Nano-Hexapod

Once the nano-hexapod is mounted, its dynamics is identified by individually exciting each of the actuators and simultaneously recording the six force sensors and six encoders signals. Two 6 by 6 FRF matrices are computed. Their diagonal elements are shown in Fig. 9 and compared with the model.

In Fig. 9a one can observe the following modes:

- From 100 Hz to 200 Hz: six suspension modes
- At 230 Hz and 340 Hz: flexible modes of the APA, also modeled thanks to the flexible model of the APA
- At 700 Hz: flexible modes of the top plate, not matching the FRF because it is modeled as a rigid body

The transfer functions from the actuators to their "collocated" force sensors have alternating poles and zeros (Fig. 9b) as expected. IFF is then applied individually on each pair of actuator/force sensor in order to actively damp the suspension modes. The optimal gain of the IFF controller is determined using the model. After applying the active

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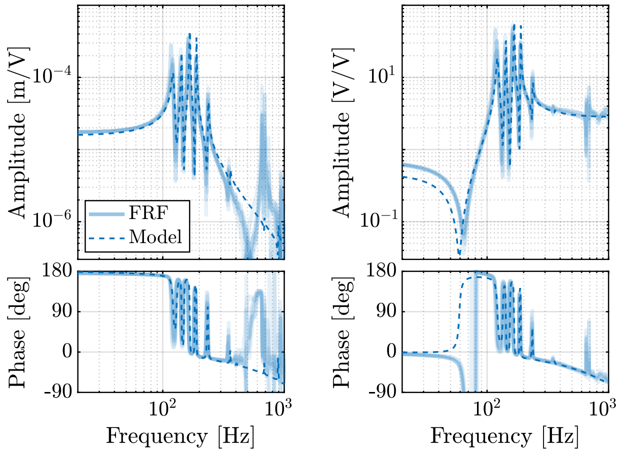
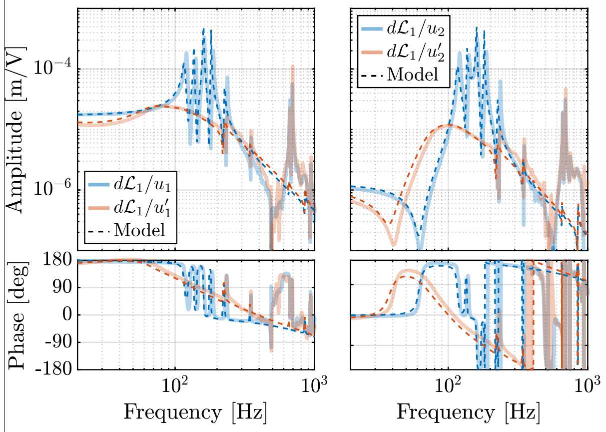
[1] PD200 from PiezoDrive
[2] Vionic from Renishaw

damping technique, the 6 by 6 FRF matrix from the actuator to the encoders is identified again and shown in Fig. 10. It is shown that all the suspension modes are critically damped, and that the model is able to predict the closed-loop behavior of the system. Even the off-diagonal elements (effect of one actuator on the encoder fixed to another strut) is very well modeled (Fig. 10b).



(a) Encoder: $d\mathcal{L}_i/u_i$ (b) Force Sensor: $V_{s,i}/u_i$

Figure 9: Comparison of the measured Frequency Response functions (FRF) with the Simscape model. From the excitation voltage to the associated encoder (a) and to the associated force sensor stack (b).



(a) Diagonal term (b) Off-Diagonal term

Figure 10: Transfer functions from actuator to encoder with and without the active damping technique applied.

CONCLUSION

The mechatronic approach used for the development of a nano active stabilization system was presented. Such approach allowed to design the system in a predictive and optimal way.

Measurements made on the nano-hexapod were found to match very well with the models indicating proper design. The current performance limitation is coming from the flexible modes of the top platform and future work will focus on overcoming this limitation.

This design methodology can be easily transposed to other complex mechatronic systems and are foreseen to be applied for future mechatronic systems at the ESRF.

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REFERENCES

[1] R. Dimper, H. Reichert, P. Raimondi, L. Ortiz, F. Sette, and J. Susini, *ESRF upgrade programme phase II (2015-2022) - technical design study*, The orange book, 2015.

[2] A. M. Rankers, "Machine dynamics in mechatronic systems: An engineering approach.", Ph.D. dissertation, University of Twente, 1998.

[3] R. M. Schmidt, G. Schitter, and A. Rankers, *The Design of High Performance Mechatronics - Third Revised Edition*. Ios Press, 2020.

[4] R. Geraldes, R. Caliari, G. Moreno, M. Ronde, T. Ruijl, and R. Schneider, "Mechatronics Concepts for the New High-Dynamics DCM for Sirius", in *MEDSI'16*, JACoW Publishing, Geneva, Switzerland, Jun. 2017. DOI: 10.18429/JACoW-MEDSI2016-MOPE19.

[5] M. Holler *et al.*, "Omny-a tomography nano cryo stage", *Review of Scientific Instruments*, 2018. DOI: 10.1063/1.5020247.

[6] M. Brendike *et al.*, "Esrf-double crystal monochromator prototype–control concept", in *17th International Conference on Accelerator and Large Experimental Physics Control Systems*, 2019.

[7] T. Dehaeze, M. M. Mattenet, and C. Collette, "Sample stabilization for tomography experiments in presence of large plant uncertainty", in *MEDSI'18*, Dec. 2018. DOI: 10.18429/JACoW-MEDSI2018-WEOAMA02.

[8] T. Dehaeze and C. Collette, "Active damping of rotating platforms using integral force feedback", *Engineering Research Express*, Feb. 2021. DOI: 10.1088/2631-8695/abe803.

[9] P. Brumund and T. Dehaeze, "Multibody simulations with reduced order flexible bodies obtained by fea", in *MEDSI'20*, Jul. 2021.

[10] A. Souleille *et al.*, "A concept of active mount for space applications", *CEAS Space Journal*, 2018.