Mechatronic approach for the design of a Nano Active Stabilization System

PhD Thesis

by

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at

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Abstract

Résumé

Acknowledgments

Contents

List of Tables

List of Figures

1. Introduction

1.1 Context of this thesis / Background and Motivation

- ESRF (Figure 1.1)

Figure 1.1.: European Synchrotron Radiation Facility

- ID31 and Micro Station (Figure 1.2)

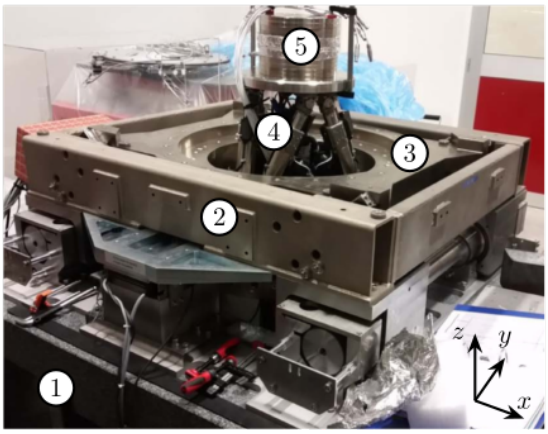


Figure 1.2.: Picture of the ID31 Micro-Station with annotations

Alternative: `id31_microstation_cad_view.png` (CAD view)

- X-ray beam + detectors + sample stage (Figure 1.3)

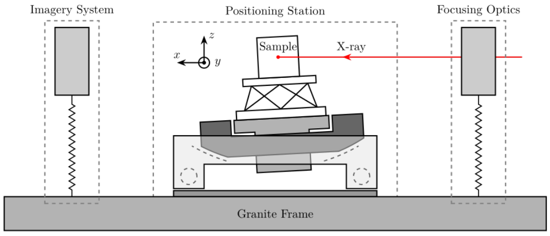


Figure 1.3.: ID31 Beamline Schematic. With light source, nano-focusing optics, sample stage and detector.

- Few words about science made on ID31 and why nano-meter accuracy is required
- Typical experiments (tomography, ...), various samples (up to 50kg)
- Example of picture obtained (Figure 1.4)

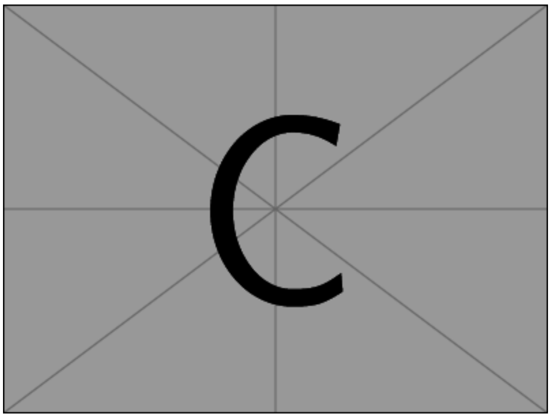


Figure 1.4.: Image obtained on the ID31 beamline

- Explain wanted positioning accuracy and why micro-station cannot have this accuracy (backlash, play, thermal expansion, ...)

1.2 Challenge definition

- 6DoF vibration control platform on top of a complex positioning platform
- **Goal**: Improve accuracy of 6DoF long stroke position platform
- **Approach**: Mechatronic approach / model based / predictive
- **Control**: Robust control approach / various payloads. First hexapod with control bandwidth higher than the suspension modes that accepts various payloads?
- Rotation aspect
- Compactness? (more related to mechanical design)

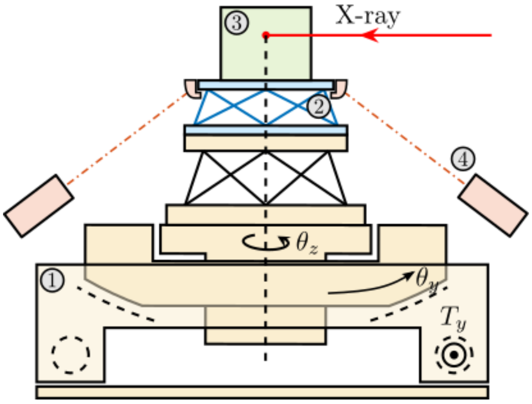
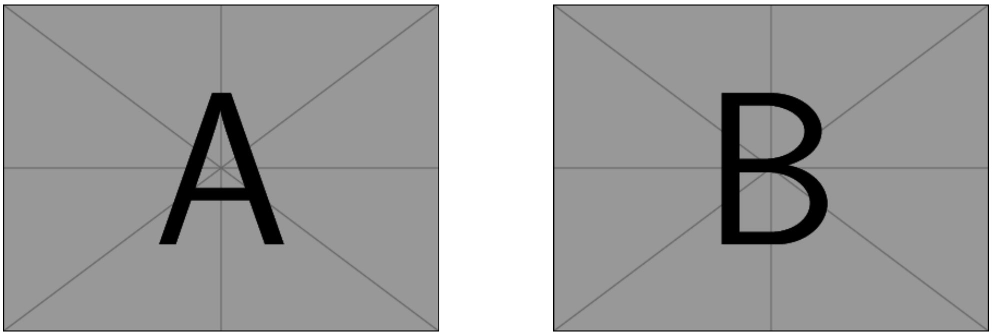


Figure 1.5.: Nass Concept. 1: micro-station, 2: nano-hexapod, 3: sample, 4: 5DoF metrology



(a) Stewart platform based on voice coil actuators

(b) Stewart platform based on piezoelectric actuators

Figure 1.6.: Examples of Stewart Platforms

1.3 Literature Review

- Hexapods **li01_simul_fault_vibrat_isolat_point bishop02_devel_precis_point_contr_vibrat hanieh03_activ_stewar afzali-far16_vibrat_dynam_isotr_hexap_analy_studies naves20_desig**
- Positioning stations
- Mechatronic approach? **rankers98_machin monkhorst04_dynam_error_budget jabben07_mechat**

1.4 Outline of thesis / Thesis Summary / Thesis Contributions

Mechatronic Design Approach / Model Based Design:

- **monkhorst04_dynam_error_budget** high costs of the design process: the designed system must be **first time right**. When the system is finally build, its performance level should satisfy the specifications. No significant changes are allowed in the post design phase. Because of this, the designer wants to be able to predict the performance of the system a-priori and gain insight in the performance limiting factors of the system.

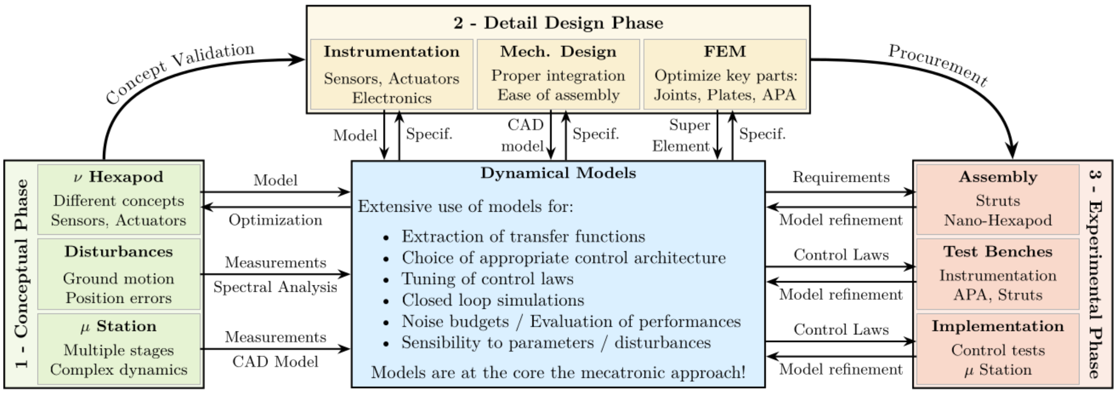


Figure 1.7.: Overview of the mechatronic approach used for the Nano-Active-Stabilization-System

2. Conceptual Design Development

Contents

Abstract Schematic that summarizes this phase. Uniaxial => Rotation => Multi body => Simulations

2.1 Constrains on the system

- Size
- Payload
- Connections to samples
- … should justify the nano-hexapod design
  - choice of parallel architecture

  Picture/schematic of the micro-station with indicated location of Nano-Hexapod

2.2 Uni-axial Model

- Explain what we want to capture with this model
- Schematic of the uniaxial model (with X-ray)
- Identification of disturbances (ground motion, stage vibrations)
- Optimal nano-hexapod stiffness/actuator: Voice coil VS Piezo (conclusion?)
- Control architecture (IFF, DVF, …)?
- Conclusion

2.2.1 Noise Budgeting

2.2.2 Effect of support compliance

study

- **goal**: make the nano-hexapod independent of the support compliance
- Simple 2DoF model

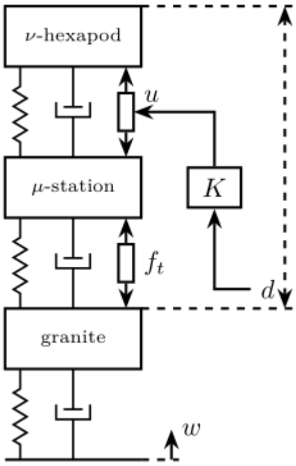


Figure 2.1.: 3-DoF uniaxial mass-spring-damper model of the NASS

- Generalized to any support compliance
- **conclusion**: frequency of nano-hexapod resonances should be lower than first suspension mode of the support

2.2.3 Effect of payload dynamics

study

- **goal**: be robust to a change of payload
- Simple 2DoF model
- Generalized to any payload dynamics

2.2.4 Active Damping

Conclusion: IFF is better for this application

Integral Force Feedback

- Mass spring damper model
- Root Locus
- Sensitivity to disturbances

Direct Velocity Feedback

- Mass spring damper model
- Root Locus

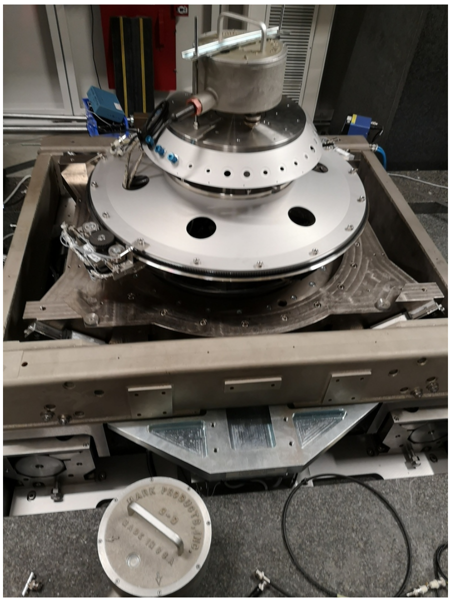


Figure 2.2.: Setup used to measure the micro-station vibrations during operation

- Sensitivity to disturbances

2.3 Effect of rotation

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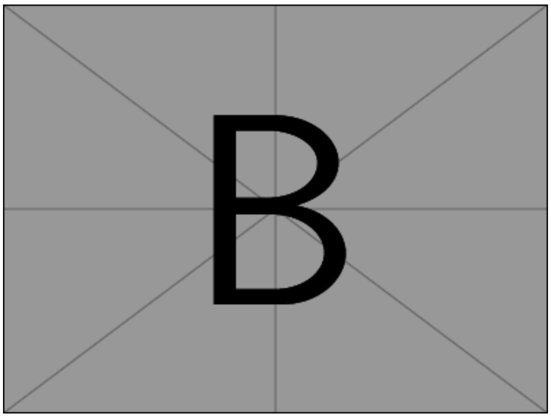

Figure 2.3.: Amplitude Spectral density of the measured disturbance sources

2.3.1 X-Y rotating platform model

- x-y-Rz model
- explain why this is representing the NASS
- Equation of motion
- Centrifugal forces, Coriolis

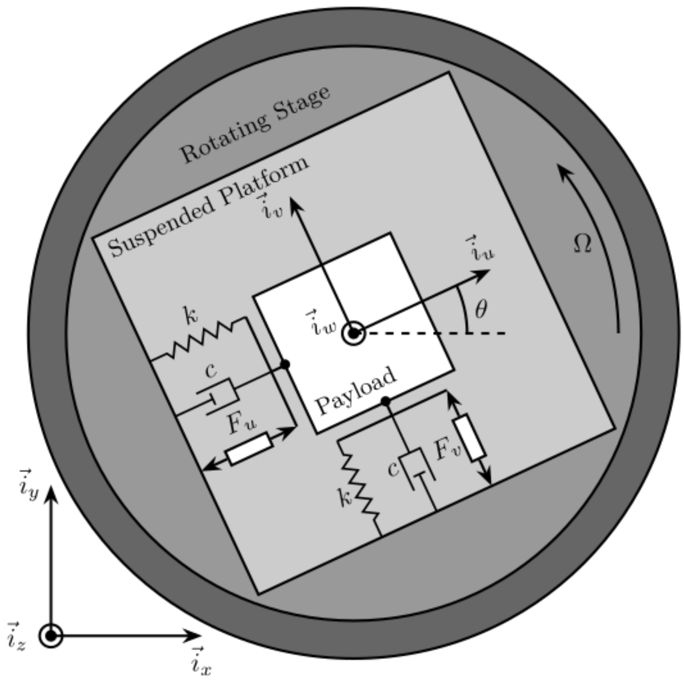

Figure 2.4.: Mass spring damper model of an X-Y stage on top of a rotating stage

2.3.2 Effect of rotational velocity on the system dynamics

- Campbell diagram

2.3.3 Decentralized Integral Force Feedback

- Control diagram
- Root Locus: unstable with pure IFF

2.3.4 Two proposed modification of IFF

- Comparison of parallel stiffness and change of controller

- Transmissibility

2.3.5 Conclusion

- problem with voice coil actuator
- Two solutions: add parallel stiffness, or change controller
- Conclusion: minimum stiffness is required
- APA is a nice architecture for parallel stiffness + integrated force sensor (have to speak about IFF before that)

2.4 Multi Body Model - Nano Hexapod

- What we want to capture with this model
- Explain what is a multi body model (rigid body, springs, etc…)
- Key elements (plates, joints, struts): for now simplistic model (rigid body elements, perfect joints, …), but in next section, FEM will be used
- Matlab/Simulink developed toolbox for the study of Stewart platforms

2.4.1 Stewart Platform Architecture

- Little review
- explain key elements:
  - two plates
  - joints
  - actuators
- explain advantages compared to serial architecture

2.4.2 Kinematics

- Well define elements, frames, …
- Derivation of jacobian matrices: for forces and for displacement
- Explain this is true for small displacements (show how small)

2.4.3 Model of an Amplified Piezoelectric Actuator

- APA test bench
- Piezoelectric effects
- mass spring damper representation (2dof)
- Compare the model and the experiment

2.4.4 Dynamics

- Effect of joints stiffnesses

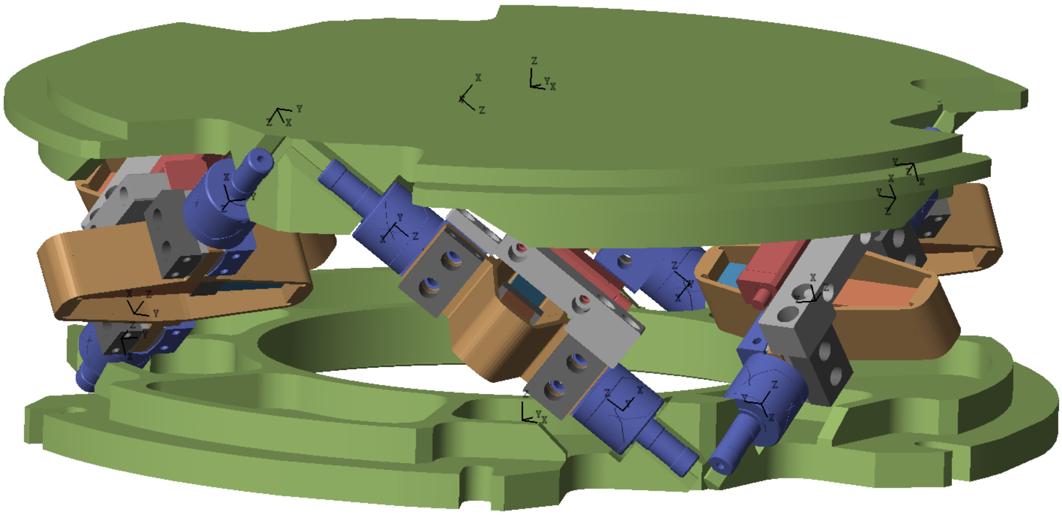

Figure 2.5.: 3D view of the multi-body model of the Nano-Hexapod (simplified)

2.5 Multi Body Model - Micro Station

2.5.1 Kinematics

- Small overview of each stage and associated stiffnesses / inertia
- schematic that shows to considered DoF
- import from CAD

2.5.2 Modal Analysis

study

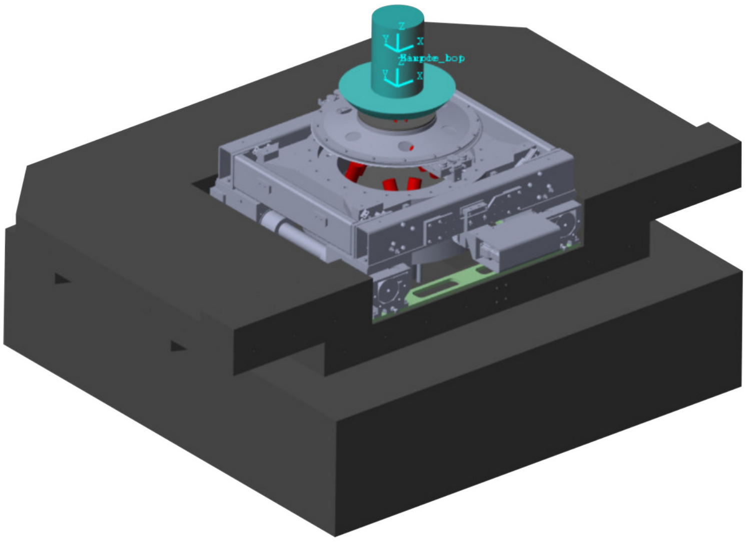

Figure 2.6.: 3D view of the multi-body model of the micro-station

- Picture of the experimental setup
- Location of accelerometers
- Show obtained modes
- Validation of rigid body assumption
- Explain how this helps tuning the multi-body model

2.5.3 Validation of the Model

- Most important metric: support compliance
- Compare model and measurement

2.6 Control Architecture

Discussion of:

- Transformation matrices / control architecture
- Control in the frame of struts or cartesian?
- Effect of rotation on IFF? => APA
- HAC-LAC

2.6.1 High Authority Control - Low Authority Control (HAC-LAC)

- general idea
- case for parallel manipulator: decentralized LAC + centralized HAC

2.6.2 Decoupling Strategies for parallel manipulators

study

- Jacobian matrices, CoK, CoM, …
- Discussion of cubic architecture
- SVD, Modal, …

2.6.3 Decentralized Integral Force Feedback (LAC)

- Root Locus
- Damping optimization

2.6.4 Control Kinematics

- Explain how the position error can be expressed in the frame of the nano-hexapod
- block diagram
- Explain how to go from external metrology to the frame of the nano-hexapod

2.6.5 Decoupled Dynamics

- Centralized HAC
- Control in the frame of the struts
- Effect of IFF

2.6.6 Centralized Position Controller (HAC)

- Decoupled plant
- Controller design

2.7 Simulations - Concept Validation

- Tomography experiment
- Open VS Closed loop results
- **Conclusion**: concept validation nano hexapod architecture with APA decentralized IFF + centralized HAC

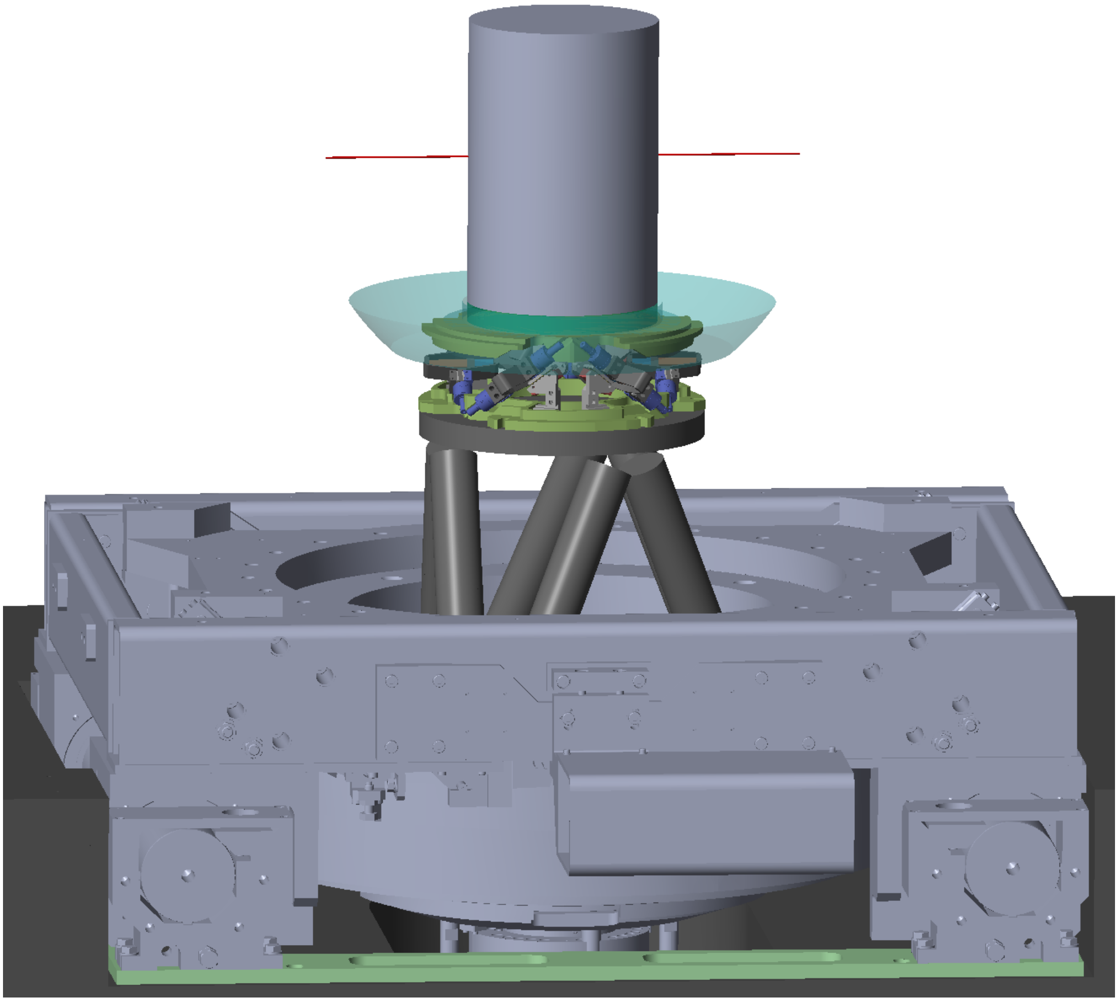

Figure 2.7.: 3D view of the multi-body model including the micro-station, the nano-hexapod and the associated metrology

2.8 Conclusion

3. Detailed Design

Contents

Abstract CAD view of the nano-hexapod with key components:

- plates
- flexible joints
- APA
- required instrumentation (ADC, DAC, Speedgoat, Amplifiers, Force Sensor instrumentation, …)

3.1 Optimal Nano-Hexapod geometry

Geometry?

Cubic architecture?

Kinematics

Trade-off for the strut orientation

Sensors required

3.1.1 Optimal strut orientation

3.1.2 Cubic Architecture: a Special Case?

3.2 Including Flexible elements in the Multi-body model

Reduced order flexible bodies **brumund21_multib_simul_reduc_order_flexib_bodies_fea**

- Used with APA, Flexible joints, Plates

3.2.1 Reduced order flexible bodies

- Quick explanation of the theory
- Implementation with Ansys (or Comsol) and Simscape

3.2.2 Numerical Validation

- Numerical Validation Ansys VS Simscape (APA)
- Figure with 0 and 1kg mass

3.2.3 Experimental Validation

- Test bench
- Obtained transfer functions and comparison with Simscape model with reduced order flexible body

3.3 Amplified Piezoelectric Actuator

study 1, study 2

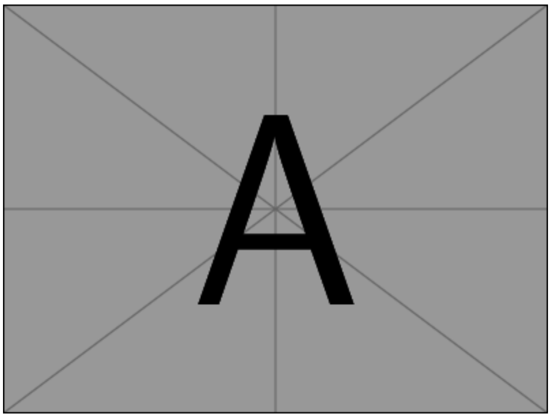

Figure 3.1.: Schematical representation of an Amplified Piezoelectric Actuator

- First tests with the APA95ML

3.3.1 Model

Piezoelectric equations

- FEM
- Simscape model
- (2 DoF, FEM, …)

3.3.2 Experimental System Identification

- Experimental validation (granite test bench)
- Electrical parameters
- Required instrumentation to read force sensor?
- Add resistor to include high pass filtering: no risk of saturating the ADC

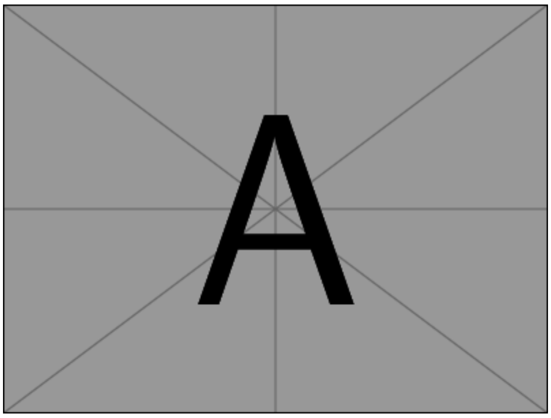

Figure 3.2.: Schematical representation of a 2DoF model of an Amplified Piezoelectric Actuator

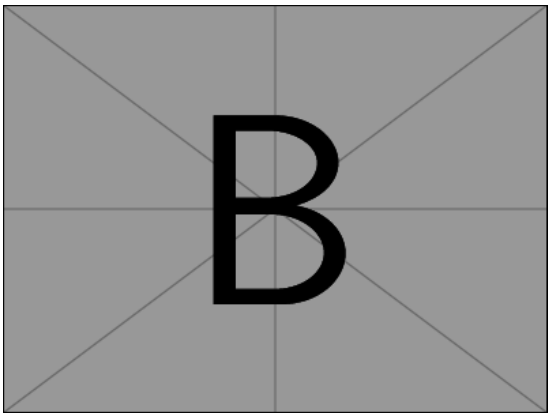

Figure 3.3.: Schematical representation of a FEM of an Amplified Piezoelectric Actuator

- Estimation of piezoelectric parameters

3.3.3 Validation with Simscape model

- Tuned Simscape model
- IFF results: OK

3.4 Flexible Joints

3.4.1 Effect of flexible joint characteristics on obtained dynamics

- Based on Simscape model
- Effect of axial stiffness, bending stiffness, …

- Obtained specifications (trade-off)

3.4.2 Flexible joint geometry optimization

- Chosen geometry
- Optimisation with Ansys
- Validation with Simscape model

3.4.3 Experimental identification

- Experimental validation, characterisation (study)
- Visual inspection
- Test bench
- Obtained results

3.5 Instrumentation

3.5.1 DAC

3.5.2 ADC

Force sensor

3.5.3 Voltage amplifier (link)

- Test Bench: capacitive load, ADC, DAC, Instrumentation amplifier
- Noise measurement
- Transfer function measurement

3.5.4 Encoder (link)

- Noise measurement

3.6 Obtained Mechanical Design

- CAD view of the nano-hexapod
- Chosen geometry, materials, ease of mounting, cabling, …

4. Experimental Validation

Contents

Abstract Schematic representation of the experimental validation process.

- APA
- Strut
- Nano-hexapod on suspended table
- Nano-hexapod with Spindle

4.1 Amplified Piezoelectric Actuator (link)

APA alone:

- **Goal**: Tune model of APA

  FRF and fit with FEM model

  Show all six FRF and how close they are

  IFF

4.2 Struts

Strut (APA + joints):

  FRF, tune model

  Issue with encoder (comparison with axial motion)

IFF

4.3 Nano-Hexapod

Mounting

Test bench on top of soft table:

- **Goal**: Tune model of nano-hexapod, validation of dynamics
- modal analysis soft table (first mode at xxx Hz => rigid body in Simscape)
- FRF + comp model (multiple masses)
- IFF and robustness to change of mass

4.4 Rotating Nano-Hexapod

- **Goal**: validation of control strategy with rotation
- Interferometers to have more stroke

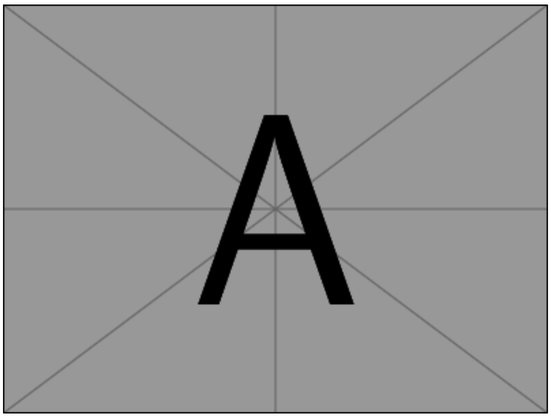

Figure 4.1.: Schematic of the rotating nano-hexapod test bench

4.5 ID31 Micro Station

- **Goal**: full validation without the full metrology

5. Conclusion and Future Work

Appendix A.

Stewart Platform - Kinematics

Appendix B.

Comments on something

List of Publications