Design and optimization techniques for a nano-positioning system

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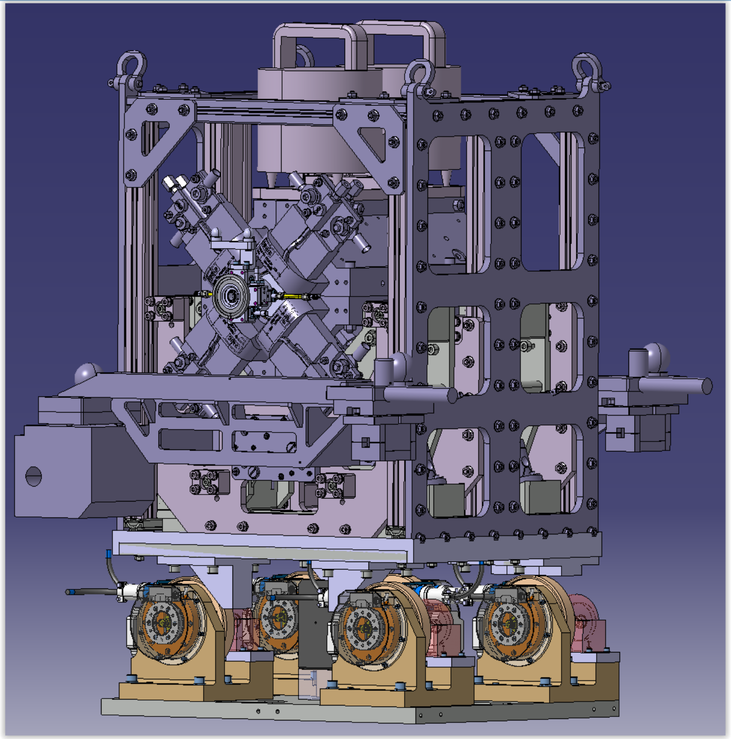
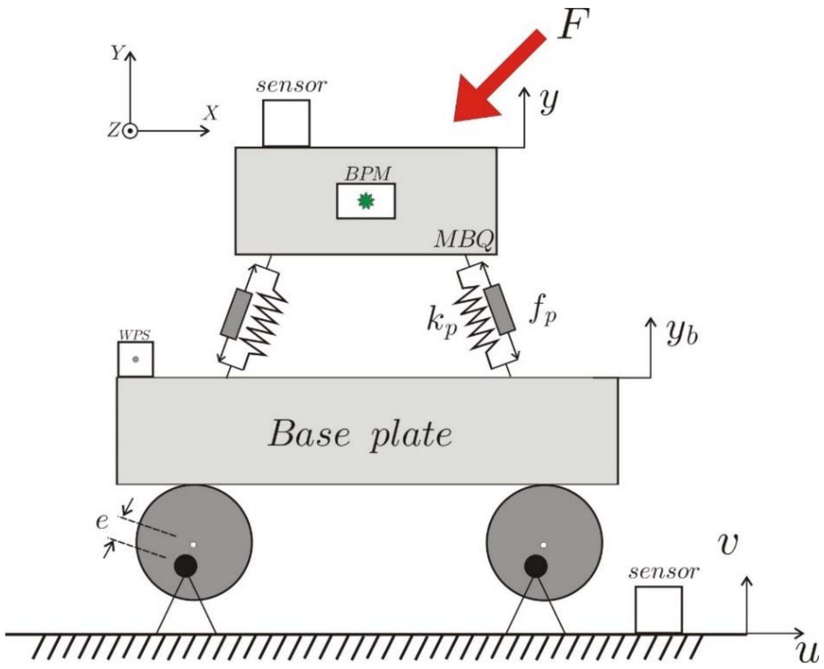
Outline

- Context and research objectives
- Matlab toolbox for Compliance matrix method
- CATIA- ANSYS parametric modelling
- Fem-based State space model extraction of Multiple inputs multiple output dynamic systems
- Conclusion and next steps

Current system overview



Magnet mass: 80kg



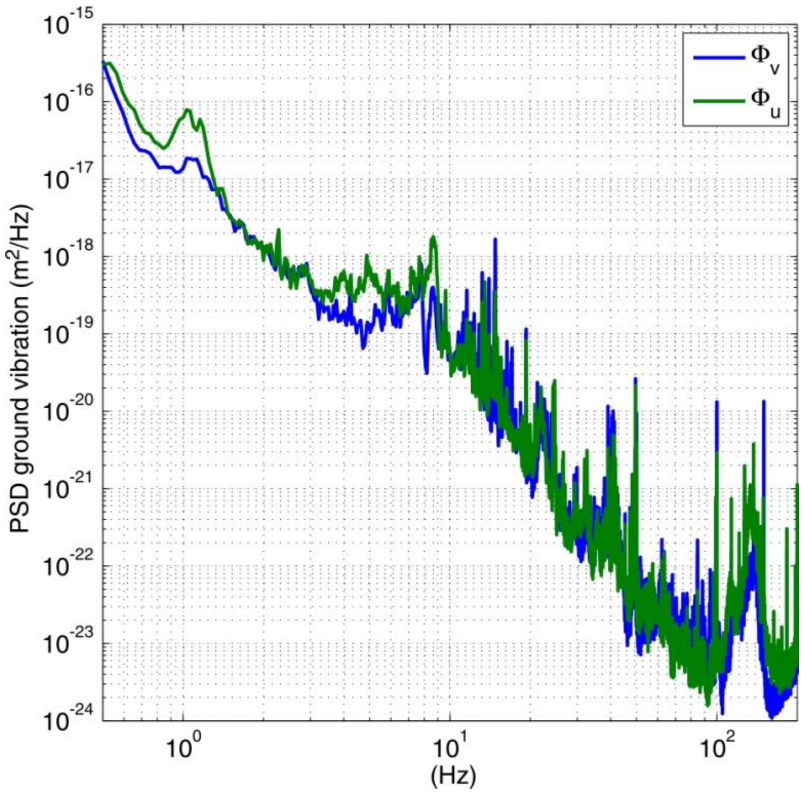
Coarse stage (cams)
- locked after pre-alignment
- Resolution : 0.35µm
- Stroke: 3mm

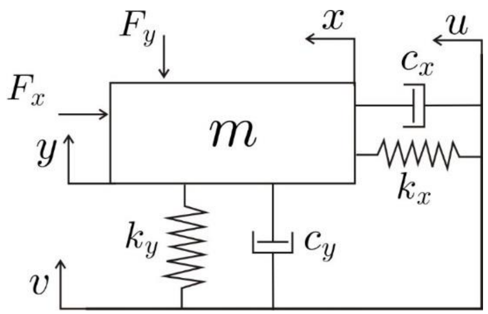
Fine stage (piezo stacks)
- Resolution: 0.15nm
- Stiffness : 480N/µm
- Useful Stroke: 10 µm

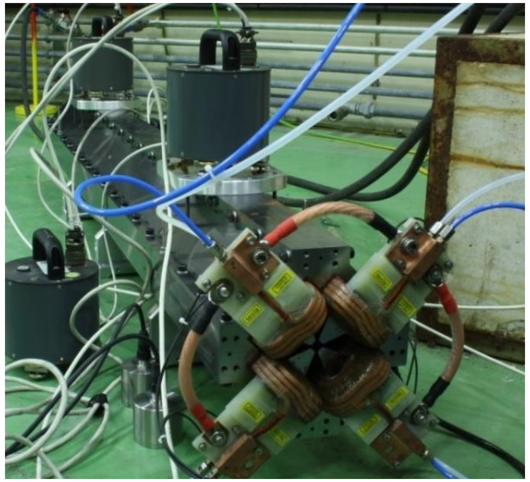
Limitations:
- ~50 days of operation using fine stage only
- insuficient stroke of fine stage for thermal load compensation in tunnel (>100 µm)
- Limited precision of coarse stage (1 µm achievable after several iterations)

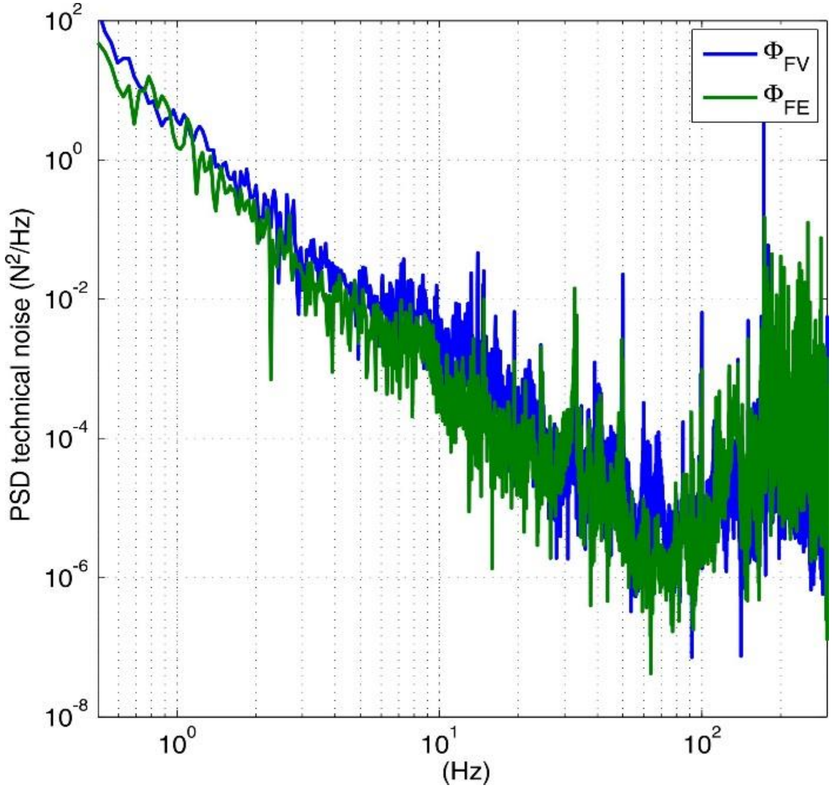
→ Upgrade of existing type 1 module
Alternative concept for long range actuator

Disturbance sources on CLIC MBQ









- Ground motion
- External forces
  (Water cooling, ventilation,…)
- Stiff connection to the rock

5 Phases in magnet life cycle + Positioning stage requirements

Functions :

- 5dofs Alignment (before beam)
- 2dofs Nanopositioning (beam-based alignment phase + nominal beam operation phase)
- 2dofs Vibration isolation (nominal beam operation phase)
  Stability requirements: 1.5nm rms @ 1Hz (vertical)
  5nm rms @ 1 Hz (lateral)

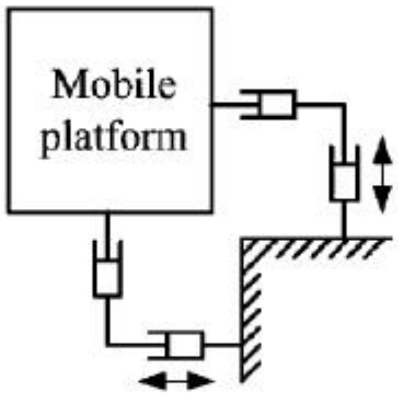
Study of an integrated positioning system with **high stiffness** (>100N/µm) capable of moving **heavy loads** (>50 kg) with **high resolution** (<1nm) over a **large range** (≥1mm)

Parameters	Value
Resolution	<0.25nm
step displacement	0.25 up to 50nm
Stroke	± 3mm
Pitch angle	6µrad
Yaw angle	6µrad
Roll angle Max	100µrad
Speed	≥ 50µm/s
Settling time t1->t2	10ms≤ts≤15ms
On-axis stiffness (vertical/lateral)	400 N/µm
Force capacity (positioning)	5N+20N
Force capacity (isolation)	10N

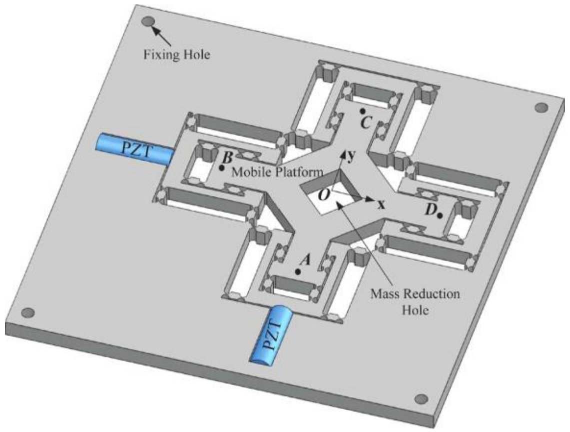
Compliance matrix method

7 Conceptual design of a nano-positioning system

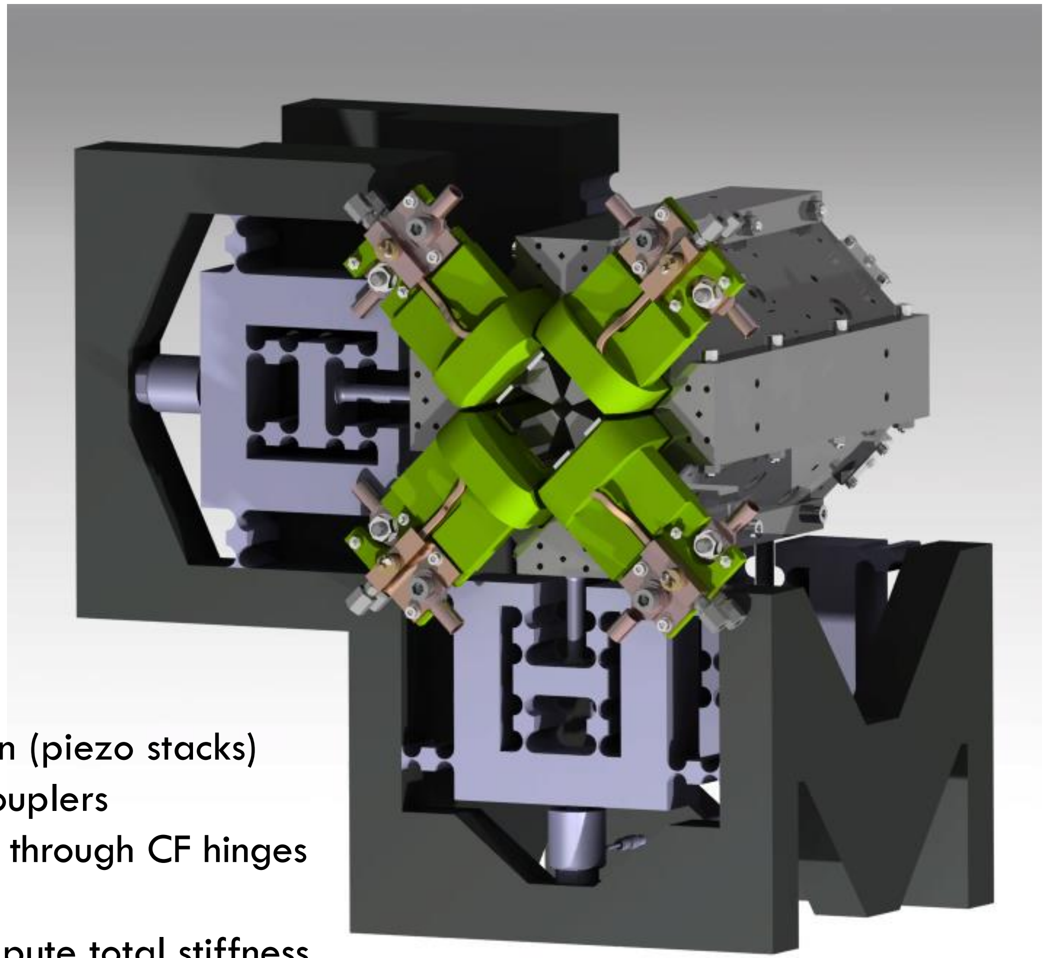
- Most of decoupled XY stages based on 2PP mechanism
- Depending on requirement each module can be built out of notches or leaf springs
- Y. Li, J. Huang, H. Tang, *A compliant parallel XY Micromotion stage with complete kinematic decoupling*



2PP mechanism



Courtesy of Y. Li



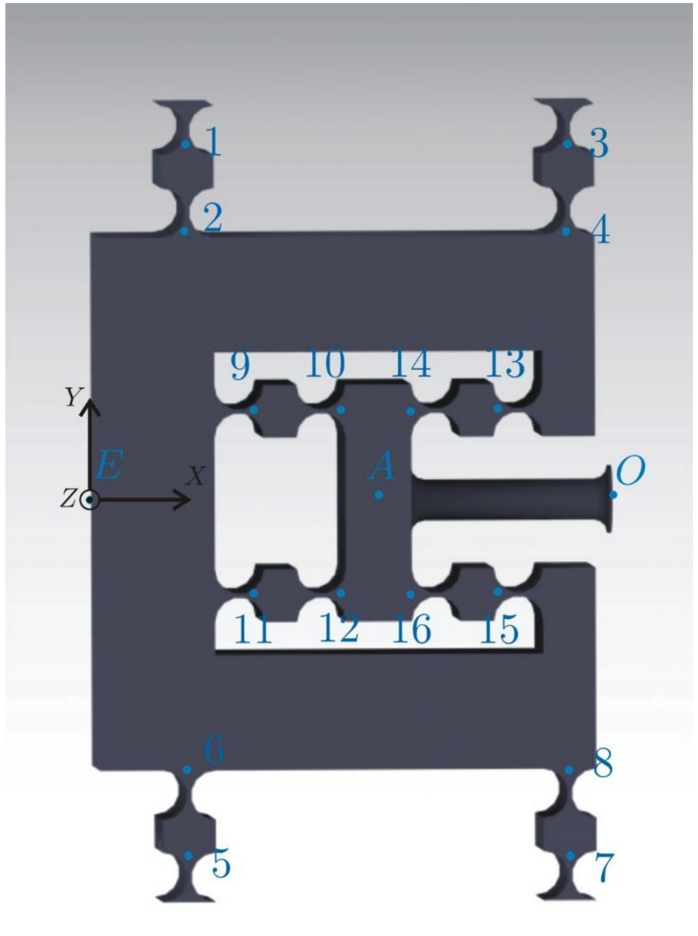
- 4 dofs actuation (piezo stacks)
- Compliant decouplers
- Rotational dofs through CF hinges compliance
- Objective: Compute total stiffness matrix

8 Compliance matrix method

- Overall compliance computation in 6 dofs at point of interest (i.e. O and E)
- Based on analytical compliance matrices of elementary hinges
- Boundary conditions: base of notch hinges 1,3,5,7 clamped

- Script validated on elementary hinges and sub-parts of the module

$$C=\begin{pmatrix} c_{x,Fx} & 0 & 0 & 0 & 0 & 0 \\ 0 & c_{y,Fy} & 0 & 0 & 0 & c_{rz,Fy} \\ 0 & 0 & c_{z,Fz} & 0 & c_{ry,Fz} & 0 \\ 0 & 0 & 0 & c_{rx,Mx} & 0 & 0 \\ 0 & 0 & c_{z,My} & 0 & c_{ry,My} & 0 \\ 0 & c_{y,Mz} & 0 & 0 & 0 & c_{rz,Mz} \end{pmatrix}$$



- Notch hinges dimensions:
  - R= $7mm$
  - $t = 1mm$
  - $d = 50mm$
- CF hinge dimensions:
  - $L = 51.6mm$
  - $R = 6.2mm$
  - $r_f = 4.2mm$

- Material: structural steel

Output Compliance at point O (without actuator)

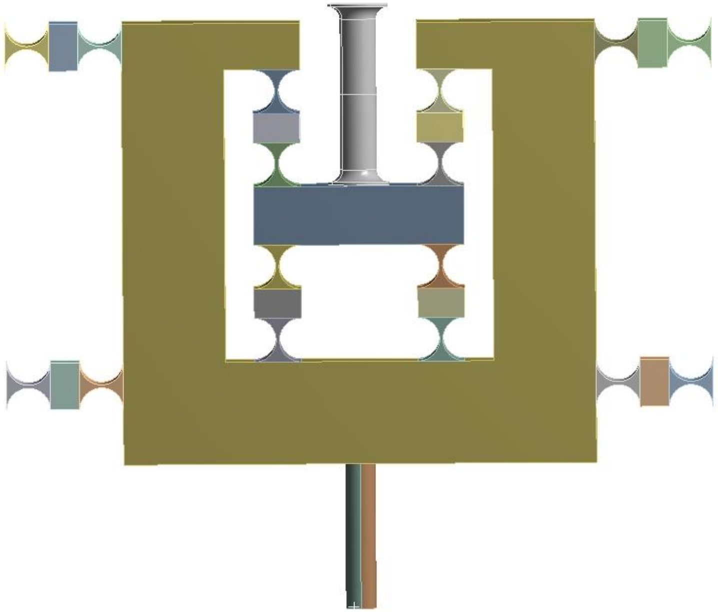
Input parameters	Analytical	FEA Flexible
On axis Compliance $c^O_{x,Fx}$	0.311um/N	0.293um/N
Transverse Compliance $c^O_{y,Fy}$	0.644um/N	0.611um/N
In-plane bending Compliance $c^O_{rz,Mz}$	2.92e-4rad/Nm	2.51e-4rad/Nm
In-plane bending Compliance $c^O_{y,Mz}$	1.02e-5m/Nm	7.8e-6m/Nm
Out-of-plane Compliance $c^O_{z,Fz}$	0.341um/N	0.328um/N
Out-of-plane Compliance $c^O_{ry,My}$	2.92e-4rad/Nm	2.52e-4rad/Nm
Out-of-plane Compliance $c^O_{z,My}$	1.02e-5m/Nm	7.8e-6m/Nm

9 Compliance matrix method

- Overall compliance computation in 6 dofs at point of interest (i.e. O and E)
- Based on analytical compliance matrices of elementary hinges

- Actuator modeled as a cylinder with the desired axial stiffness (e.g. 480N/um)
- Additional BC: base of actuator clamped

$$C=\begin{pmatrix} c_{x,Fx} & 0 & 0 & 0 & 0 & 0 \\ 0 & c_{y,Fy} & 0 & 0 & 0 & c_{rz,Fy} \\ 0 & 0 & c_{z,Fz} & 0 & c_{ry,Fz} & 0 \\ 0 & 0 & 0 & c_{rx,Mx} & 0 & 0 \\ 0 & 0 & c_{z,My} & 0 & c_{ry,My} & 0 \\ 0 & c_{y,Mz} & 0 & 0 & 0 & c_{rz,Mz} \end{pmatrix}$$



Output Compliance at point O (with actuator)

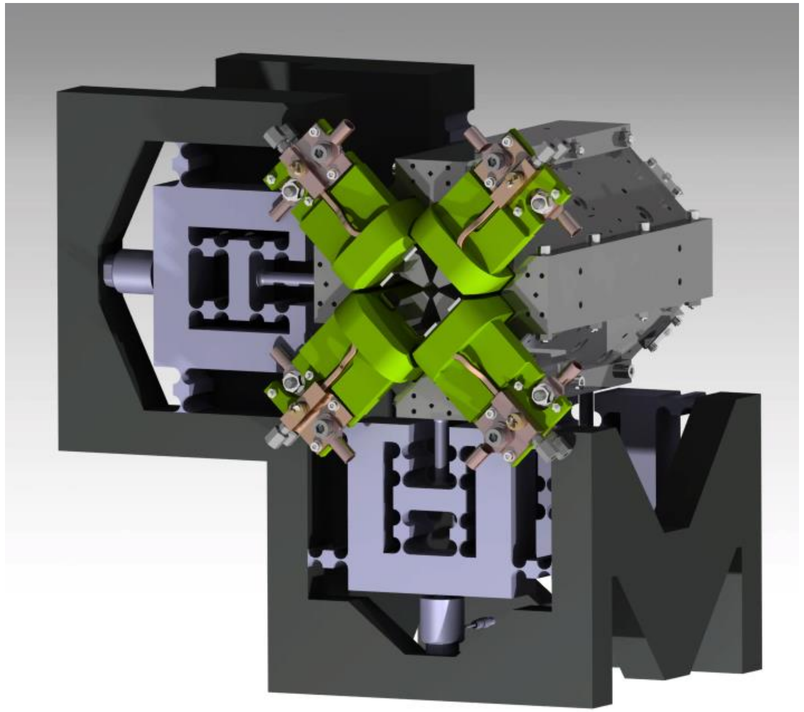
Input parameters	Analytical	FEA Flexible
On axis Compliance $c^O_{x,Fx}$	5.27nm/N	5.68nm/N
Transverse Compliance $c^O_{y,Fy}$	0.645um/N	0.611um/N
In-plane bending Compliance $c^O_{rz,Mz}$	2.92e-4rad/Nm	2.51e-4rad/Nm
In-plane bending Compliance $c^O_{y,Mz}$	1.02e-5m/Nm	7.8e-6m/Nm
Out-of-plane Compliance $c^O_{z,Fz}$	0.341um/N	0.328um/N
Out-of-plane Compliance $c^O_{ry,My}$	2.92e-4rad/Nm	2.52e-4rad/Nm
Out-of-plane Compliance $c^O_{z,My}$	1.02e-5m/Nm	7.8e-6m/Nm

Input parameters	Analytical
On axis Stiffness $k^O_{x,Fx}$	190N/um
Transverse Stiffness $k^O_{y,Fy}$	3.47N/um
In-plane bending Stiffness $k^O_{rz,Mz}$	7.67kNm/rad
Out-of-plane Stiffness $k^O_{z,Fz}$	42N/um
Out-of-plane Stiffness $k^O_{ry,My}$	49.04kNm/rad

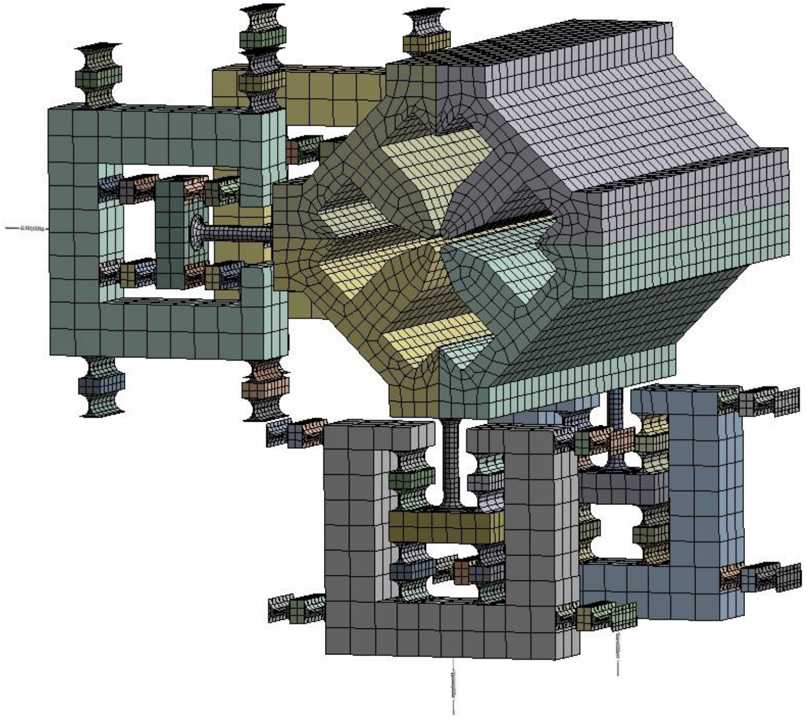
The requirement of static stiffness is almost reached!
(i.e. 200N/um per module in direction of actuation)

Parametric modelling

Parametric modelling



CAD NEXUS



CATIA V5

ANSYS WB

- ❑ CAD parameters exchange and bi-directional update
- ❑ Input parameters:
  - Remote magnet displacement (P2)
  - Notch hinges thicnkess (P4)
  - Diameter pillar (P5)
  - Fillet radius pillar (P6)
  - Notch hinges depth (P7)
- ❑ Output parameters:
  - Equivalent Max stress (P1)
  - First eigen frequency (P3)
  - Vertical magnet displacement (P8)

Powerful tool for automatized sensitivity and optimization study

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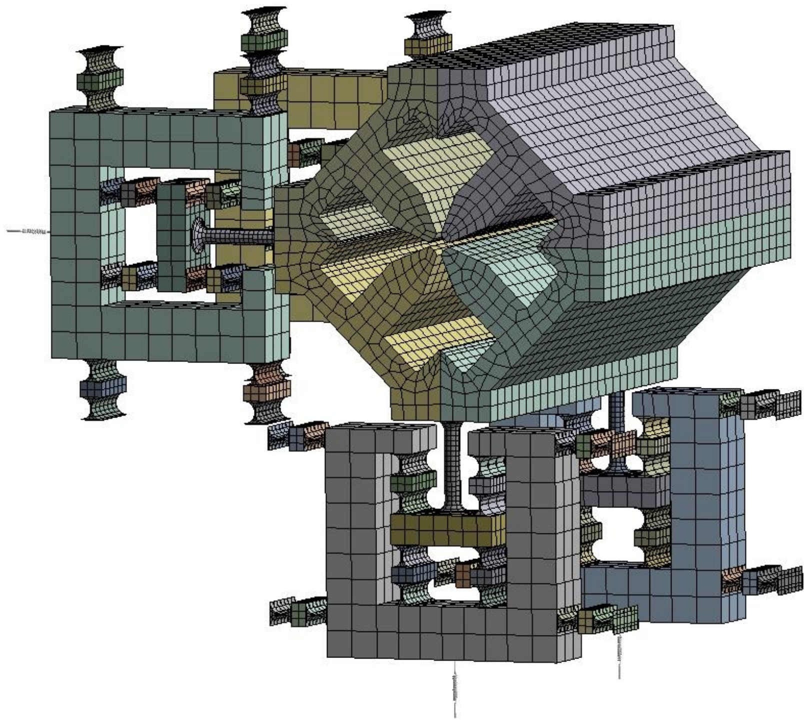
Parametric modelling: Design of experiments

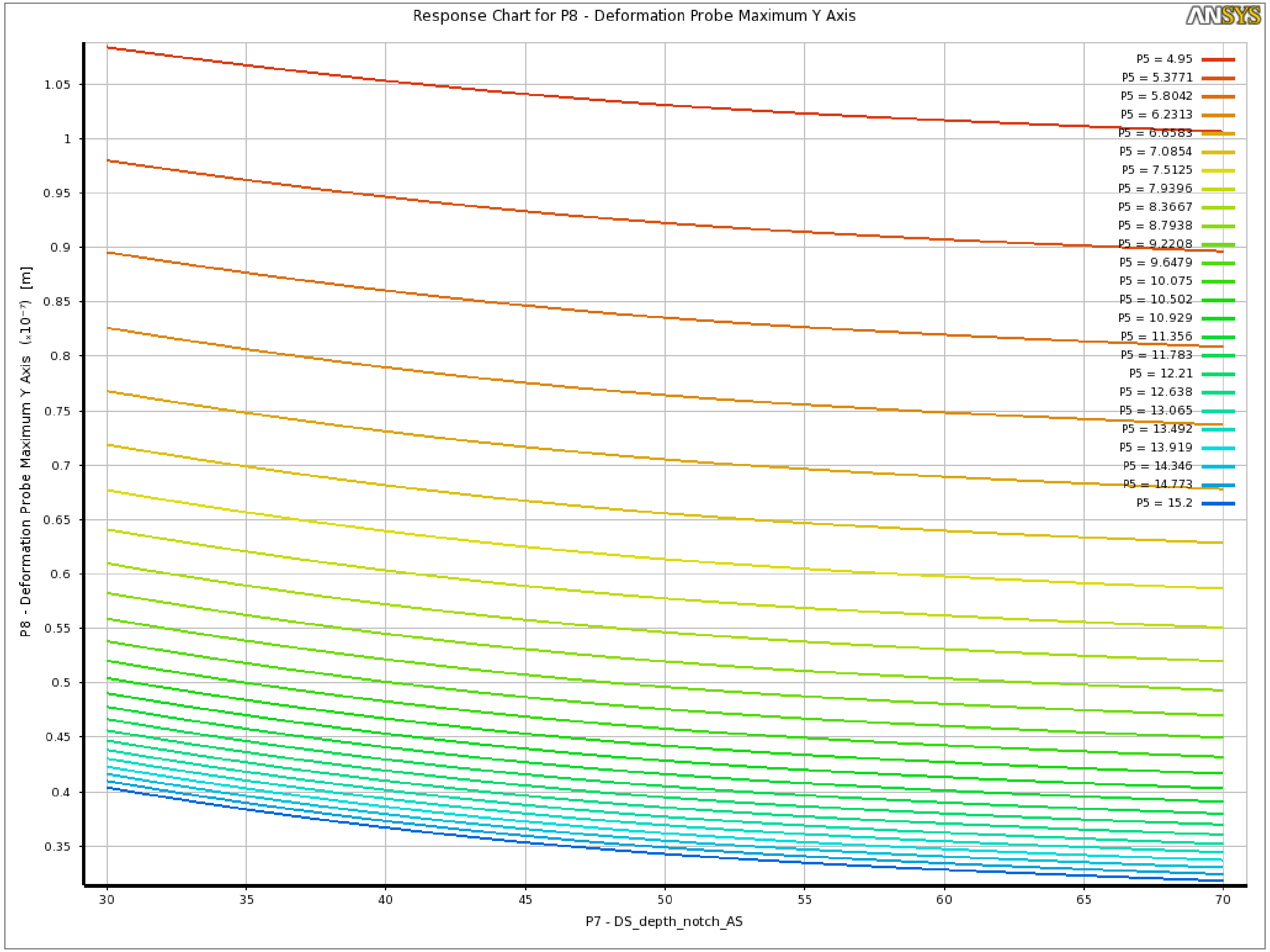
Design of experiments settings	
DOE type	Latin Hypercube Sampling design
Samples type	User-defined Samples
Number of samples	40

Design parameters range	
Remote magnet displacement (P2)	0.9 µm → 20 µm
Notch hinges thickness (P4)	0.2 mm → 1.8 mm
Pillars diameter (P5)	4.95 mm → 15.2 mm
Pillars fillet radius (P6)	2 mm → 7 mm
Notch hinges depth (P7)	30 mm → 70 mm



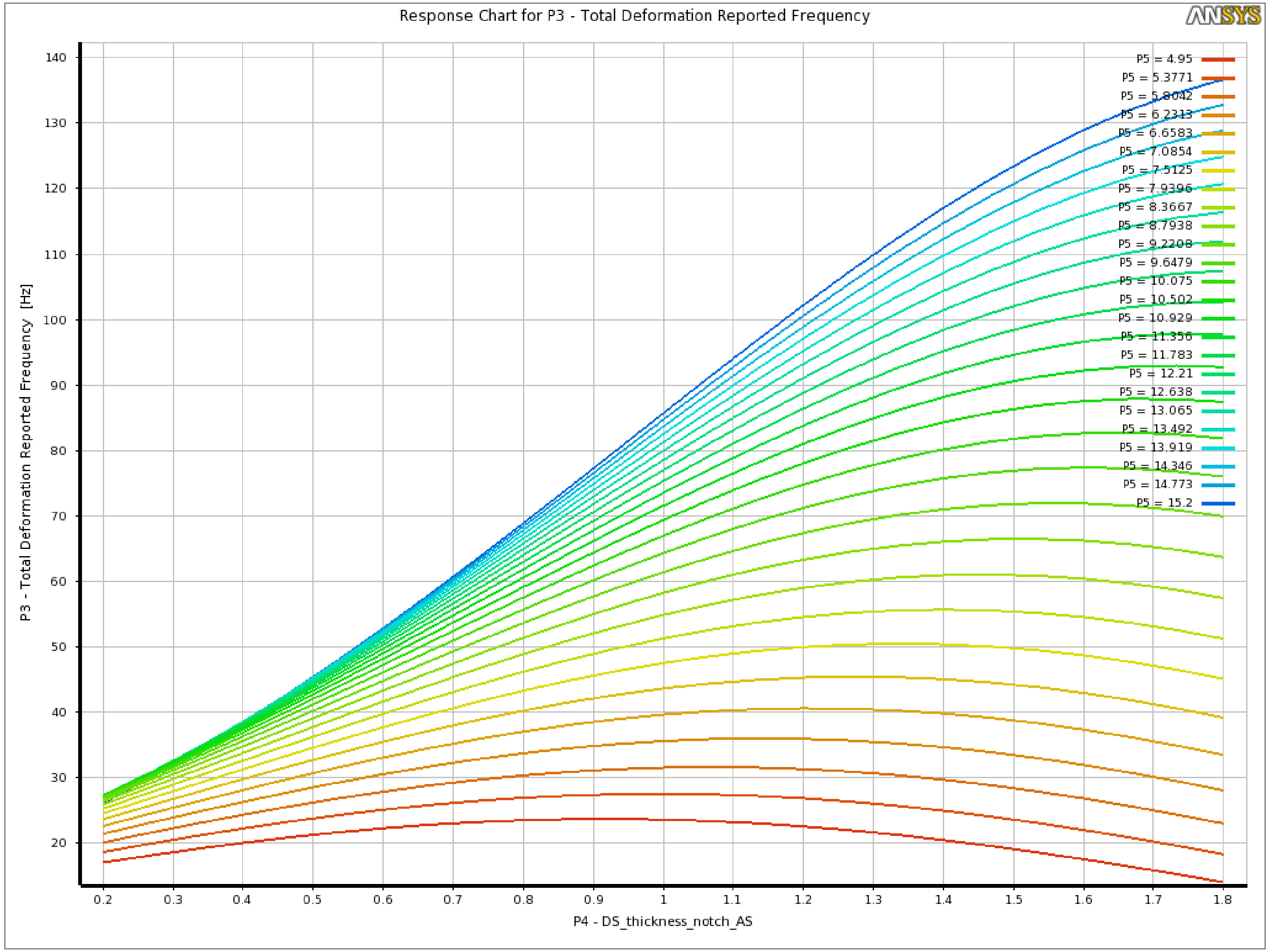
Parametric modelling: Sensitivity study

- Deformation to P5 and P7
- Stiffness information
- Assymptotic limit of diameter contribution to the stiffness



Parametric modelling: Sensitivity study

- ❑ Lowest eigen frequency to P4 and P5
- ❑ Larger diameter → larger frequency increase in a fixed interval of notch thickness
- ❑ Assymptotic limit of diameter contribution to the frequency
- ❑ Local maximum for a fixed diameter value



Parametric modelling: Optimization

Desired output results from optimizer:

- Pilars dimesnsions
- Notch hinges dimensions

Pb: Minimize magnet displacement (P8)

With constraints:

- $P_3 \geq 100\ Hz$
- $P_2 \cong 15\ \mu m$
- $P_1 \leq 250\ MPa$

Candidate point	
Notch hinges thickness (P4)	1.21 mm
Pillars diameter (P5)	14.58 mm
Pillars fillet radius (P6)	5.81 mm
Notch hinges depth (P7)	51.4 mm

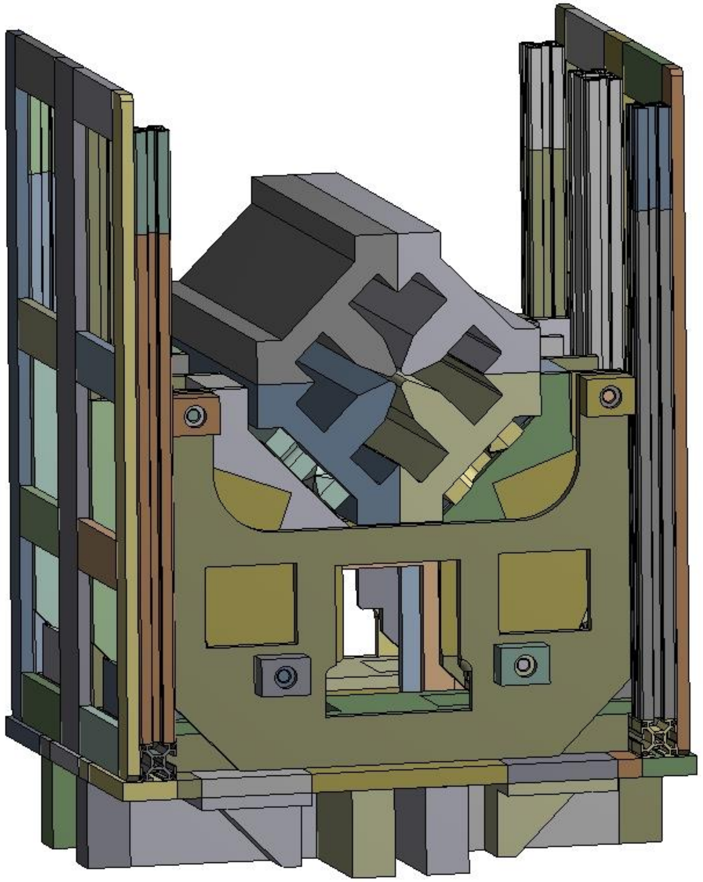
↔

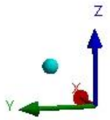
Control parameters	
Vertical magnet displacement (P8)	34 nm
First eigen frequency (P3)	101 Hz
Remote magnet displacement (P2)	15.7 µm
Max equivalent stress (P1)	26 MPa

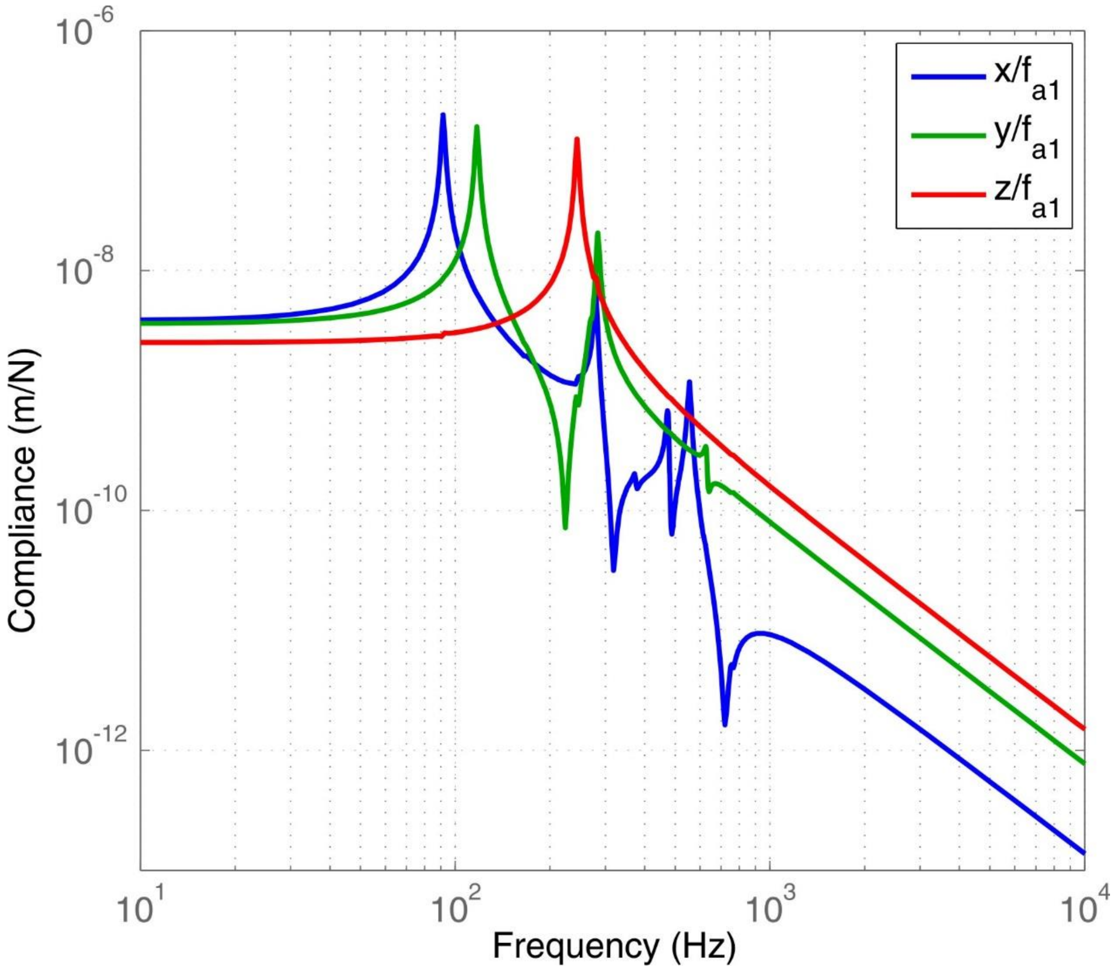
- Static stiffness of 300 N/µm !
- Optimization problem statements for other studies possible (e.g. max P3 with P8=25 nm)

FEM-based State space model generation

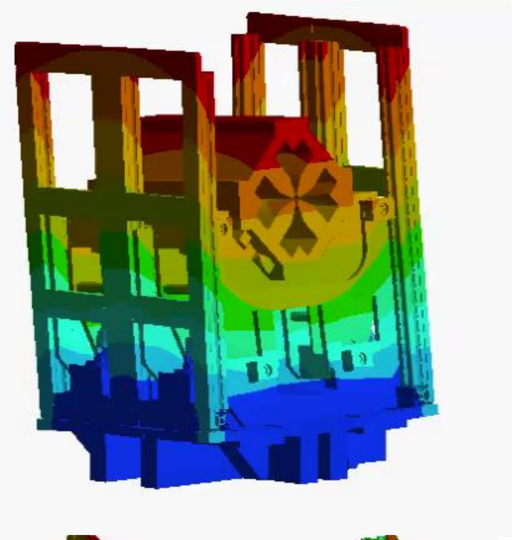
Type1 bench MIMO model

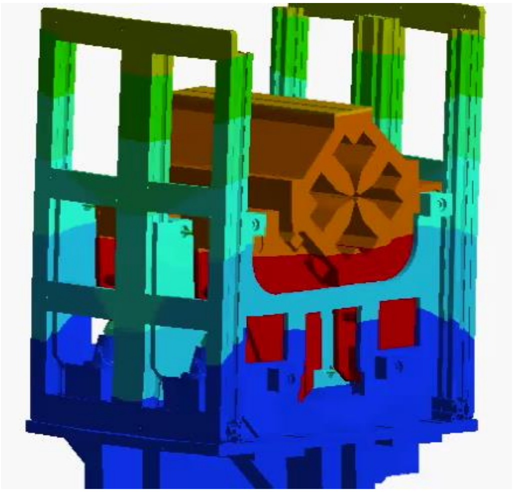


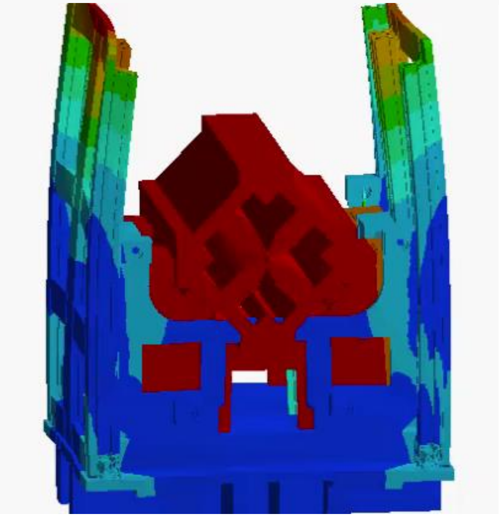


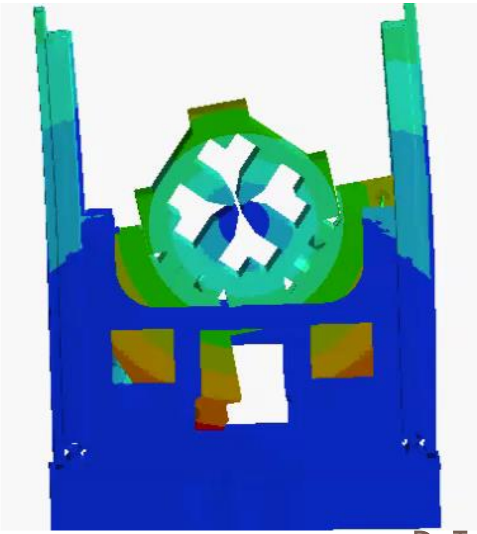


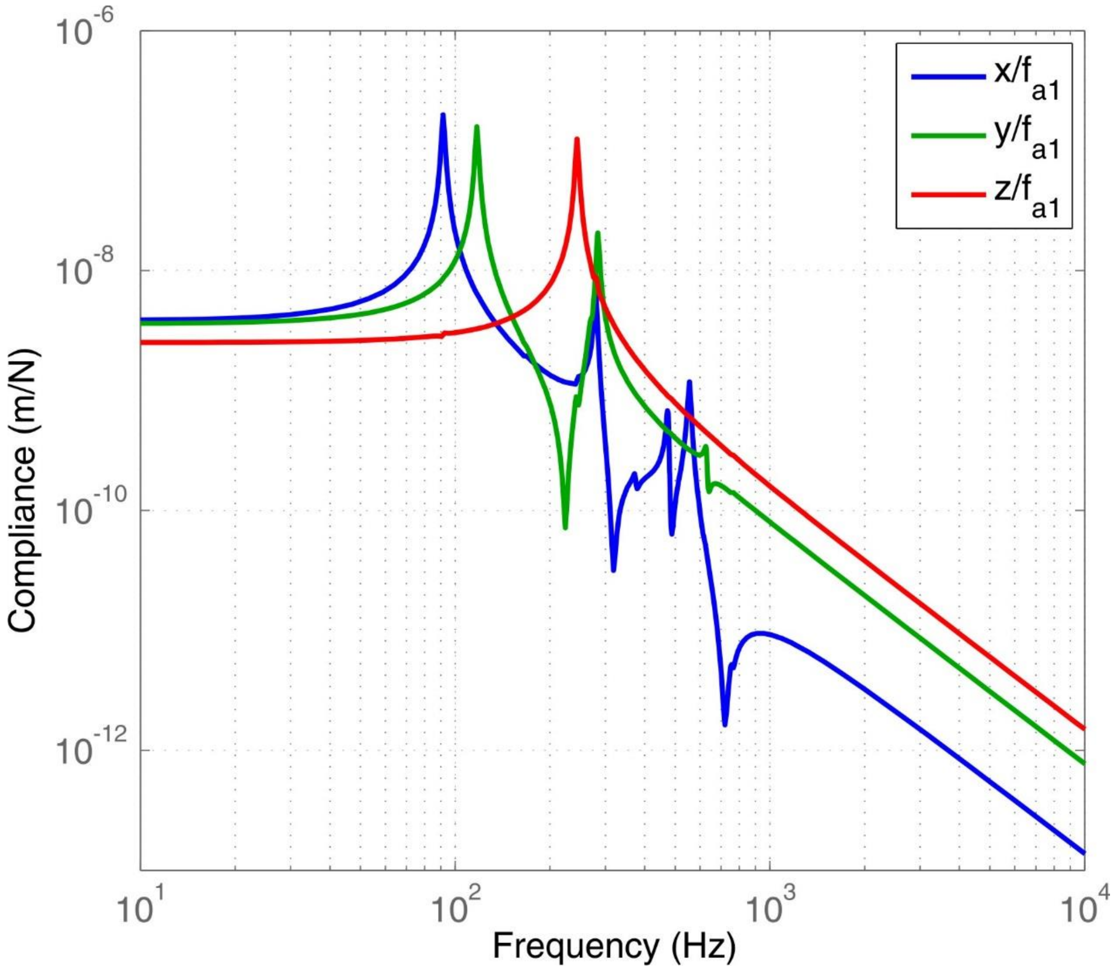
Type1 bench MIMO model









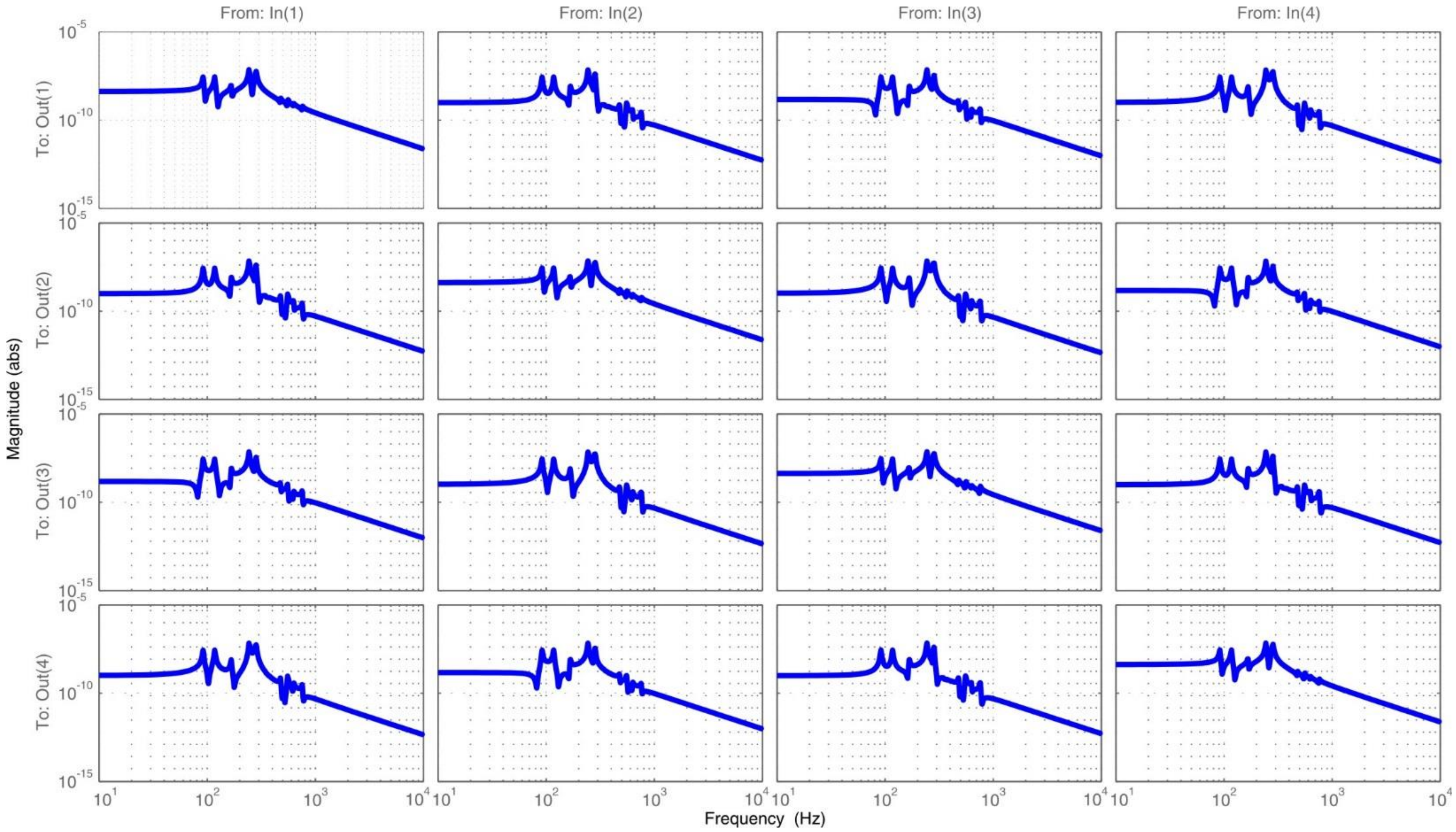


Coupled inputs and Outputs

- In(1): front left leg
- In(2): front right leg
- In(3): back left leg
- In(4): back right leg

- Out(1): front lateral encoder
- Out(2): front vertical encoder
- Out(3): back lateral encoder
- Out(4): back vertical encoder

- Interactive MIMO system $G(s)$
  - ➡ Controller design of $C(s)$
    - ➡ Improve reference tracking
    - ➡ Decrease I/O interaction



Closed loop reference tracking

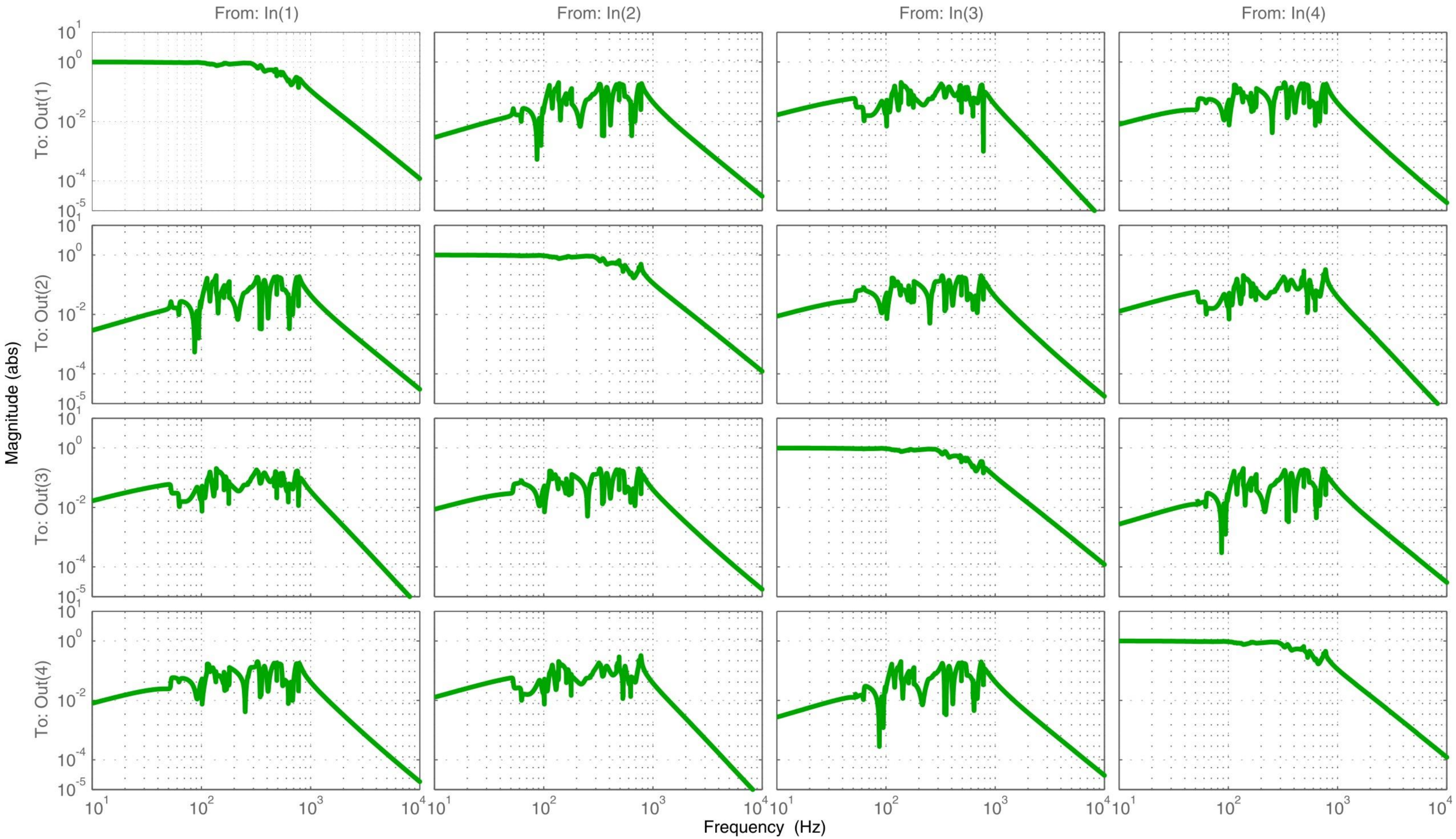
- In(1): reference signal 1
- In(2): reference signal 2
- In(3): reference signal 3
- In(4): reference signal 4

- Out(1): front lateral encoder
- Out(2): front vertical encoder
- Out(3): back lateral encoder
- Out(4): back vertical encoder

- SVD-controller

- MIMO system $G_{cl}(s)$

$$G_{cl}(s) = \frac{C(s)G(s)}{I(s)+C(s)G(s)}$$



Conclusion

Tools and technique to :

- Evaluate analytically the static stiffness and eigen modes of a compliant mechanism in several dofs
- Perform automatized sensitivity and optimization studies of any CAD assembly
- Generate reduced MIMO state space model based on the FEM of any CAD assembly

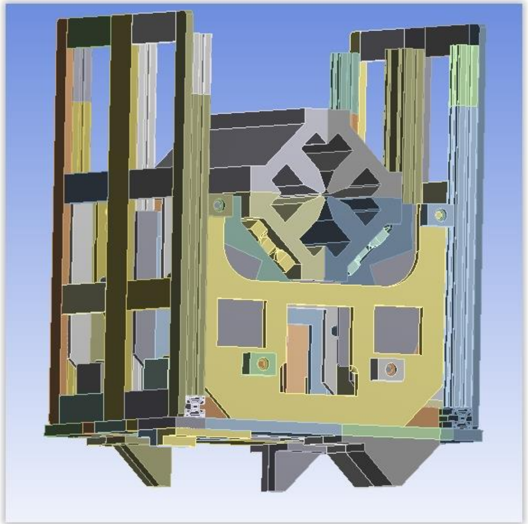
Next steps:

- Controller design for nano-positioning of type 1 module (Closed loop Vs Open loop)
- Experimental comparative tests of positioning controllers
- Test bench design for proof of concept of long range nano-positioning actuator (mechanical design, FEM-based optimization, controller design, experimental validation)

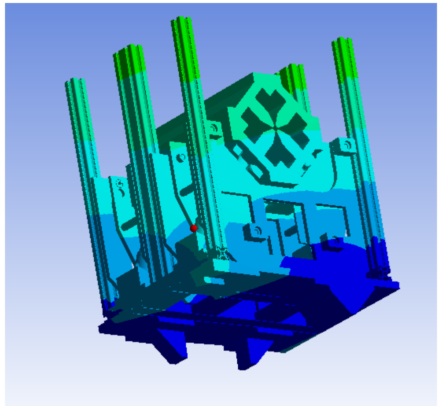
The END

Type 1prototype parasitic modes

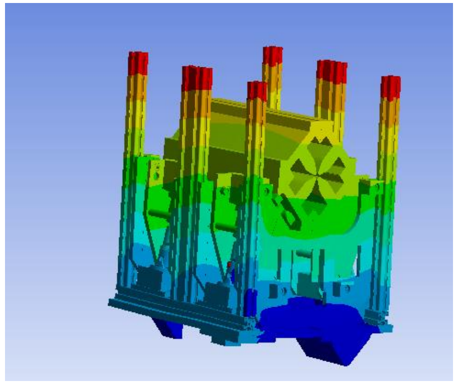
Root causes and solution



1. Longitudinal + plate bend



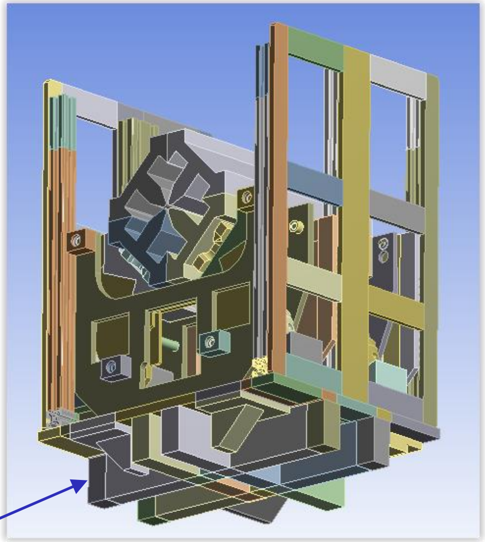
2. side mode + bend



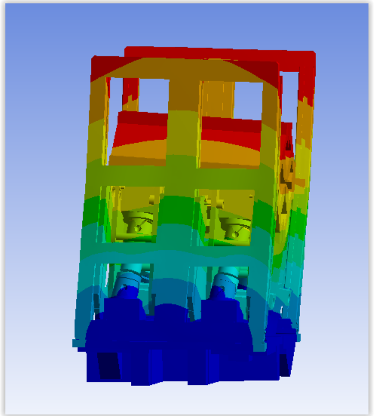
Mode 1: 48.135 Hz
Mode 2: 70.269 Hz
Mode 3: 123.35 Hz

Issues:

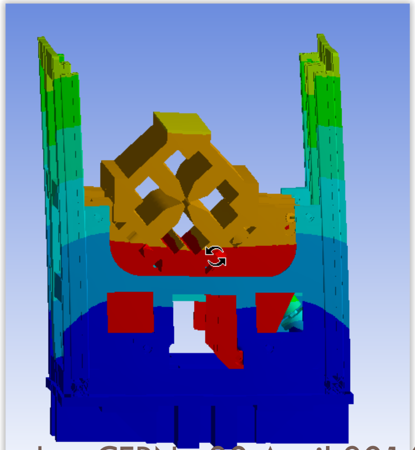
- Non constant support at interface point supported by a manually adjustable jack
- Assembly method of the base plate components
- Base plate stiffness



1. Longitudinal mode



2 Side mode



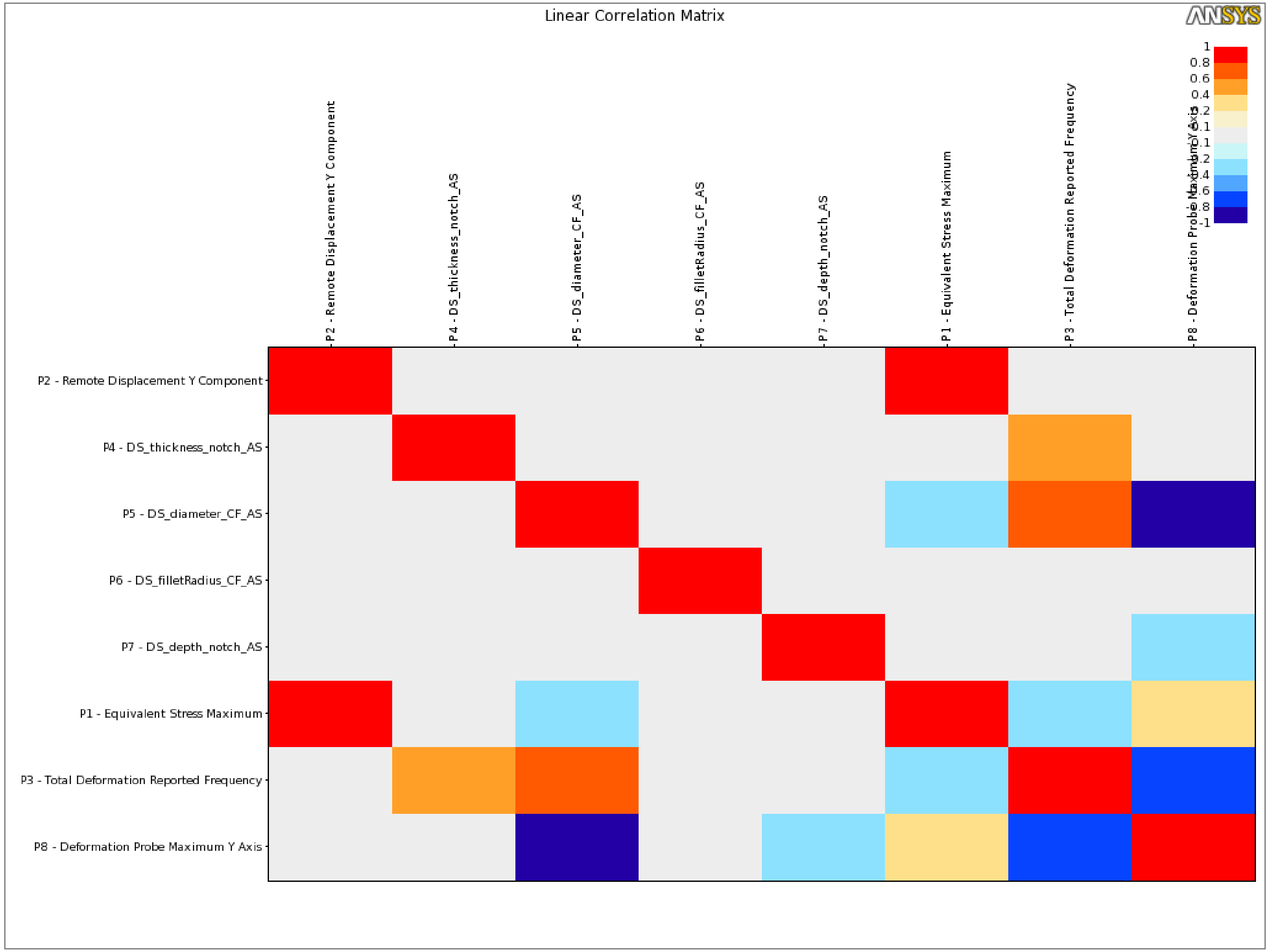
Mode 1: 91.6 Hz
Mode 2: 117.2 Hz
Mode 3: 167.14 Hz

- Larger flat contact surface with ground
- Base plate reinforcement (longitudinal)
- Gluing + bolting base plate components
- Lowest mode in longitudinal direction
  - ➡ Not an issue

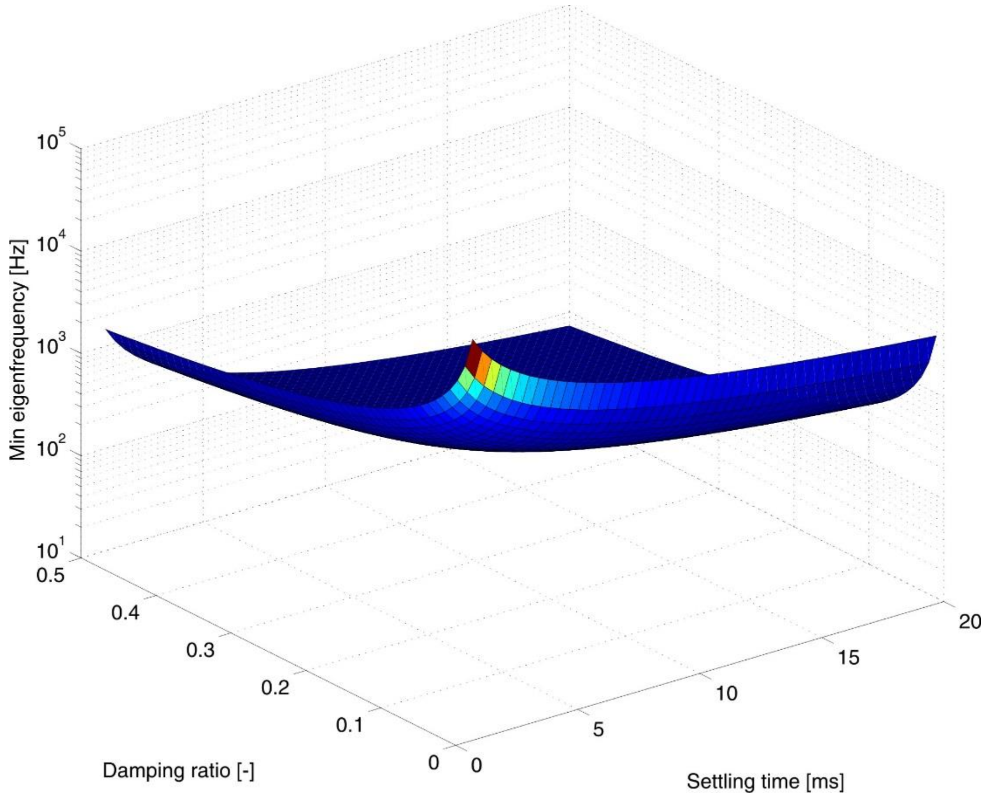
➡ Upgraded base plate designed

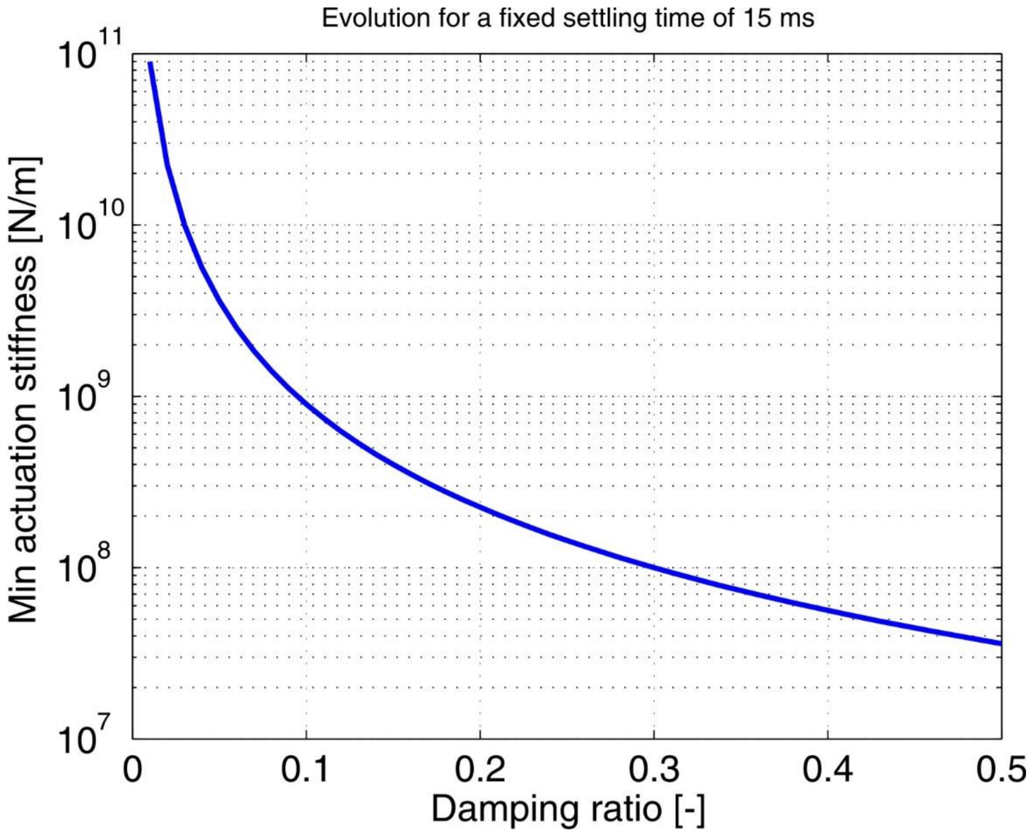
Parametric modelling: Sensitivity study

- Parameters Correlation study
- Dark colours ⟷ Strong correlation
- Useful to decrease the number of input parameters
- Lowest eigen frequency correlated to P4 and P5
- Static stiffness correlated to P5 and P7



Required stiffness for positioning

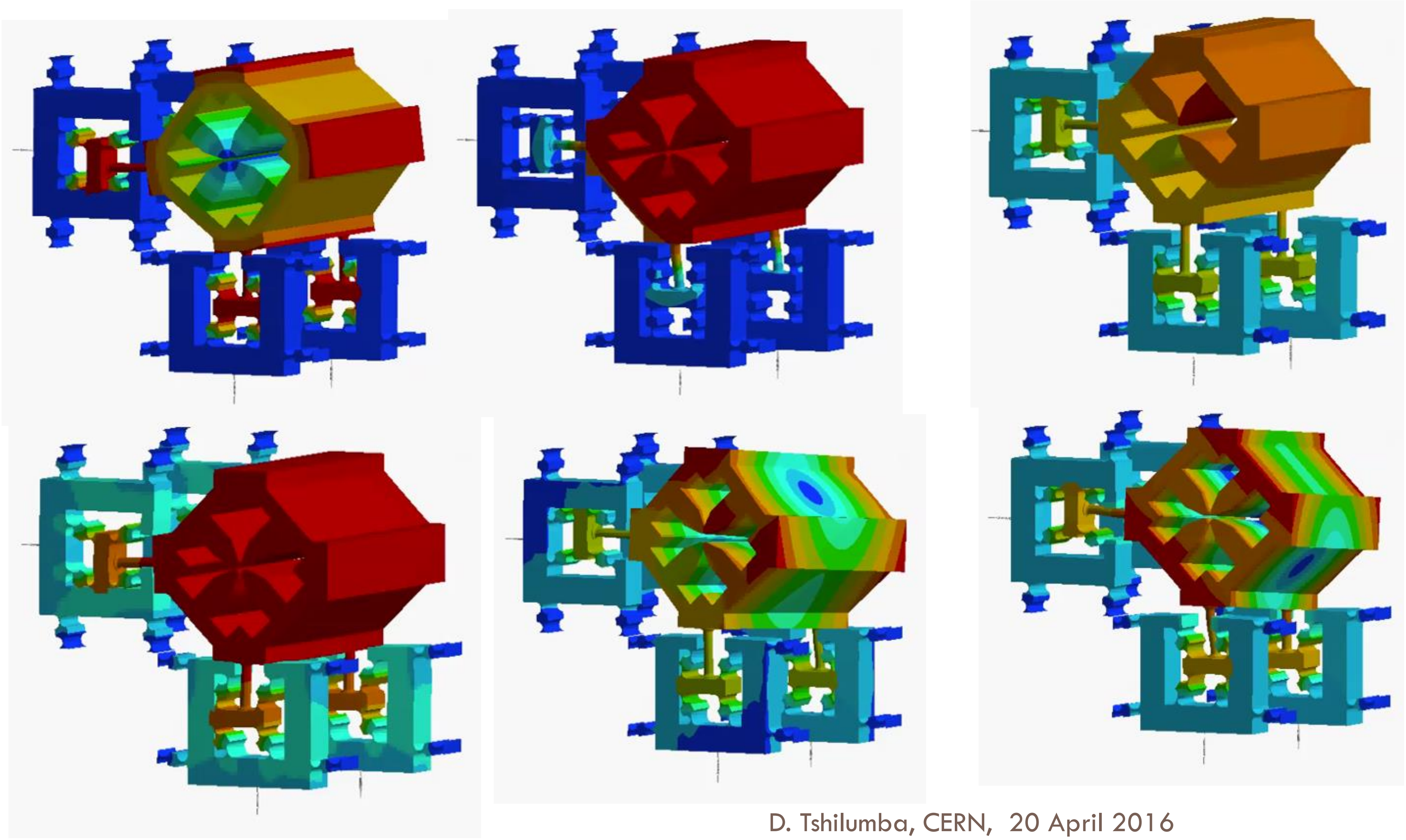




Conclusion: With a settling time $t_s = 15ms$ and a damping ratio $\xi = 0.15$, the required stiffness support is $k_{sup} = 400N/\mu m$ for a positioning step of 50 nm

Required force for nanopositioning: $F_{Inertia} + F_{elastic} = 2N + 20N$

Compliance matrix method

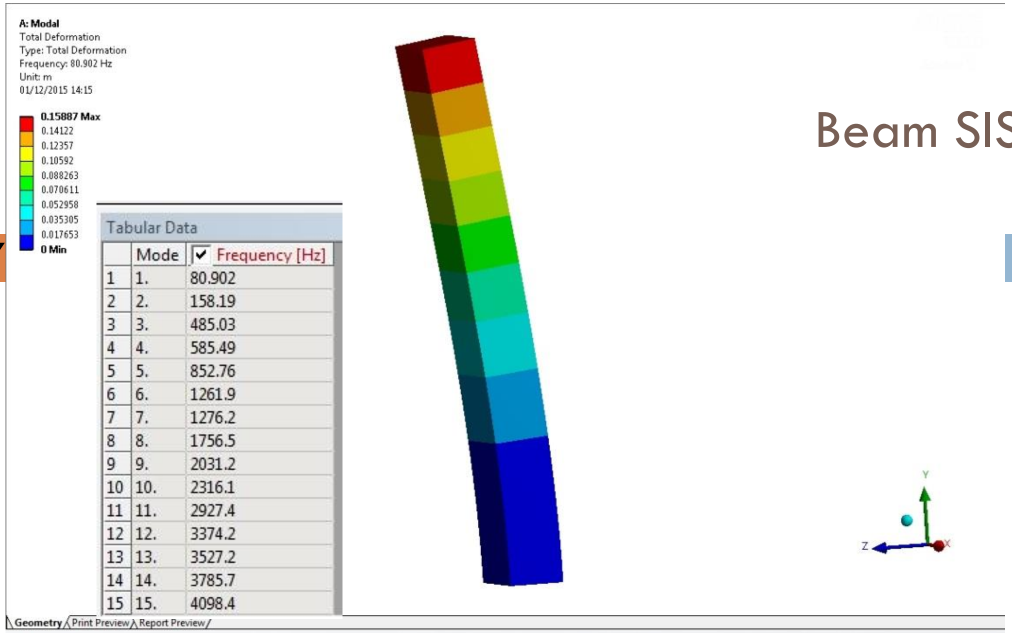


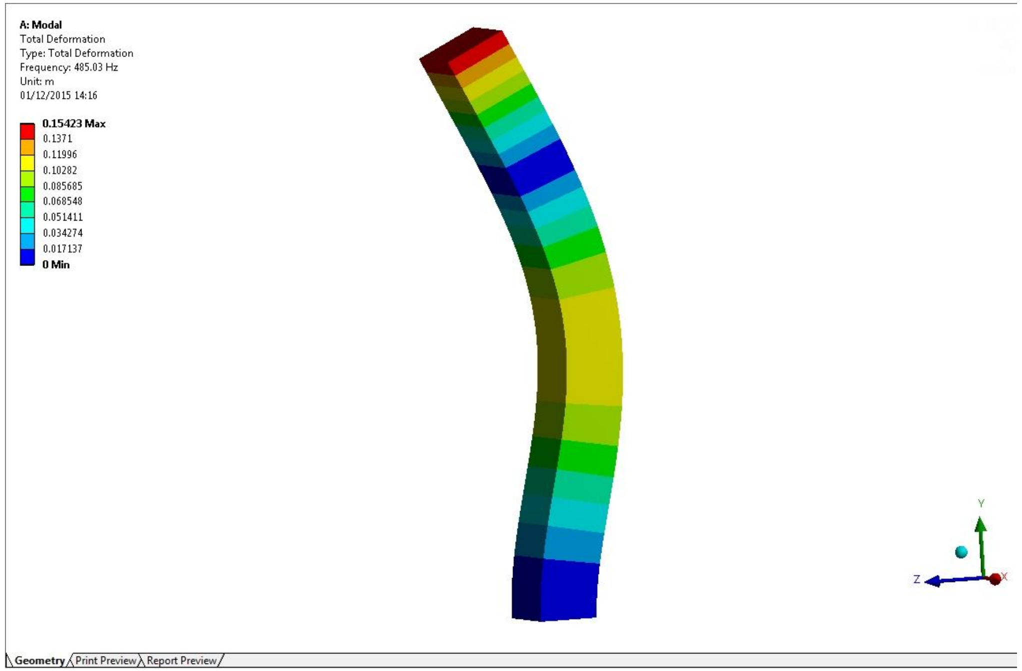
	Analytical	FEA
Mode 1	43 Hz	42 Hz
Mode 2	65 Hz	55 Hz
Mode 3	65 Hz	58 Hz
Mode 4	107 Hz	111 Hz
Mode 5	195 Hz	124 Hz
Mode 6	295 Hz	167 Hz

Beam SISO model

Introduction

- ❑ Beam with Clamped-free boundary conditions
- ❑ Transfer functions extraction from FEM (dynamics)
  - Choice in actuators and sensors placement (observability, controllability)
  - Evaluation of response to known excitation spectra
  - Starting point for controller design



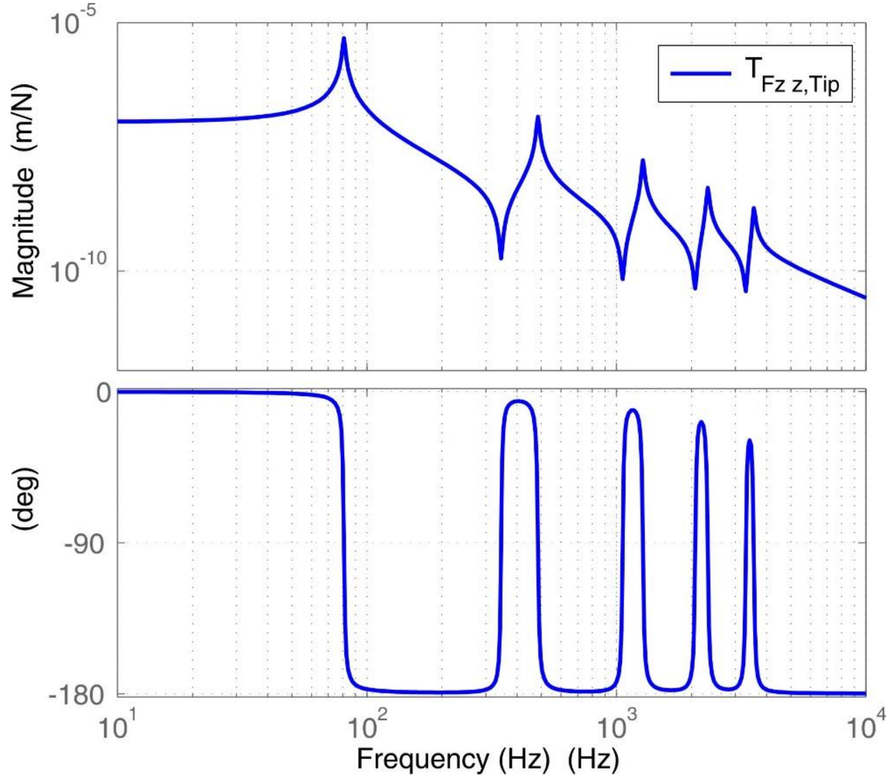


Total transfer function and modal contributions

- Beam with Clamped-free boundary conditions
- All the nodes of the FE model retained

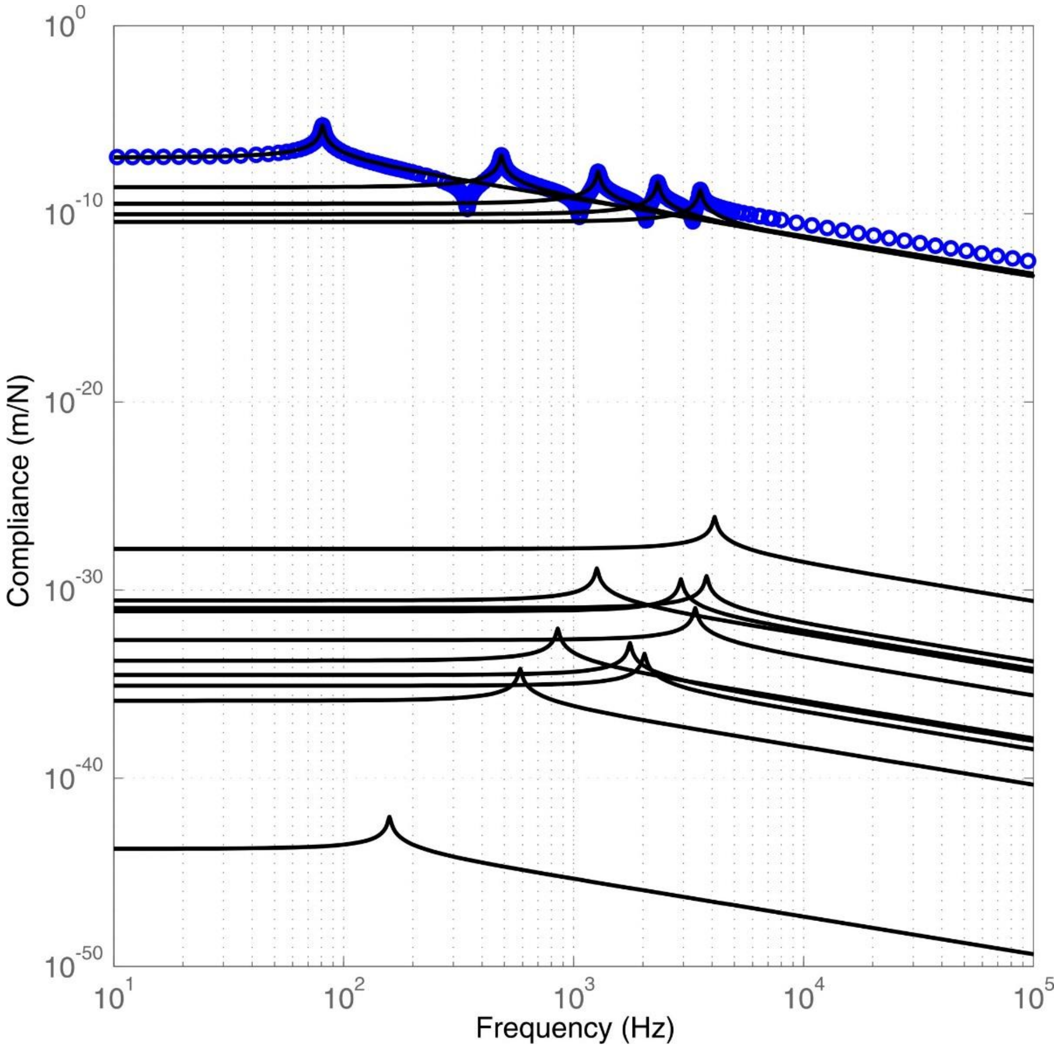
  ➡ Modal matrix of the whole FE model constructed

- Choice in input and output dofs (e.g. x, y, z at the tip)



$$\frac{z_j}{F_k} = \sum_{i=1}^{m} \frac{\phi_{ji}\phi_{ki}}{s^2 + 2\zeta_i\omega_i + \omega_i^2}$$

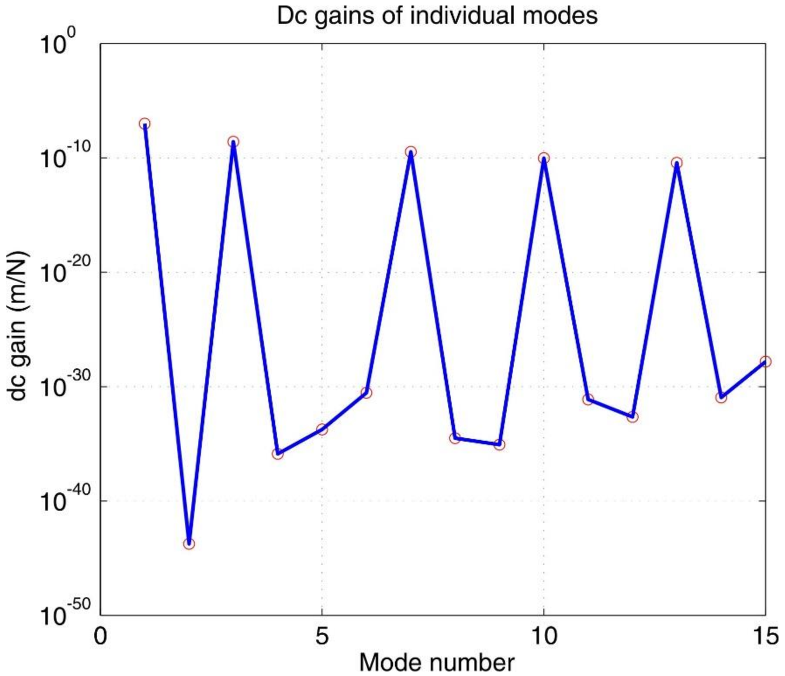
ϕ Mass normalized modal matrix

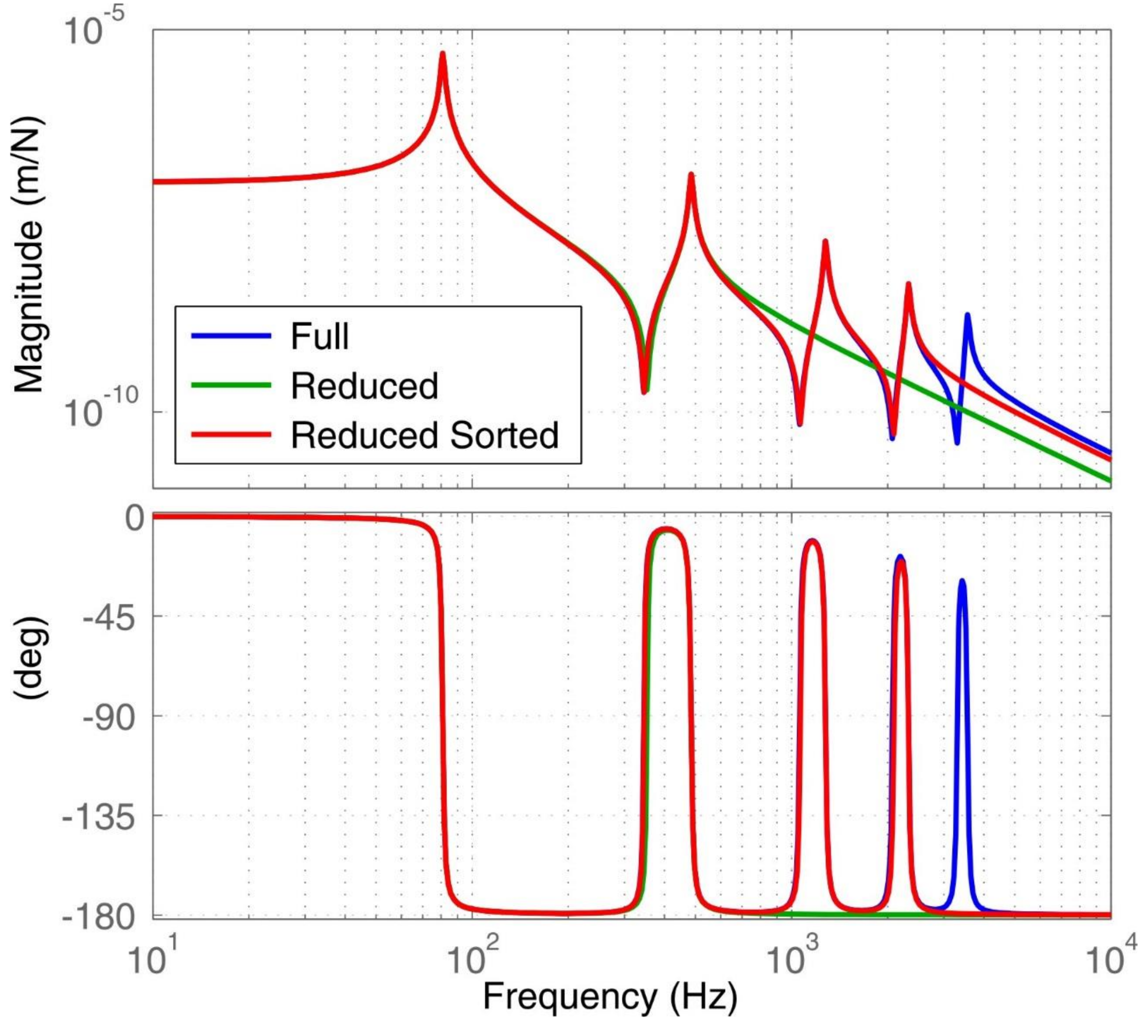


Model order reduction

- Reduction of the order of the state space model by keeping the first p modes (e.g. $p = 4$)
- Ranking increases the amount of resonances kept in the reduced model
- Advantage: reduction of the number of poles in the transfer function

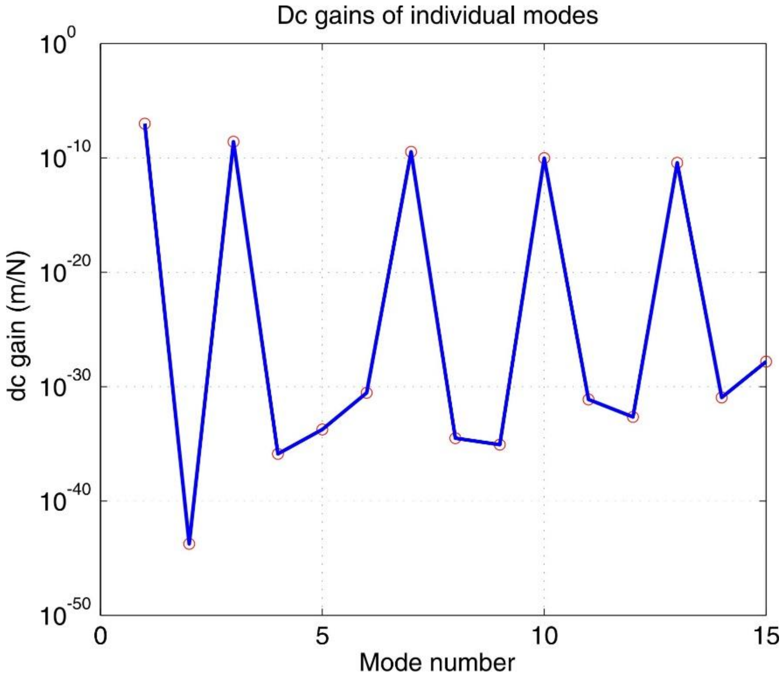
➡ Controller design simplified

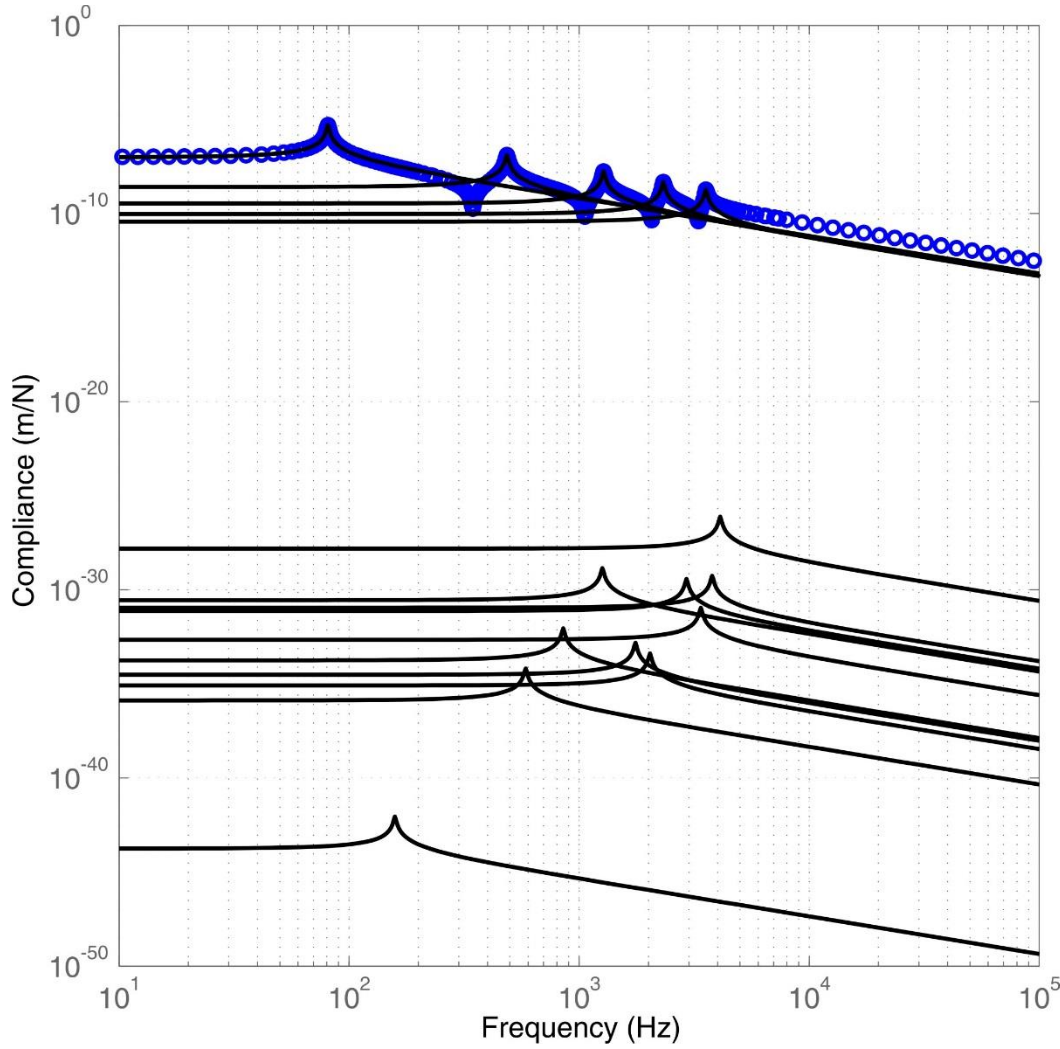




Modes ranking by dc gains

- Ranking of the modes by decreasing order of dc gains in state space model
- Sorting has an influence for the reduction of the state space model
- Dc gain value for mode i: $dc_i = \dfrac{\phi_{ji}\phi_{ki}}{\omega_i^2}$
- Modes 1, 3, 7, 10 and 13 have the highest dc gains

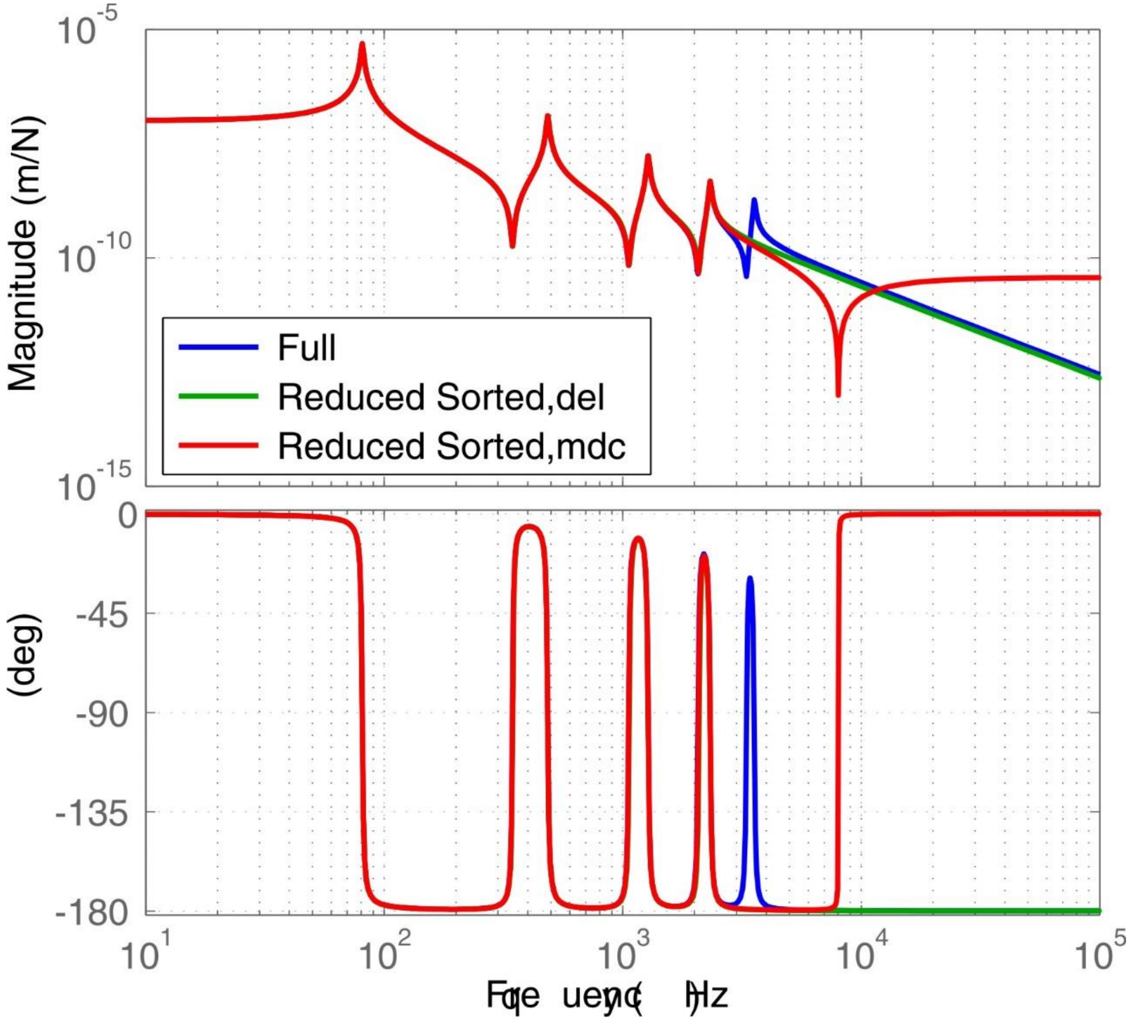




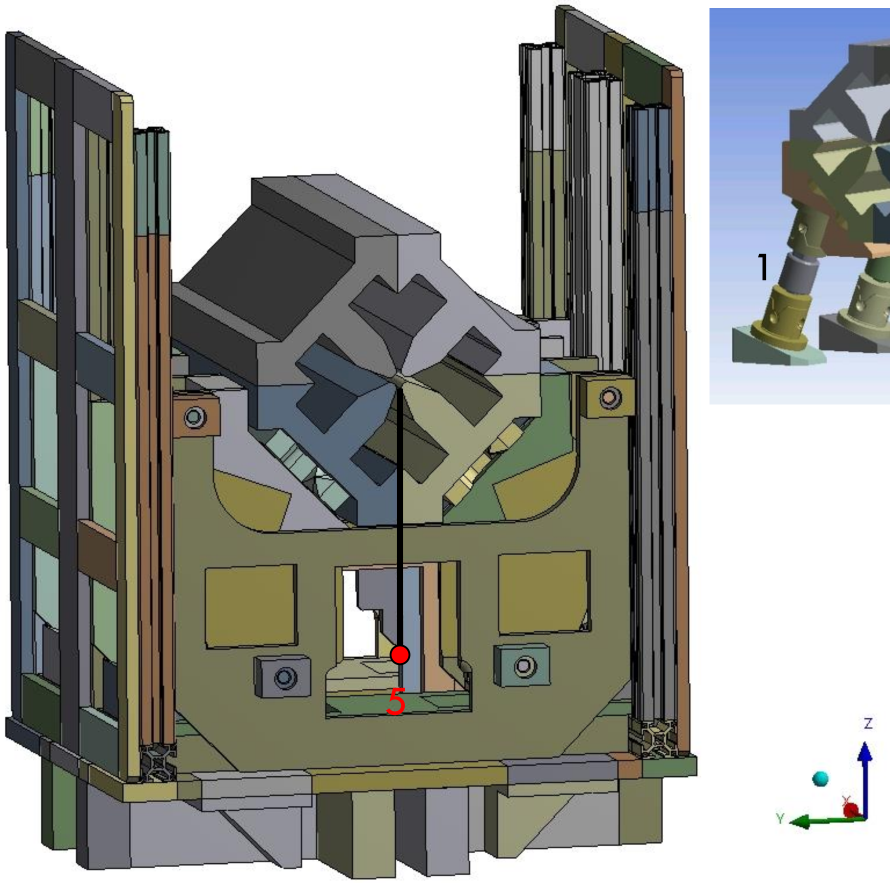
Model reduction

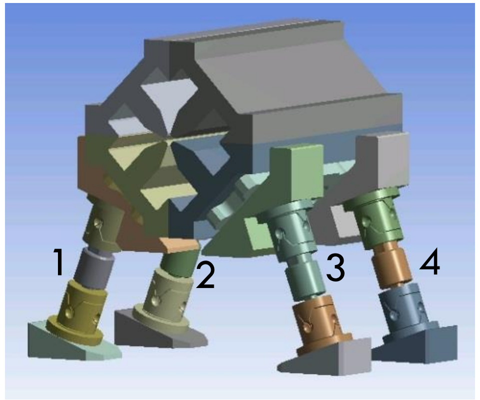
- Comparison beween « matched dc gain » technique and « suppression » techinque
- Reduction of the order of the state space model by keeping the first p modes (e.g. $p = 4$)
- Superelement method uses matched dc gain reduction

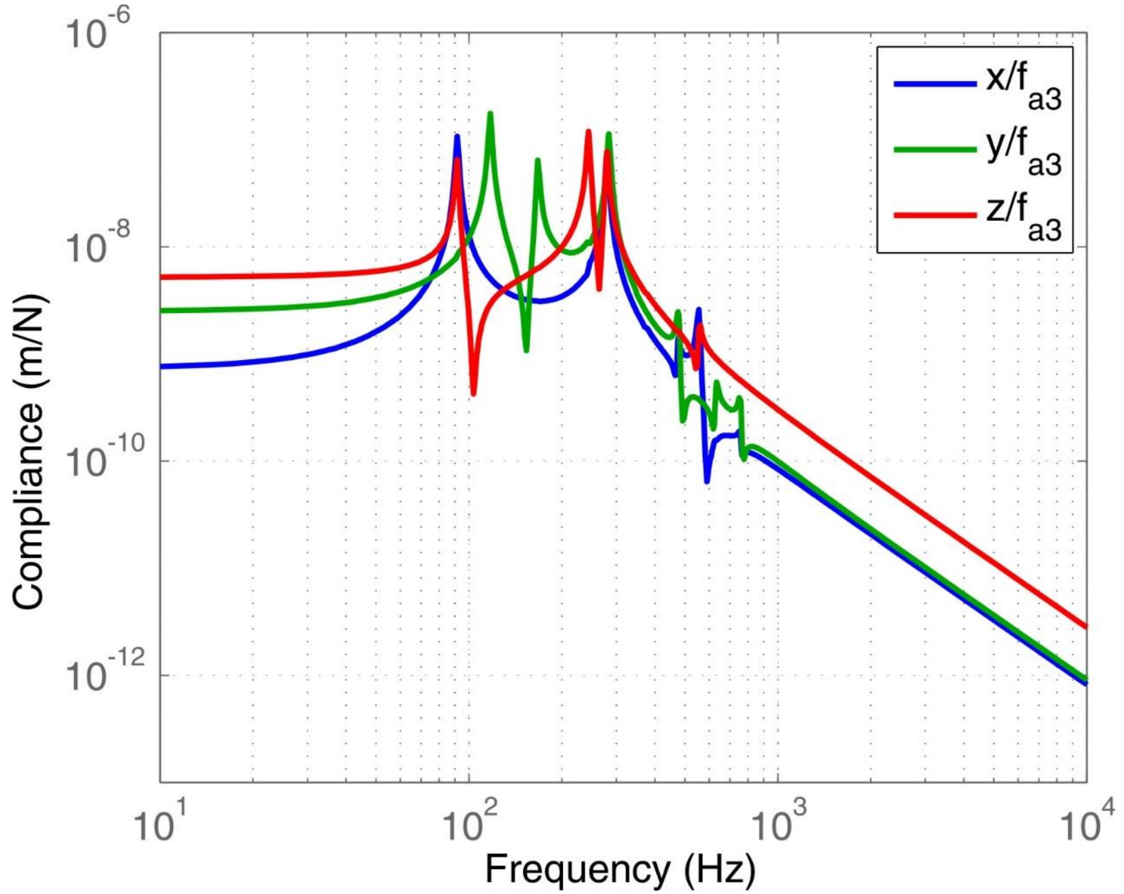
Matched dc gain	suppression
• The eliminated modes are condensed with a transformation matrix T $x_r = Tx = T\begin{bmatrix} x_r \\ x_e \end{bmatrix}$ • Exact dc gain guaranteed ➡ dc gain ranking not required • Constant amplitude at high frequency due to constant term in the direct transmission matrix D_{red} of the reduced state space model	• The eliminated modes are simply suppressed ➡ dc gain ranking required • High frequency decreasing behaviour is conserved



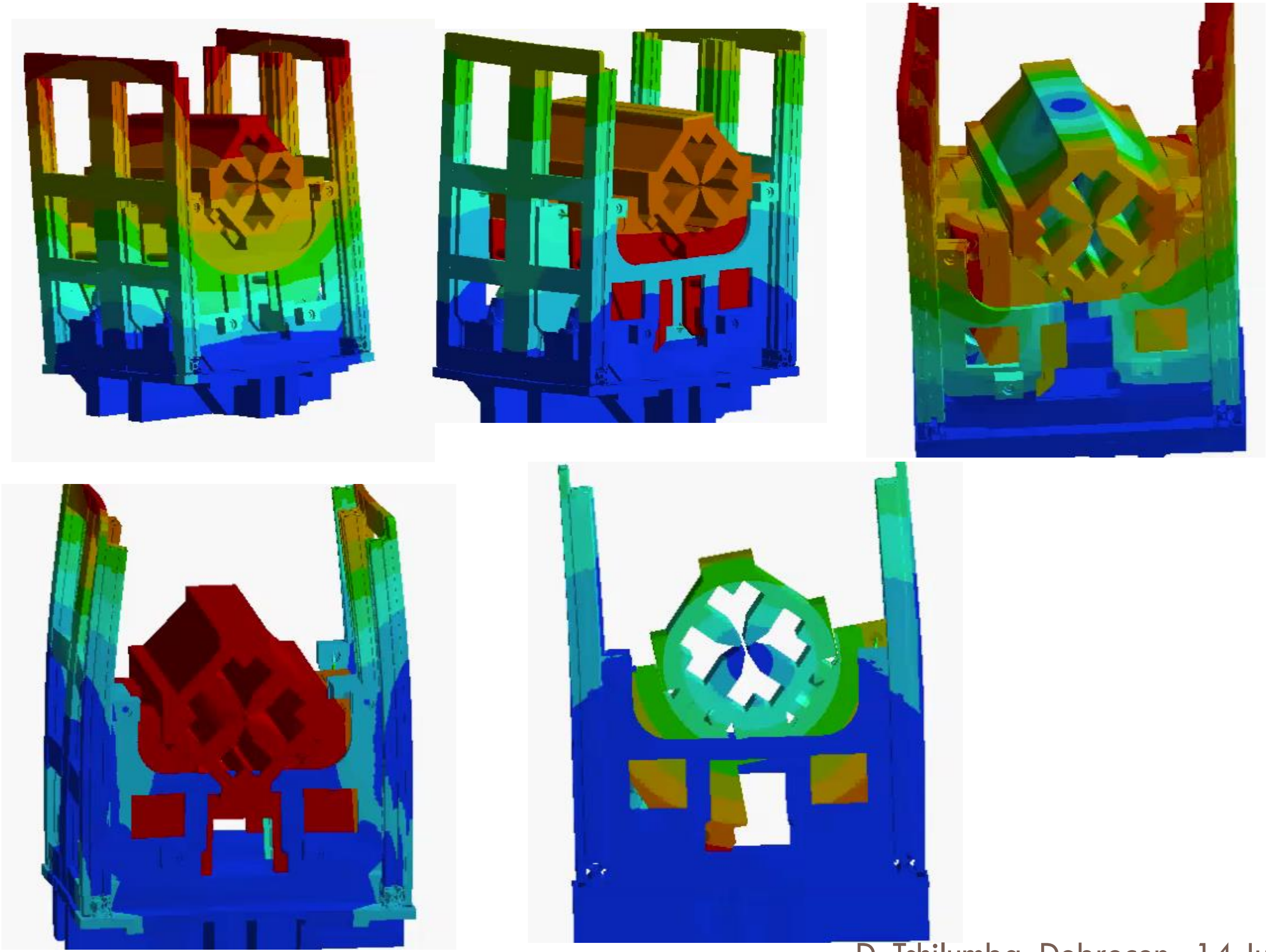
Type1 bench MIMO model

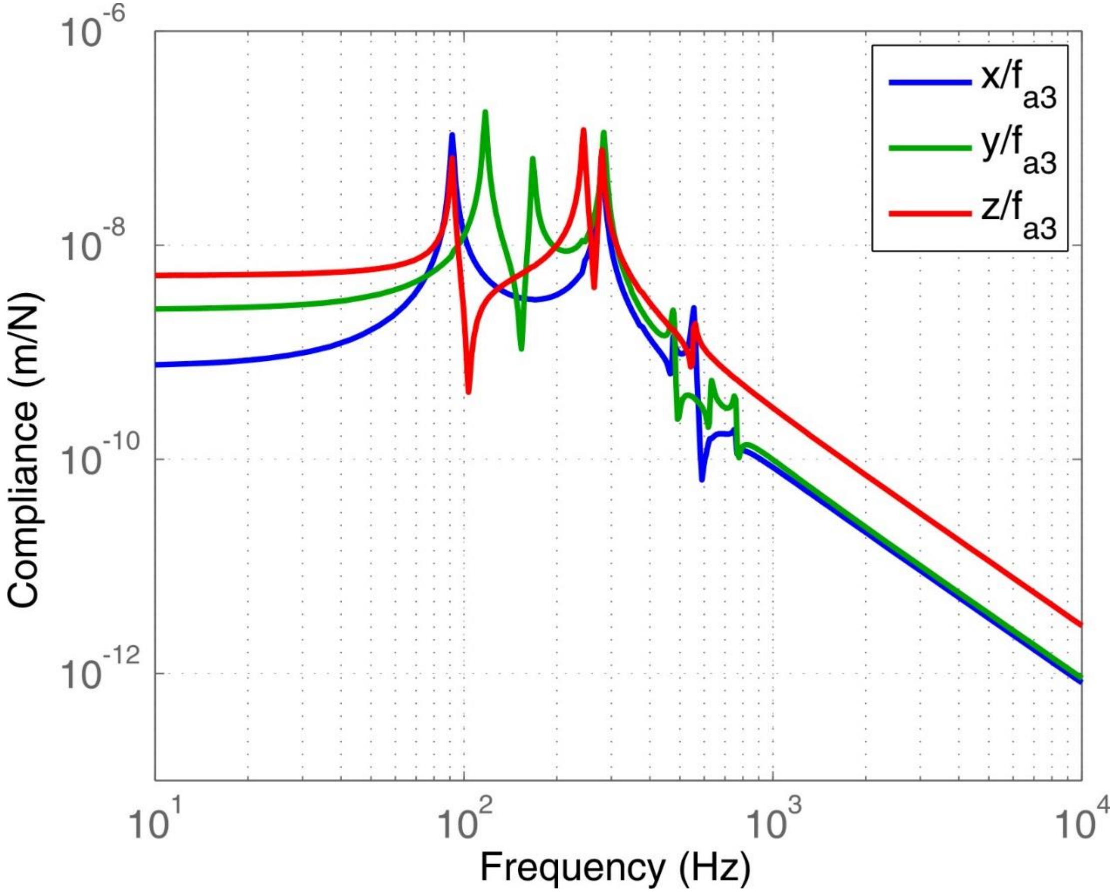






Type1 bench MIMO model



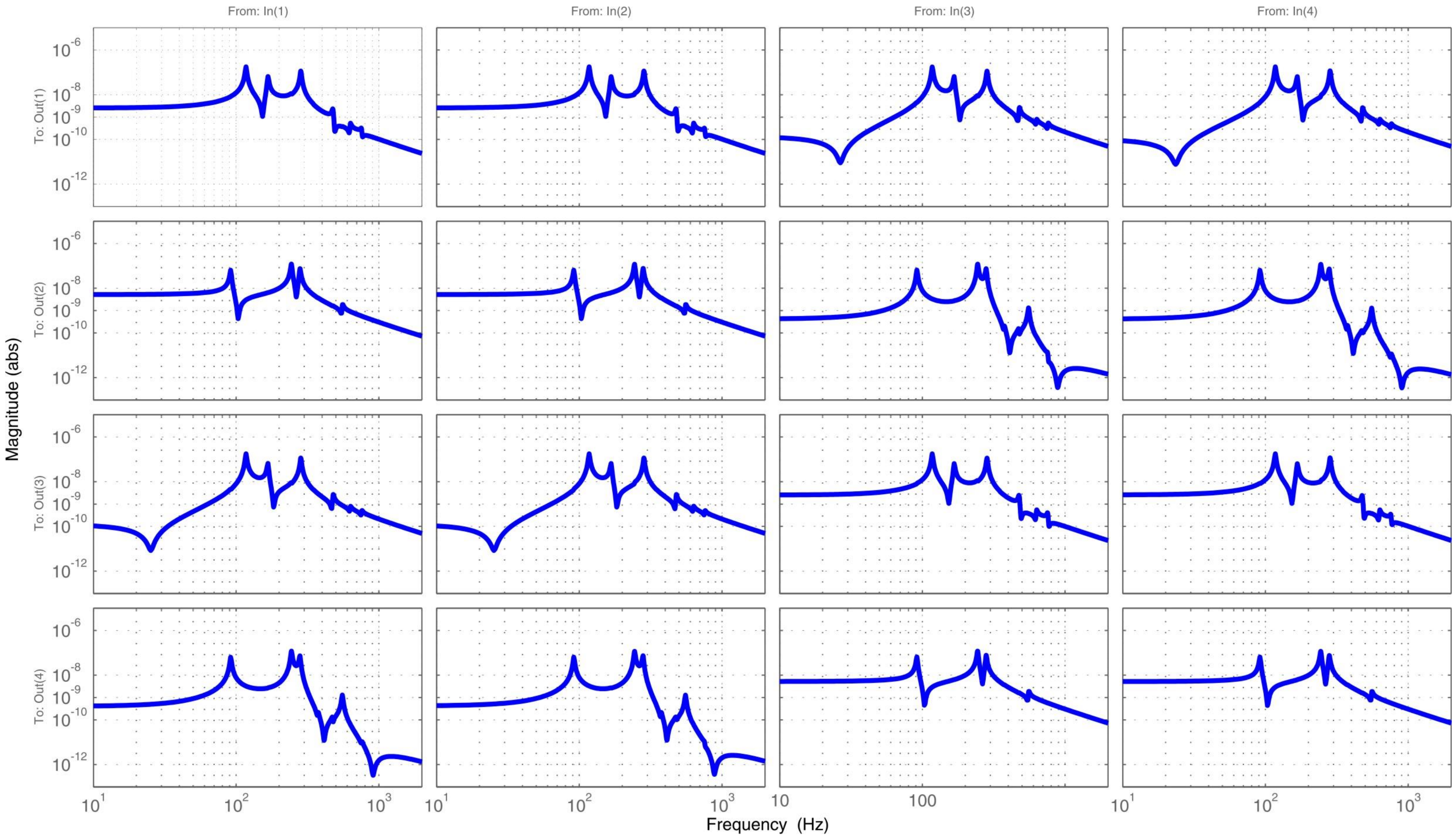


Coupled inputs and Outputs

- In(1): front left leg
- In(2): front right leg
- In(3): back left leg
- In(4): back right leg

- Out(1): front lateral encoder
- Out(2): front vertical encoder
- Out(3): back lateral encoder
- Out(4): back vertical encoder

- Interactive MIMO system $G(s)$
  - ➡ Controller design of $C(s)$
    - ➡ Improve reference tracking
    - ➡ Decrease I/O interaction



Closed loop reference tracking

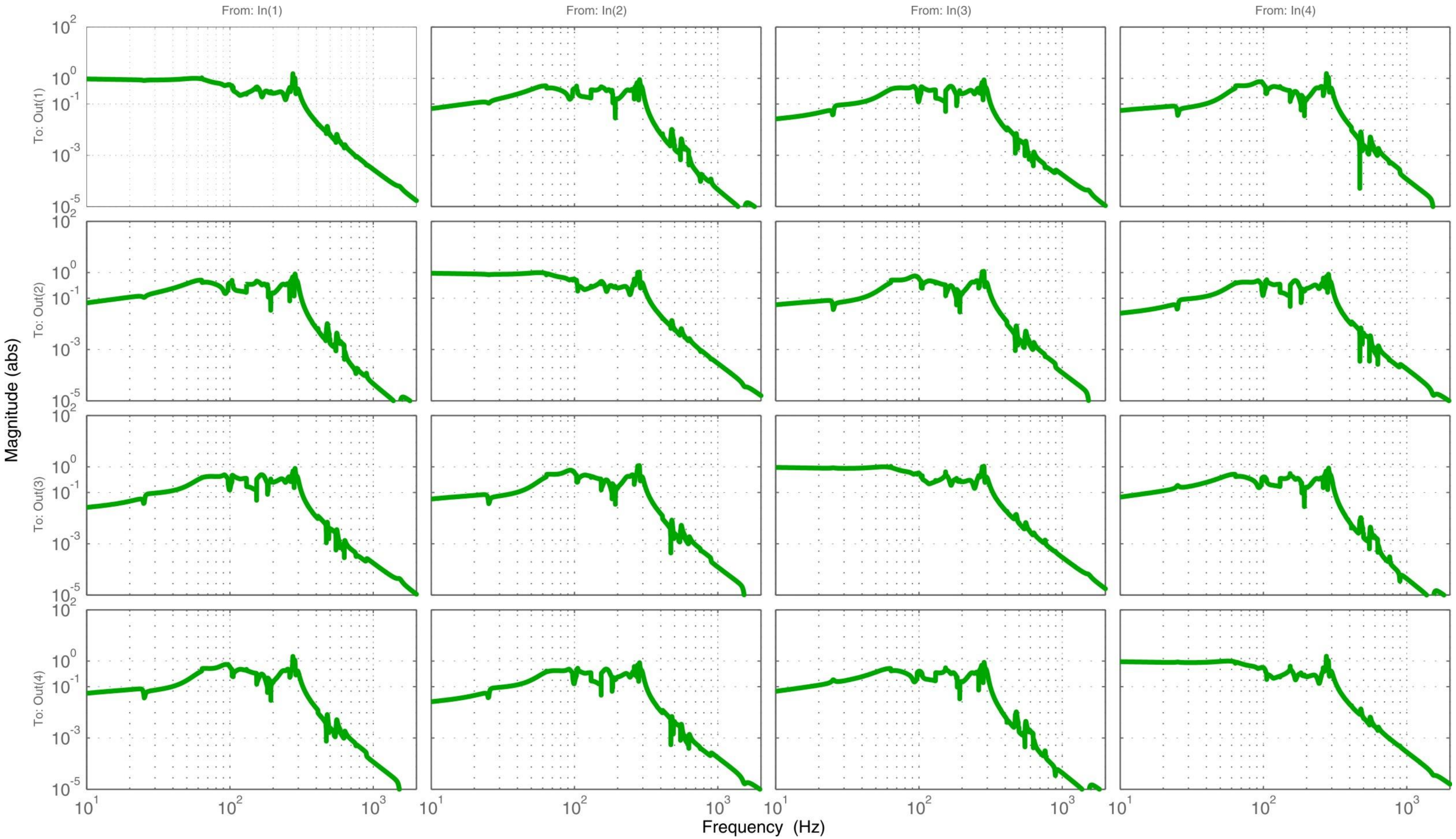
- In(1): reference signal 1
- In(2): reference signal 2
- In(3): reference signal 3
- In(4): reference signal 4

- Out(1): front lateral encoder
- Out(2): front vertical encoder
- Out(3): back lateral encoder
- Out(4): back vertical encoder

- SVD-controller

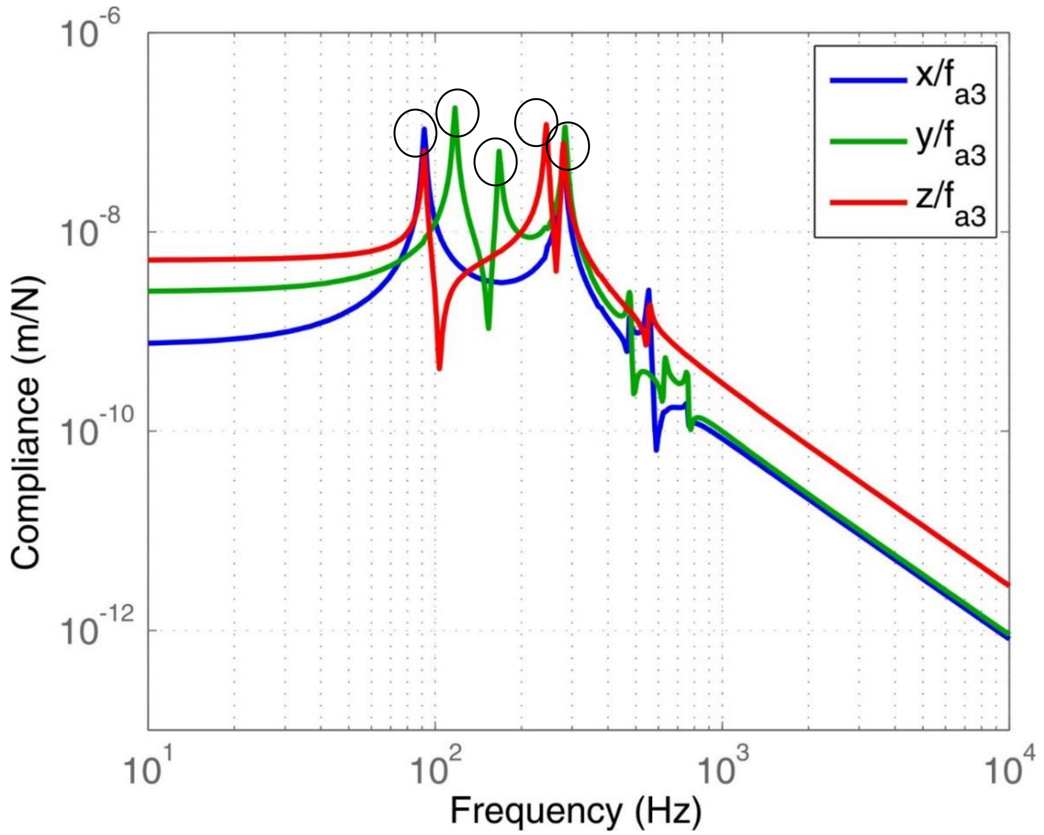
- MIMO system $G_{cl}(s)$

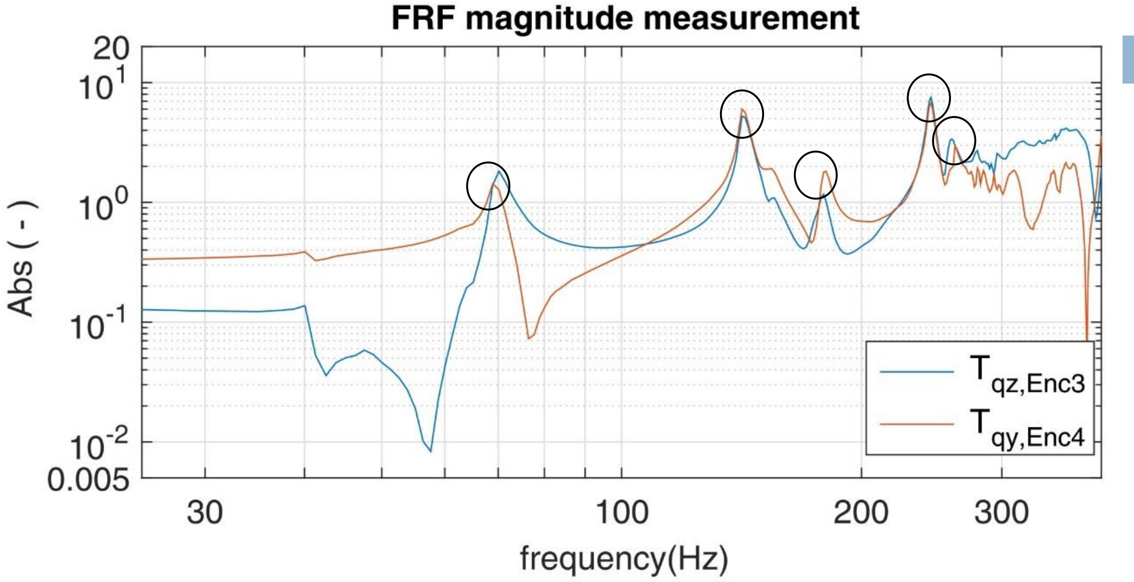
$$G_{cl}(s) = \frac{C(s)G(s)}{I(s)+C(s)G(s)}$$

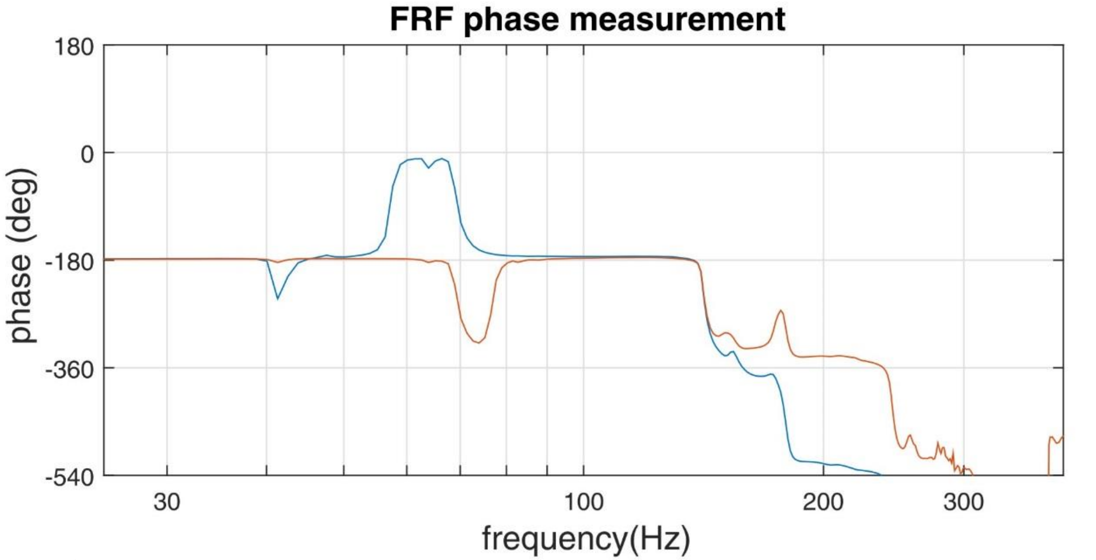


type1 bench MIMO model

Model validation



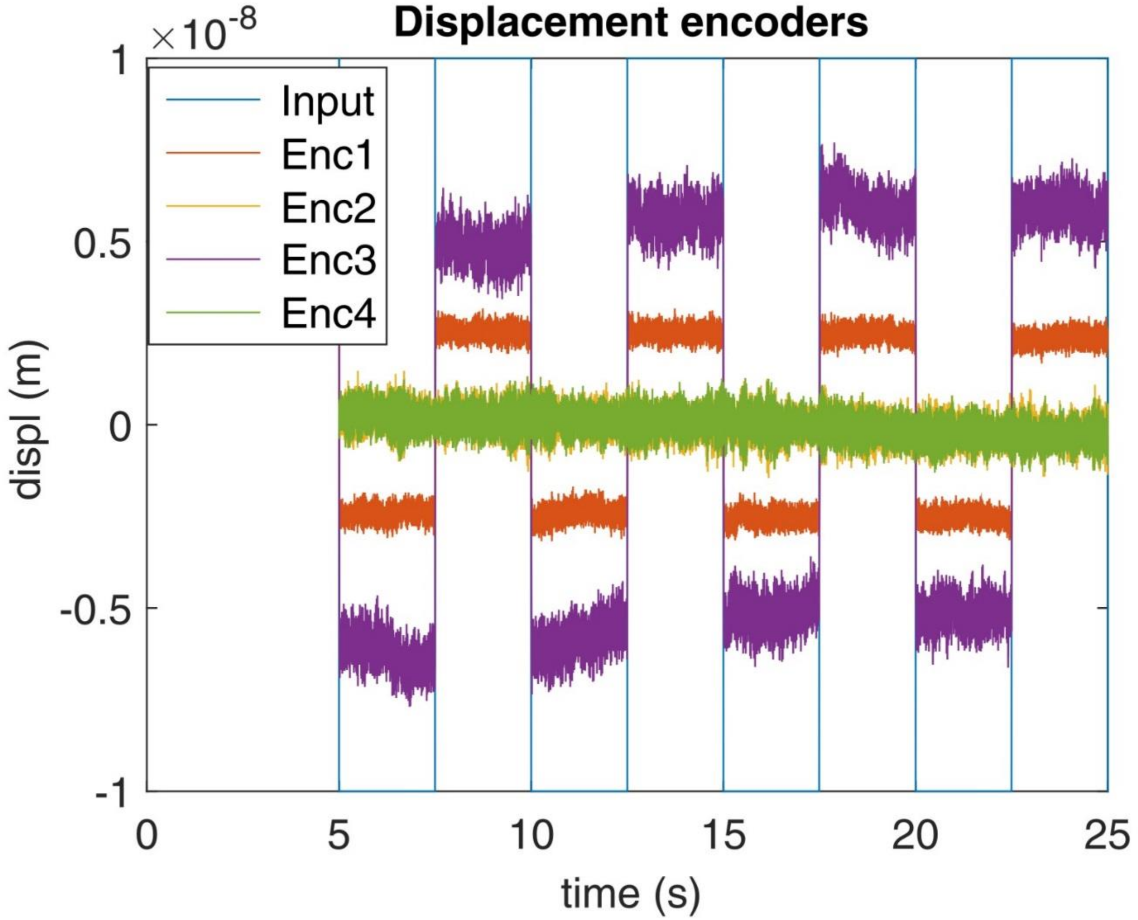




- Coupling in measured modes
- Parasitic mode at 40 Hz (mode 1)
- Measured modes 2 and 3 shifted

Potential causes : unglued reinforcement beam , distorted elements

Magnet positioning

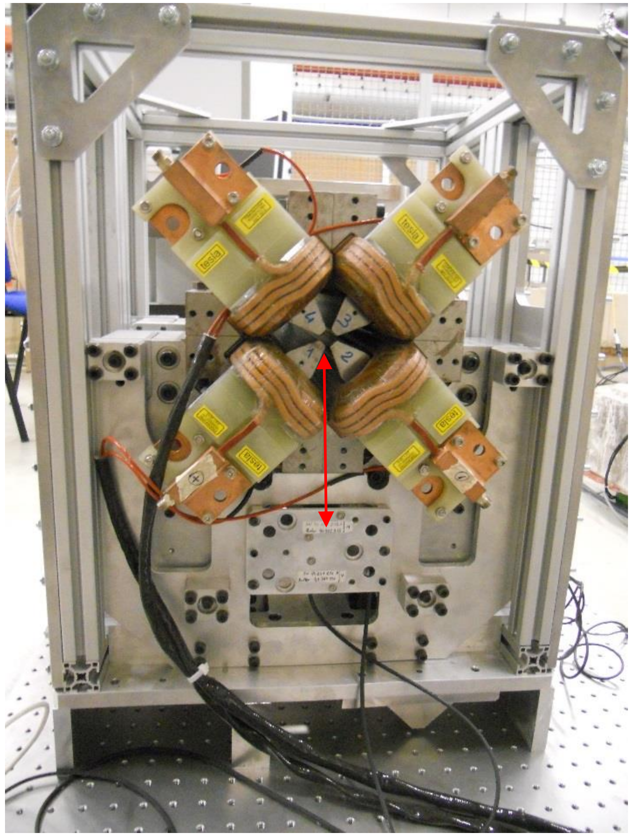


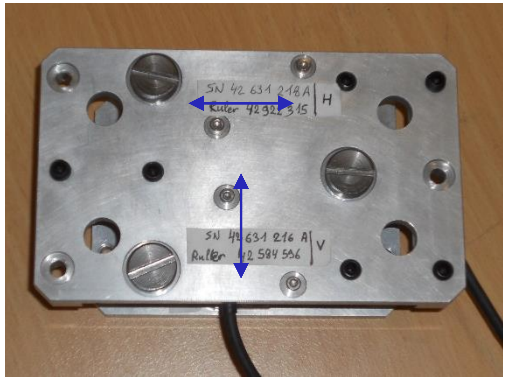
- Nominal displacement : 10 nm
- PI controllers ON
- Max Encoder1 readout : 2.5 nm
- Max Encoder3 readout : 5 nm
- Closed loop noise : 2nm
- Settling time :
  - 30 ms (Encoder 3)
  - 30 ms (Encoder 2)

Noise generated by strain gauge in closed loop

Measurement on Type 1 module: Preliminary tests

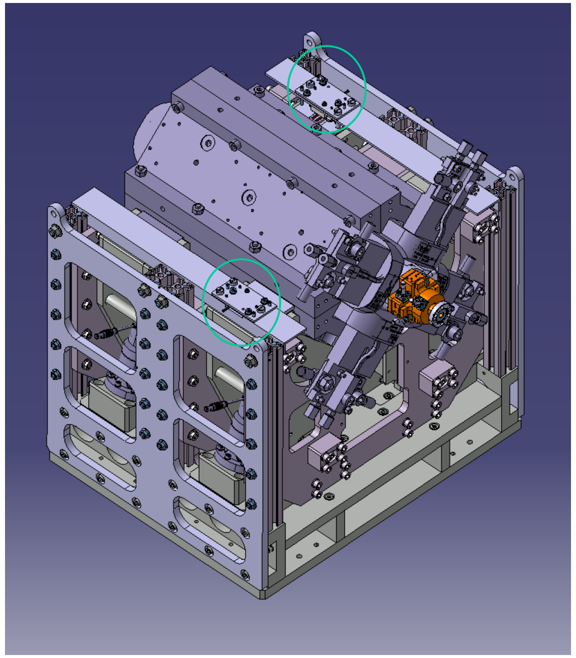
Hardware



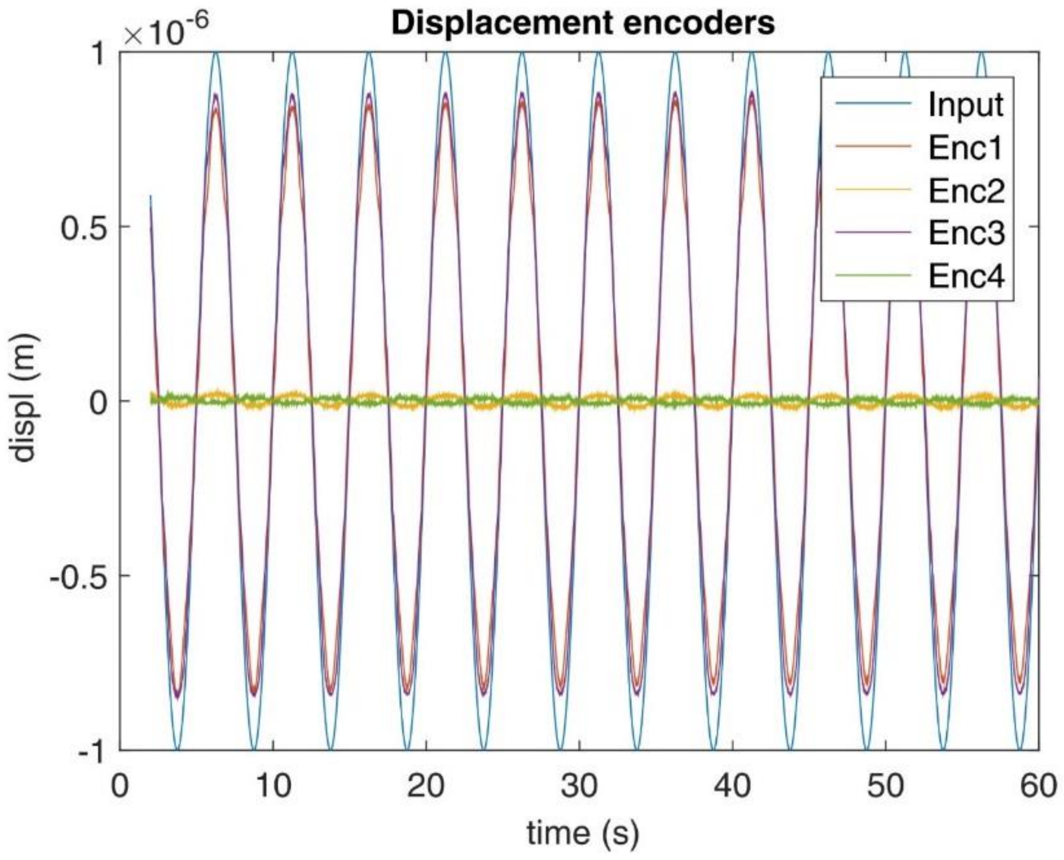


- PI Piezo stacks P225
- Integrated strain gauges
- Heidenhain LIP 281 linear encoders
- Offseted lateral encoders

➡ Upgrade foreseen



Vertical displacement

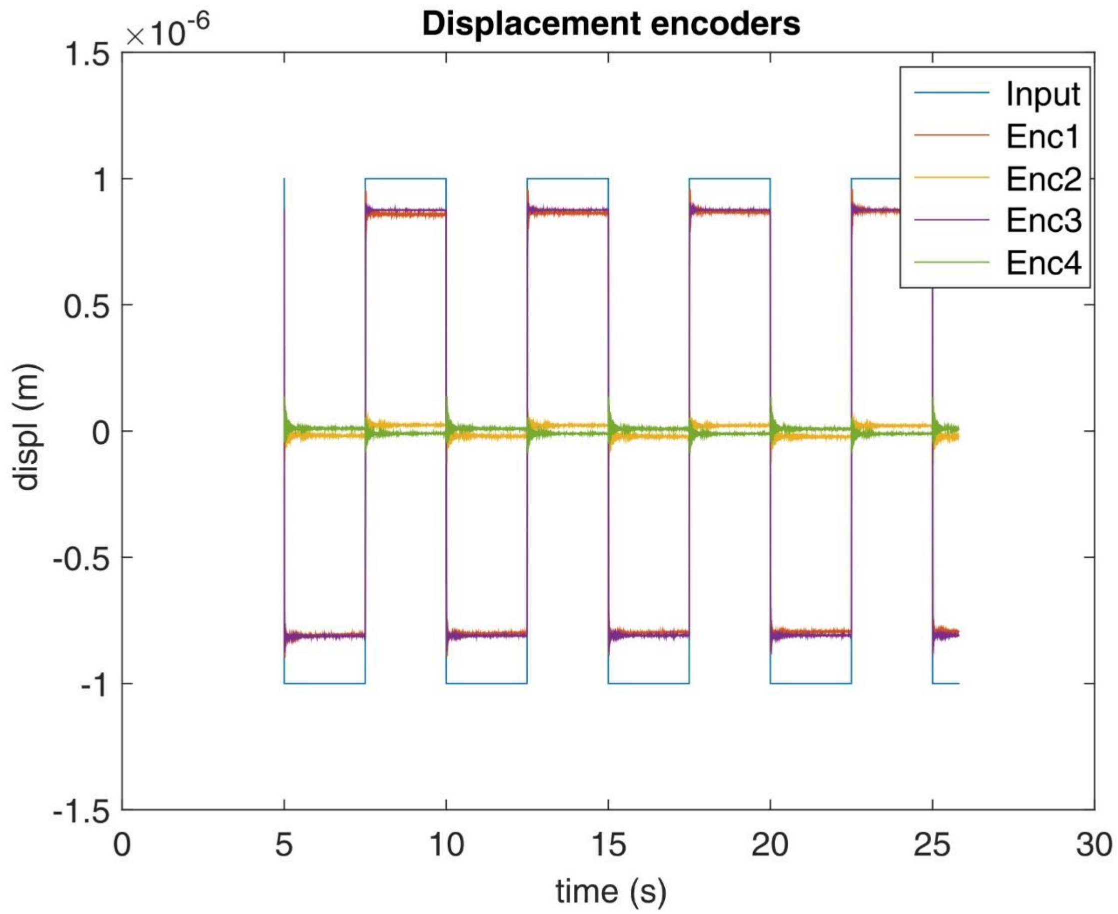


Objective: compensate imperfections from manufacturing and assembly process

- Nominal displacement : 1 µm
- PI controllers ON
- Max Encoder1 readout : 853 nm
- Max Encoder3 readout : 863 nm
- Max lateral encoder readout : 20 nm (~2%)

- DC offsets PZTs:
  - 3.2463 V (PZT 573)
  - 4.8298 V (PZT 575)
  - 4.1442 V (PZT 572)
  - 3.5819 V (PZT 574)

Vertical displacement



- Nominal displacement : 1 μm
- PI controllers ON
- Max Encoder1 readout : 866 nm
- Max Encoder3 readout : 876 nm
- Max lateral encoder readout : 20 nm (~2%)

- Closed loop noise: 2 nm (strain gauges)

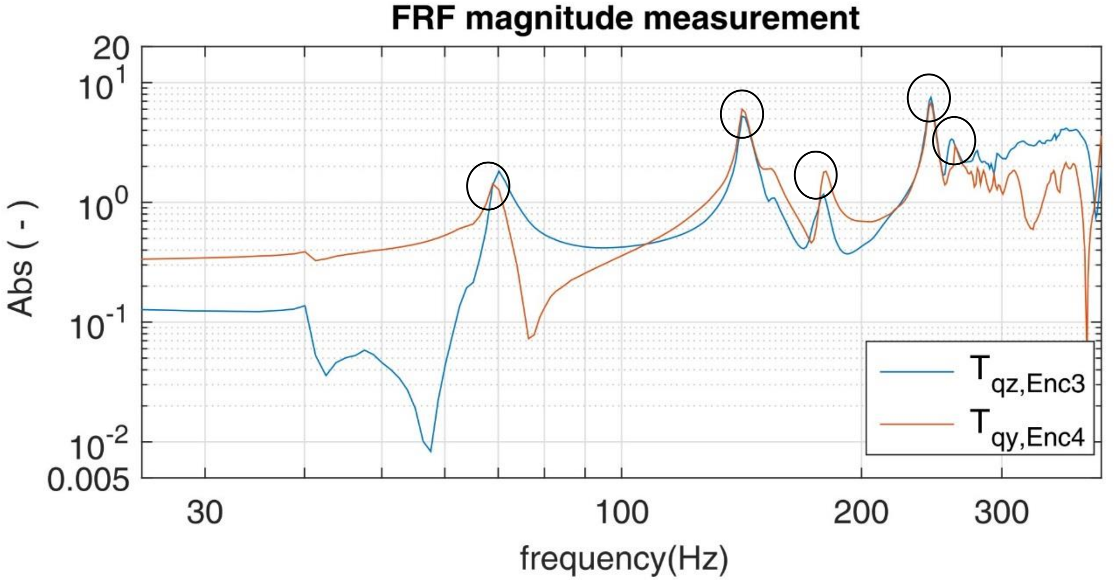
- Further tests required
    - Linearity assessment
    - Repeatability assessment
    - Encoder based active positioning

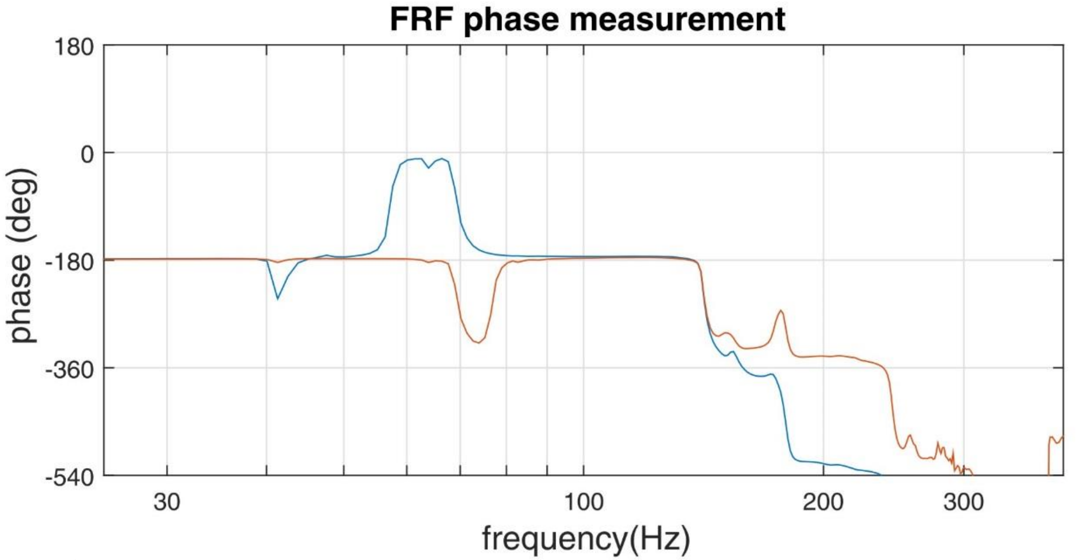
type1 bench MIMO model

Model validation

Mode	Direction	Frequency (model)
1	longitudinal	91 Hz
2	lateral	117 Hz
3	yaw	167 Hz
4	vertical	244 Hz
5	roll	270 Hz

Mode	Frequency (measurement)
1	40 Hz
2	70 Hz
3	141 Hz
4	179 Hz
5	244 Hz
6	262 Hz





- Coupling in measured modes
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Potential causes : unglued reinforcement beam , distorted elements