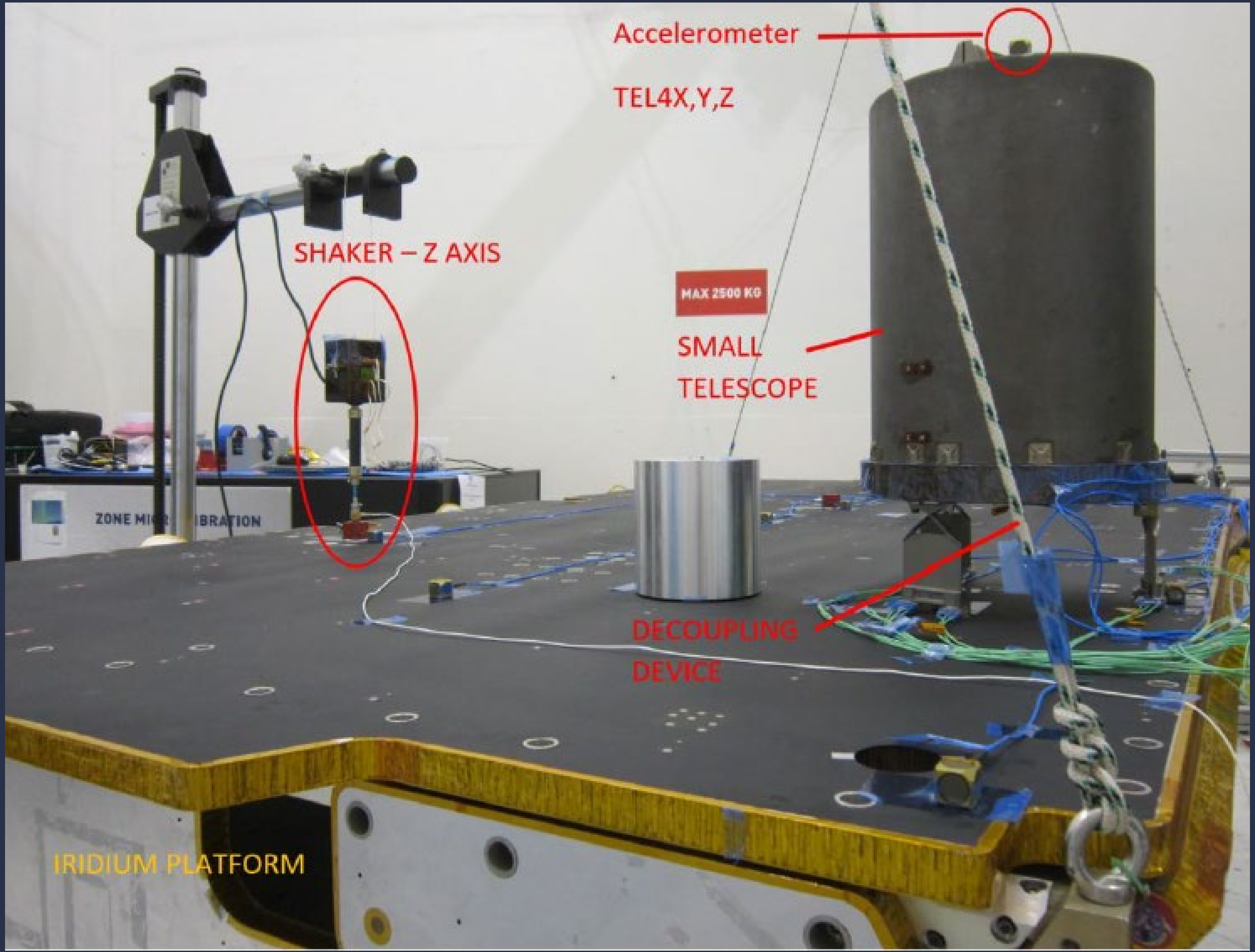
IMPROVE Improvement of Microvibration Prediction and Verification Methods



Emmanuel ONILLON (CSEM)
Gilles Carte (TAS)

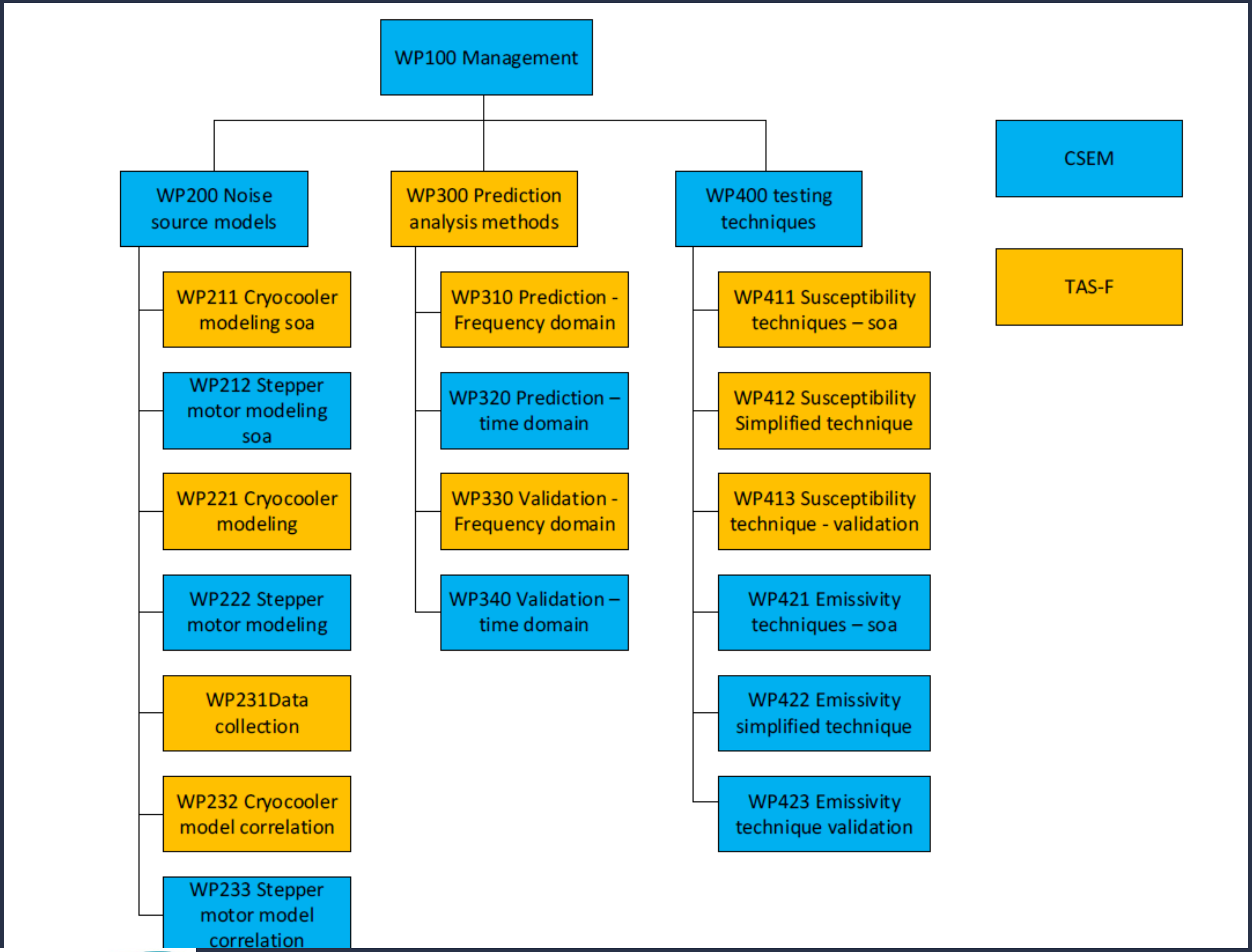
Agenda

- Project introduction, structure and organization – CSEM
- Stepper motor modelling and correlation – CSEM
- Cryo cooler motor modelling and correlation – TAS
- Time domain summation methodology – CSEM
- Frequency domain summation methodology– TAS
- Test results - CSEM / TAS
- Conclusions

Overview

- Space missions, especially Science and Earth Observation, have more and more stringent micro vibration requirements. Reaction Wheels, Cryocoolers, Stepper Motors, are among the main sources of micro vibration aboard the satellite.
- Stepper motors are widely employed for motorization in space applications, including deployment, orientation, and accurate pointing positioning mechanisms (e.g., SADM, APM, HDRM)
- Large Pulse Tube Coolers (LPTC) for Infrared focal planes are used in several missions such as the MeteoSat Third Generation (MTG) program.
- Better understand the effect of stepper motor and cryocooler w.r.t micro vibrations

WBS


WP100 Management
WP200 Noise source models
WP300 Prediction analysis methods
WP400 testing techniques
CSEM
TAS-F
WP211 Cryocooler modeling soa
WP212 Stepper motor modeling soa
WP221 Cryocooler modeling
WP222 Stepper motor modeling
WP231Data collection
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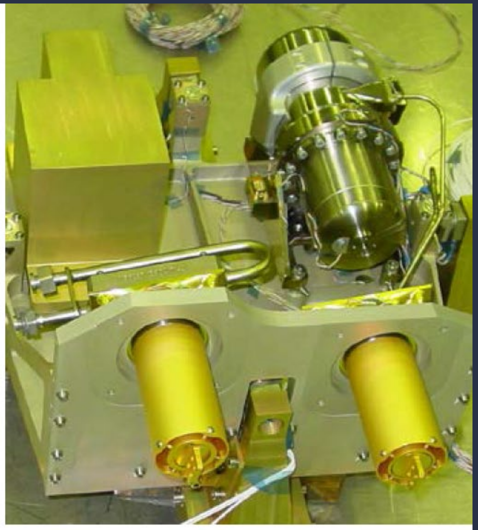
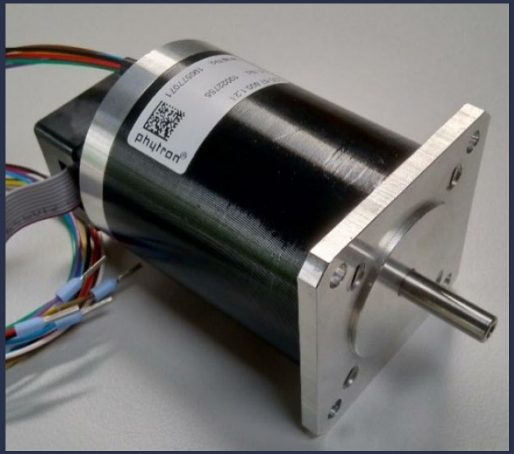
WP233 Stepper motor model correlation
WP310 Prediction - Frequency domain
WP320 Prediction – time domain
WP330 Validation - Frequency domain
WP340 Validation – time domain
WP411 Susceptibility techniques – soa
WP412 Susceptibility Simplified technique
WP413 Susceptibility technique - validation
WP421 Emissivity techniques – soa
WP422 Emissivity simplified technique
WP423 Emissivity technique validation

Elements to be modelled – Stepper motor

- Phytron stepper motor with performances close to a Sagem 35 PP
  - Load: solar array (flexible appendage)
- Large Pulse Tube Cooler, EM03Cd, incl cold finger

Mechanism for prediction method validation

- DSS mechanism developed by TAS-FR
- Diameter:
  - external diameter of the cylinder 302 mm.
- Height: The overall height of the structure is 585.8 mm.
- Resulting output will be considered at mirror level.

Original planning

- 18 months activity
- KO on 01/2019
- Planned end date 06/2020
- Final end date 02/2022
- 18 months delay

Delay root cause

- Second stepper test campaign for model development / correlation
- Complexity of cryo cooler / stepper modelling & correlation
- Development and commissioning of CSEM uvib test facility
- Lack of resources on TAS-FR side

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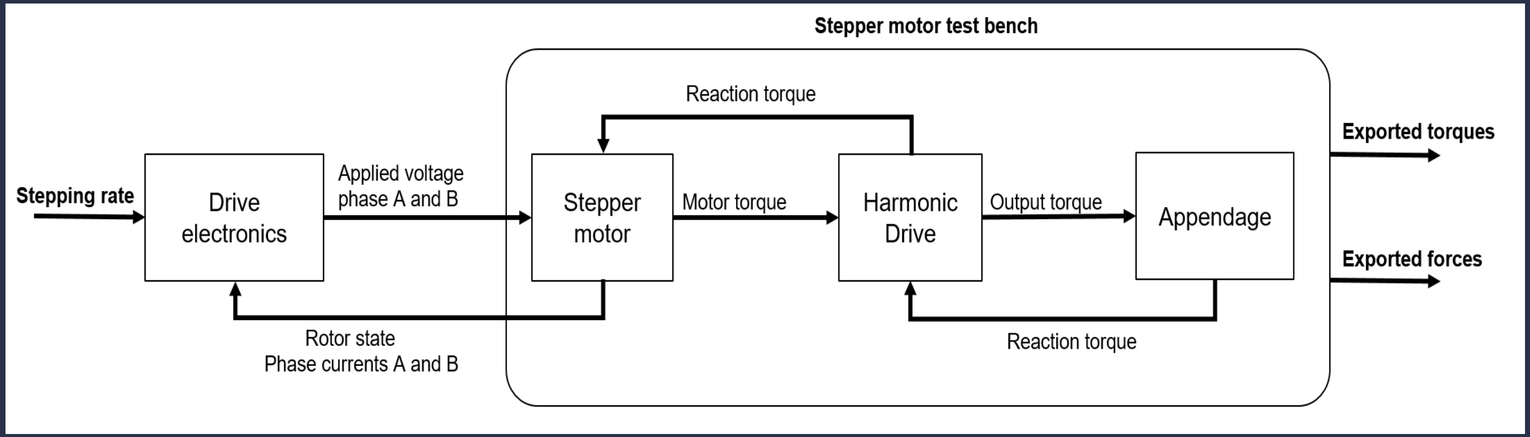
Model architecture

- Model of:
  - The drive electronics
  - Stepper motor
  - Harmonic drive
  - Inertia



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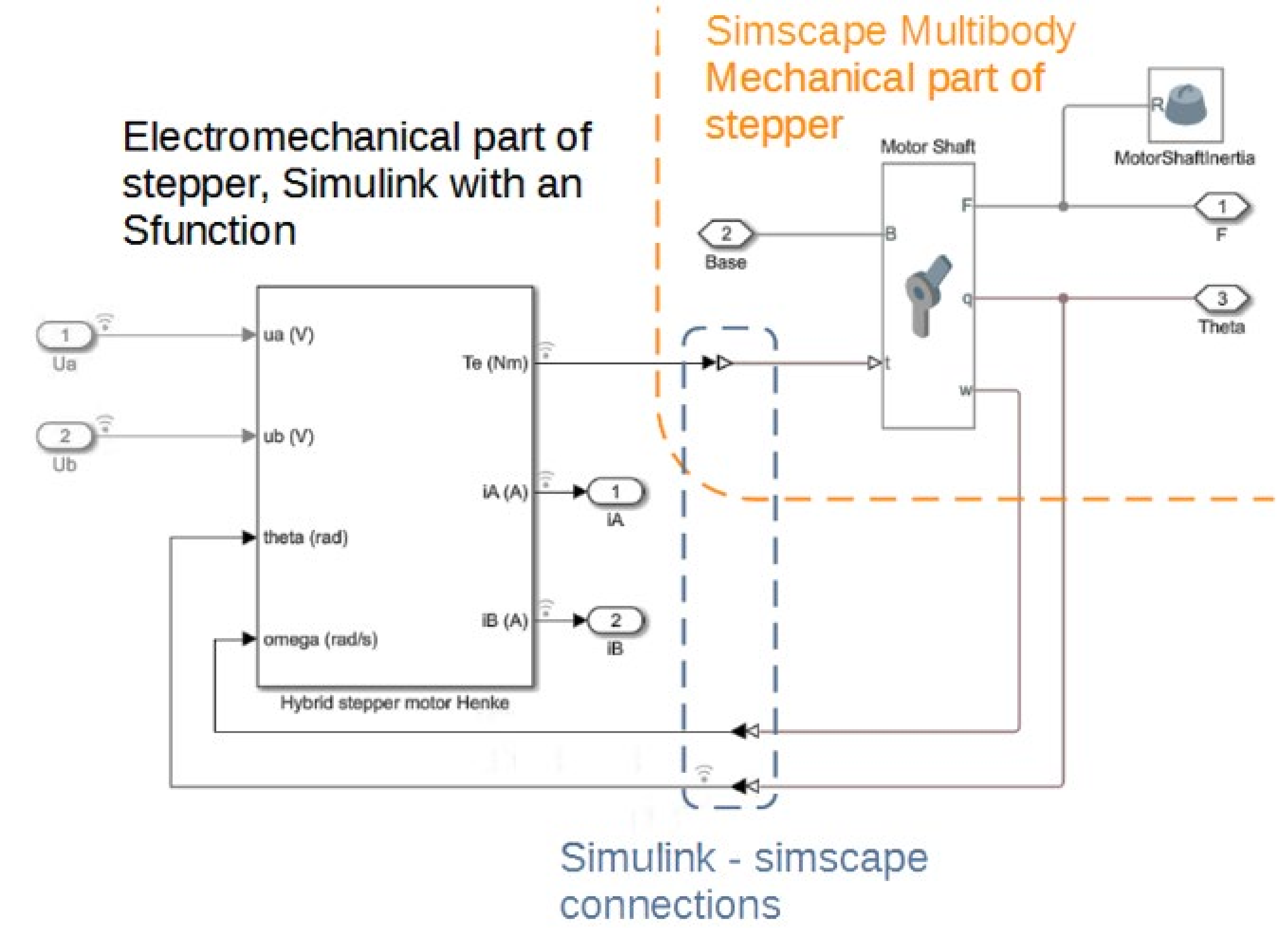
Model architecture: stepper motor – Henke model

- $\frac{d\omega}{dt} = \frac{1}{J}(T_{el} - T_{det}(\varphi) - T_{load})$
- $\frac{d\theta}{dt} = \omega$
- $\theta = \frac{\varphi}{p_p} = \frac{2}{P}\varphi$
- φ is the electrical angle and is related to θ / p_p is the number of pole pairs and P the number of poles
- The electromagnetic torque comprises two components:
  - the Lorentz force between the permanent magnet in the rotor and the electromagnetic stator windings;
  - the reluctance force between the electromagnetic stator windings and the salient iron end caps of the rotor.
  - Ψ_{M} is the flux constant resulting from the permanent magnetic flux caused by the permanent magnet in the rotor, i_a and i_b are the currents flowing in the phases, and L is the 2x2 inductance matrix.
- $\mathrm{T_{el}} = \mathrm{p}\Psi_{\mathrm{M}} \begin{bmatrix} i_a \\ i_b \end{bmatrix}^T \begin{bmatrix} -\sin\varphi \\ \cos\varphi \end{bmatrix} + \frac{1}{2} p_P \begin{bmatrix} i_a \\ i_b \end{bmatrix}^T \frac{\partial L(\varphi)}{\partial \varphi} \begin{bmatrix} i_a \\ i_b \end{bmatrix}$
- $L(\varphi) = L_0 \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} + L_1 \begin{bmatrix} \cos 2\varphi & \sin 2\varphi \\ -\sin 2\varphi & -\cos 2\varphi \end{bmatrix}$
- $\begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \end{bmatrix} = L(\varphi)^{-1} \left(\begin{bmatrix} u_a \\ u_b \end{bmatrix} - R \begin{bmatrix} i_a \\ i_b \end{bmatrix} - \dot{\varphi} \frac{\partial L(\varphi)}{\partial \varphi} \begin{bmatrix} i_a \\ i_b \end{bmatrix} - \Psi_{\mathrm{M}} \dot{\varphi} \begin{bmatrix} -\sin\varphi \\ \cos\varphi \end{bmatrix} \right)$
- $\mathrm{T_{det}} = \sum_{k=1}^{n} a_k \sin k\varphi$

Model architecture: stepper motor

- Implementation in Simulink / Simscape



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Model architecture: harmonic drive

- $J_{Gear}\frac{d\omega_{Gear}}{dt} = K_{Gear}\left(\frac{\theta}{N_{red}} - \theta_{Gear}\right) - B_{st_{Gear}}\operatorname{sign}(\omega_{Gear}) - B_{dyn_{Gear}}\omega_{Gear}$
- Reaction torque produced by the HD: $T_{GearRot} = -K_{Gear}\frac{1}{N_{red}}\left(\frac{\theta}{N_{red}} - \theta_{Gear}\right)$
- Implemented in Simulink

J_{Gear} gearbox inertia

θ_{Gear} ω_{Gear} outer shaft position / speed of gearbox

K_{Gear} stiffness associated to the connection between the rotor and the outer shaft

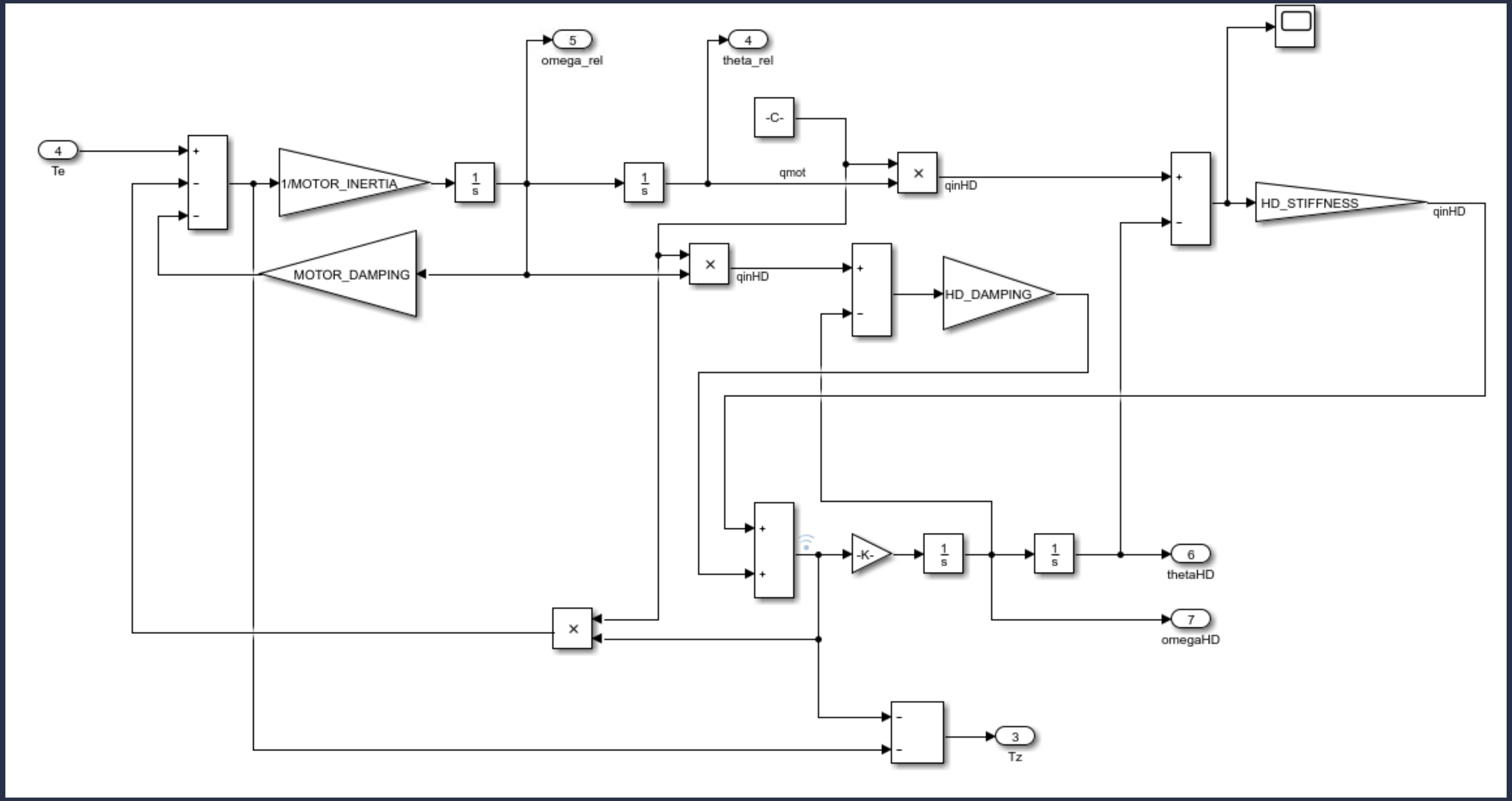
$B_{st_{Gear}}$ and $B_{dyn_{Gear}}$ are the static / viscous friction coefficients

Model architecture: harmonic drive

- $J_{HD}\ddot{\theta} = K_{HD}\left(\frac{\theta}{N_{red}} - \theta_{HD}\right) + B_{HD}\left(\frac{\dot{\theta}_{mot}}{N_{red}} - \dot{\theta}_{HD}\right)$
- Reaction torque produced by the HD: $T_{HD} = -J_{HD}\ddot{\theta}$
- Implemented in Simulink

For forces:

Similarly a second unbalance is added to the HD output inertia



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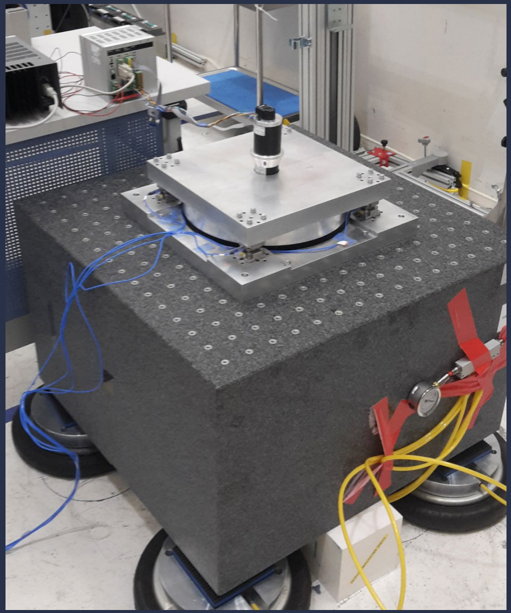
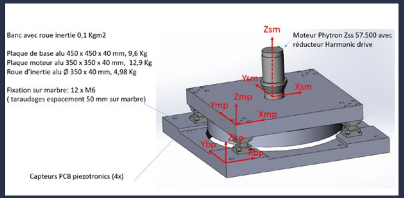
Stepper motor

Configuration

- Phytron ZSS 57.500

Parameters	Value
Motor pole pairs p_P	125
Harmonic drive reduction ratio N_{red}	100
Motor inertia J_{Mot}	Motor: 2.4e-5 kgm^2 Harmonic drive 3.3e-6 kgm^2 Total 2.7e-5 kgm^2
Motor constant (equal to $p\Psi_M$)	0.338 Nm/A
Motor detent torque coefficients a_k, with k from 1 to 4.	[30 mNm 0 0 1 mNm]
Current amplifier closed-loop bandwidth	1000 Hz



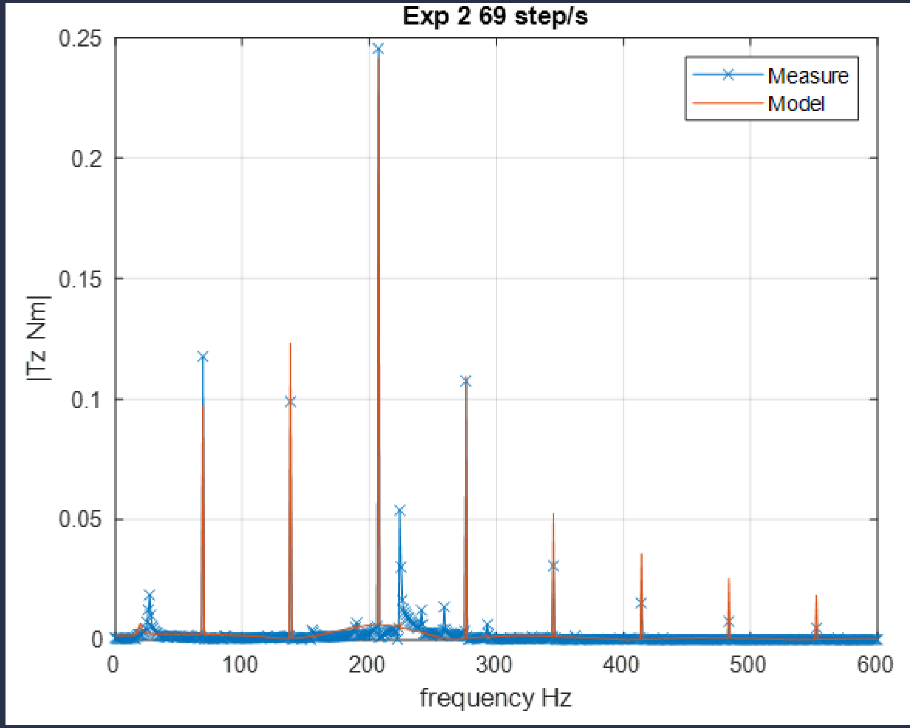


Associated with an harmonic drive from the CSG-CH family with a 100-reduction factor to drive a flexible appendage.

First campaign results - Exported torque

- Full system measurement at TAS-FR

Parameters	Range	Optimized value
Harmonic drive viscous friction $B_{dyn_{Gear}}$ (Nms/rad)	[0.5 3]	0.90894
Harmonic drive output stiffness K_{Gear} (Nm/rad)	[1500 2900]	1501.1
Motor viscous damping $B_{dyn_{Mot}}$ (Nms/rad)	[1e-2 0.1]	0.014265
Motor inertia J_{Mot} (kgm2)	2.7e-5 3.5e-5	3.145e-05
Cost function (estimated 0-600 Hz)	N.A.	271.3



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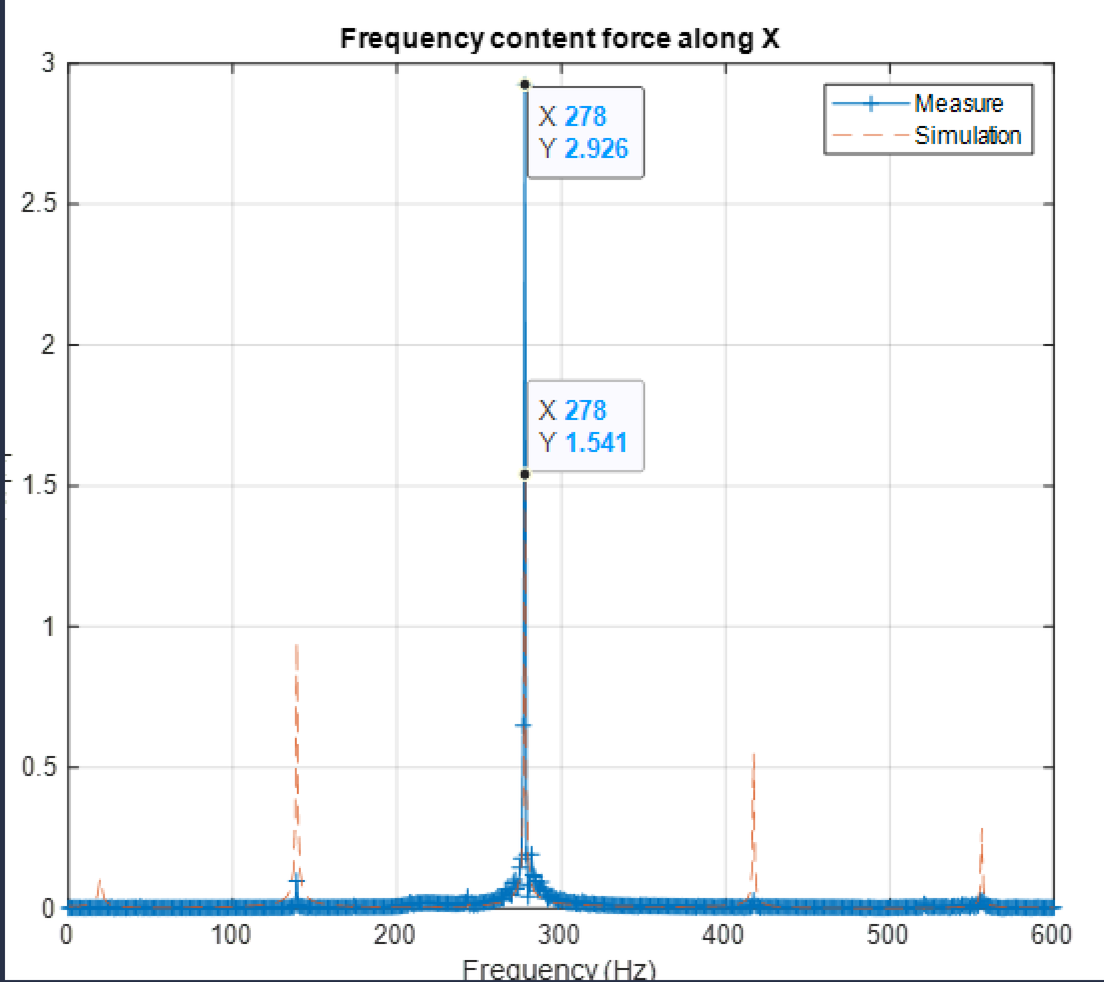
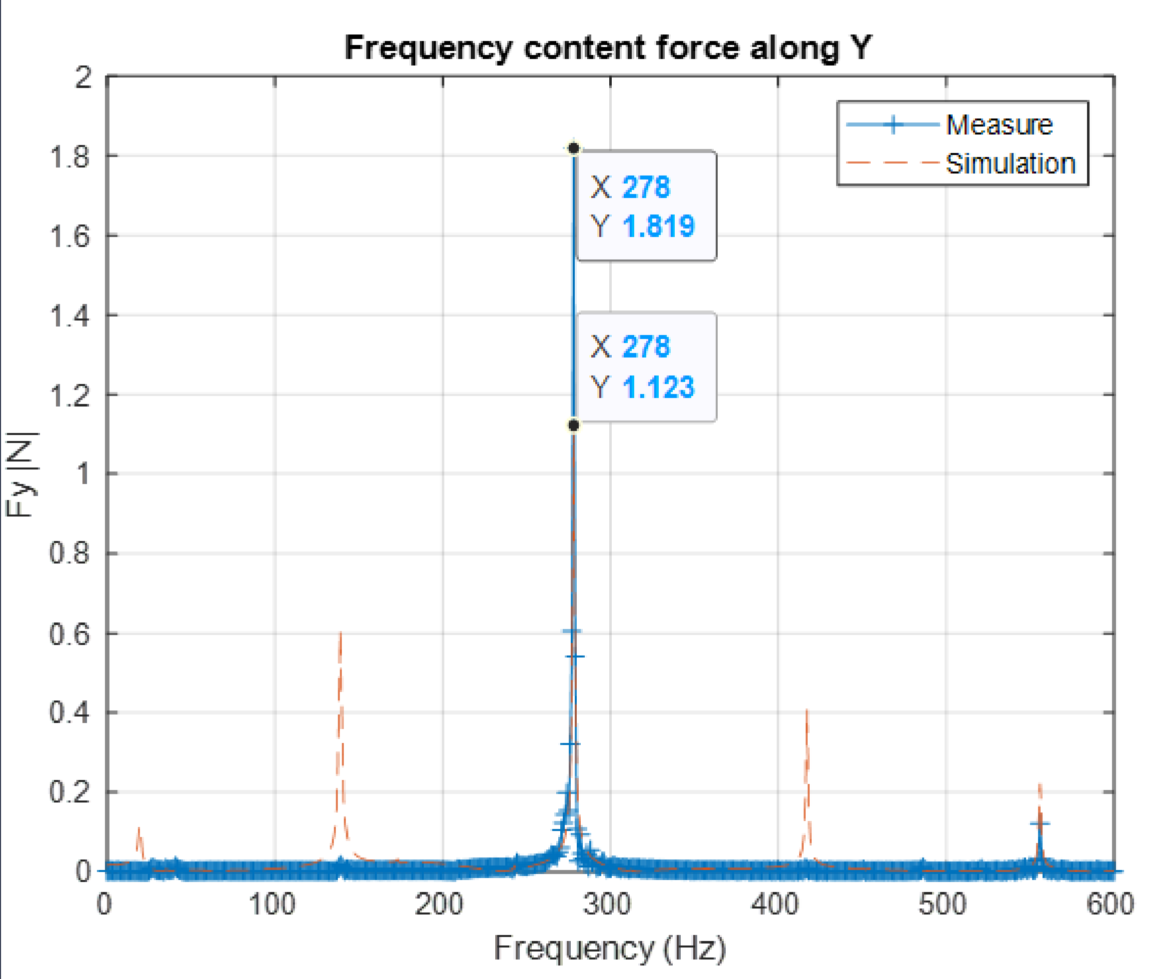
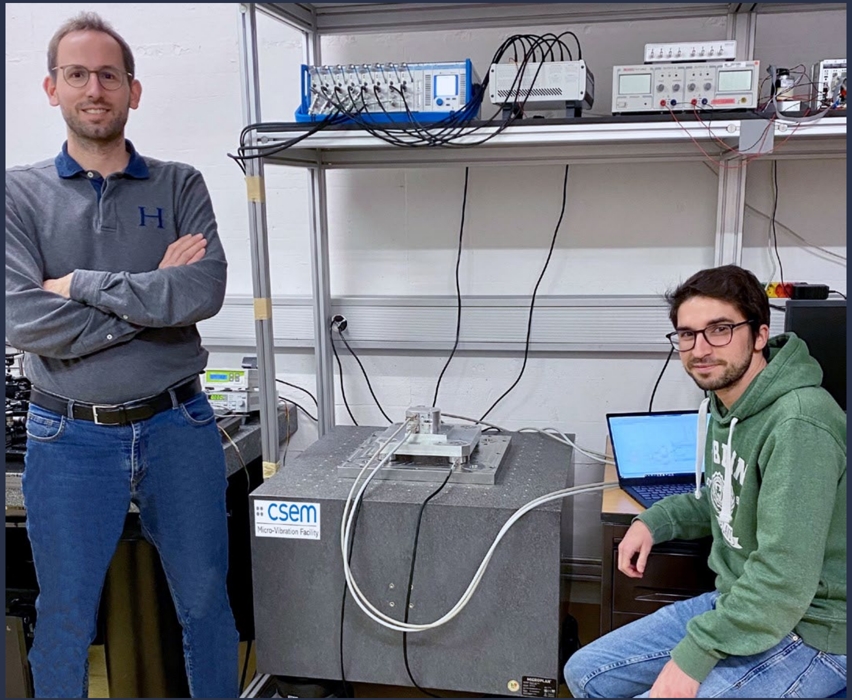
First campaign results -. Exported forces



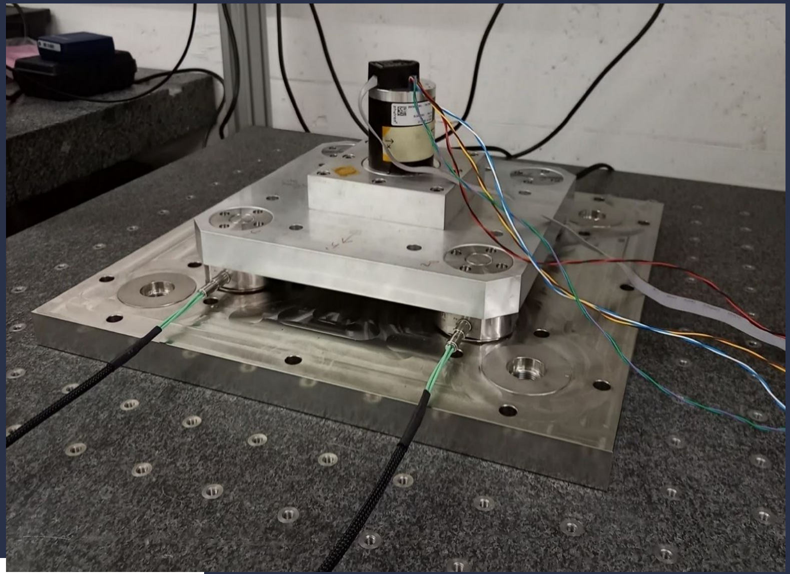


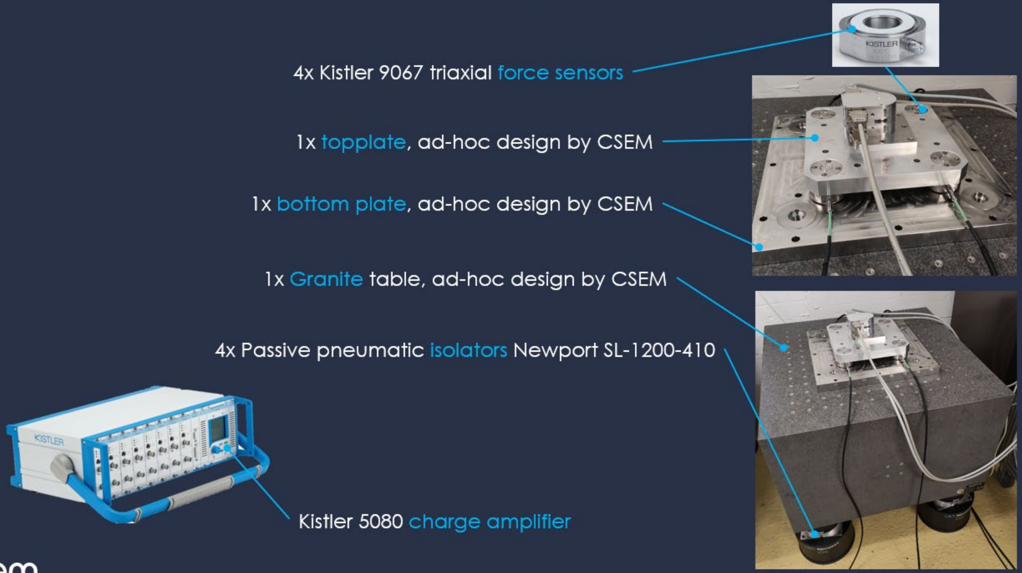
Second test campaign

- Dedicated test campaign element per element
- Development of a dedicated micro-vibration facility
- Support of HEIG-VD for HD characterization



Vibration characterization facility

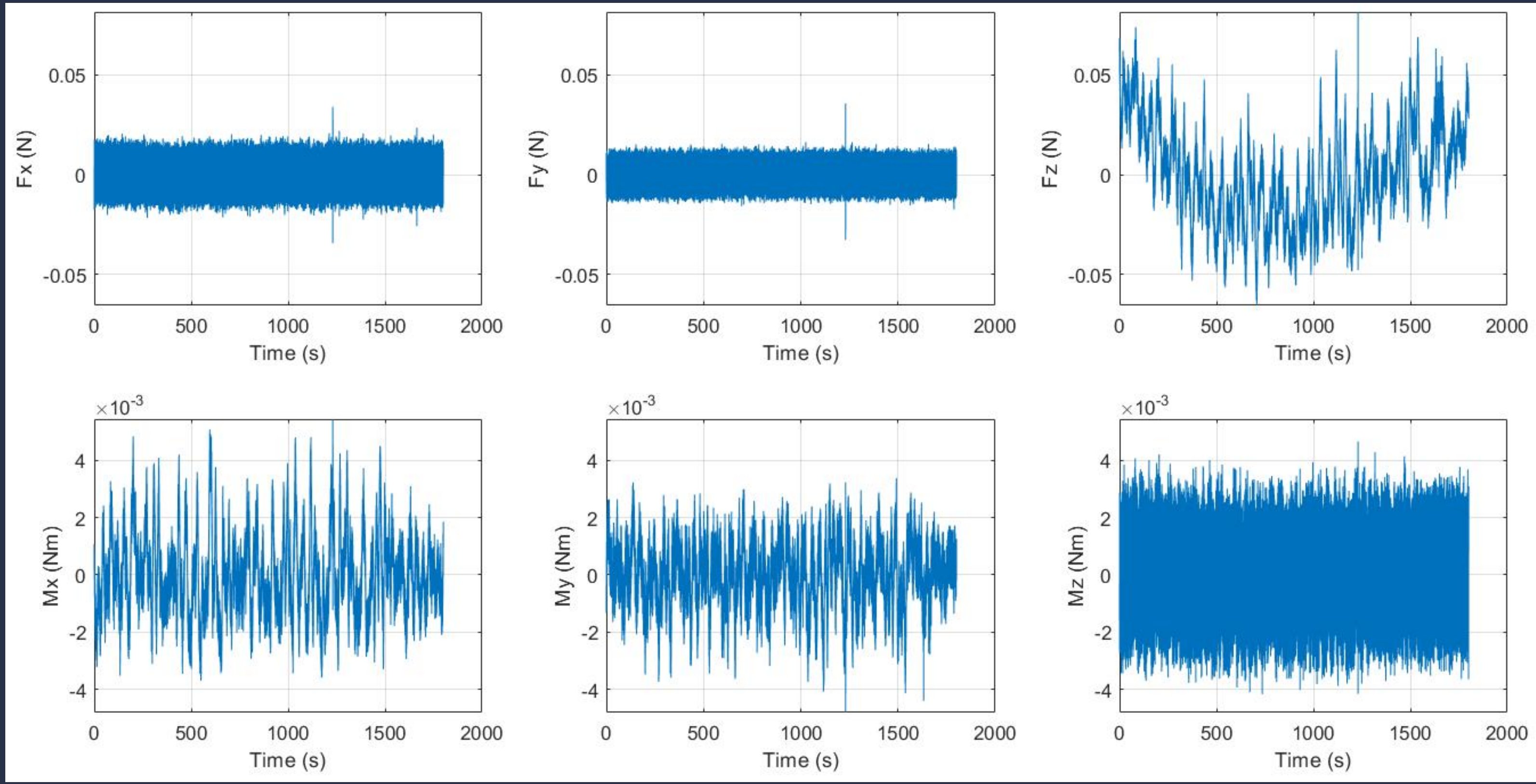


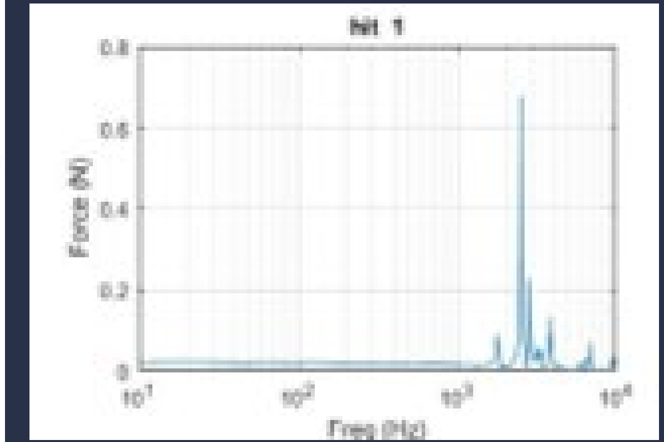


Stepper motor

Second test campaign

- Noise 50 mN in force / 4 mNm in torque
- Hammer tests to see mechanical modes: above 2 kHz





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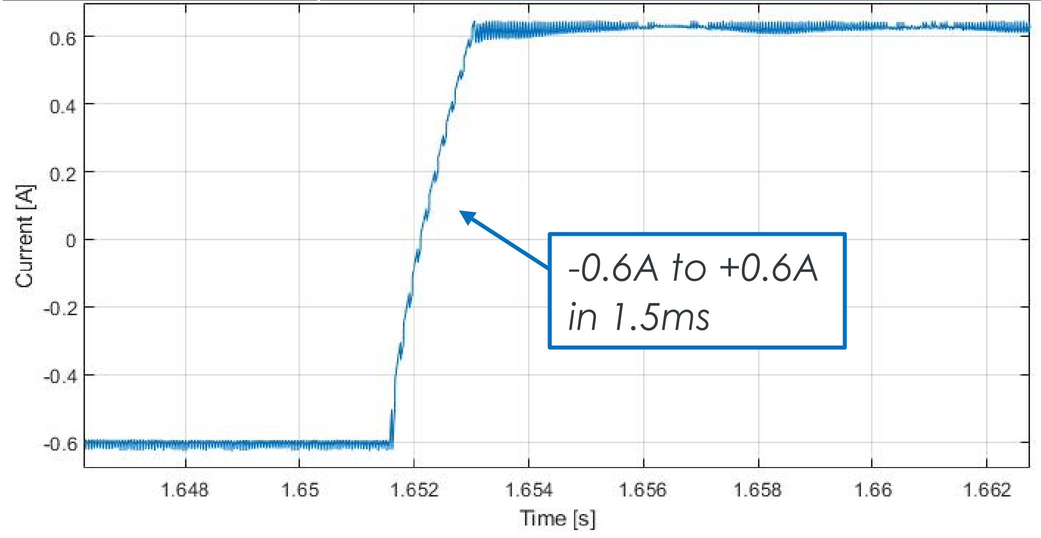
Stepper motor

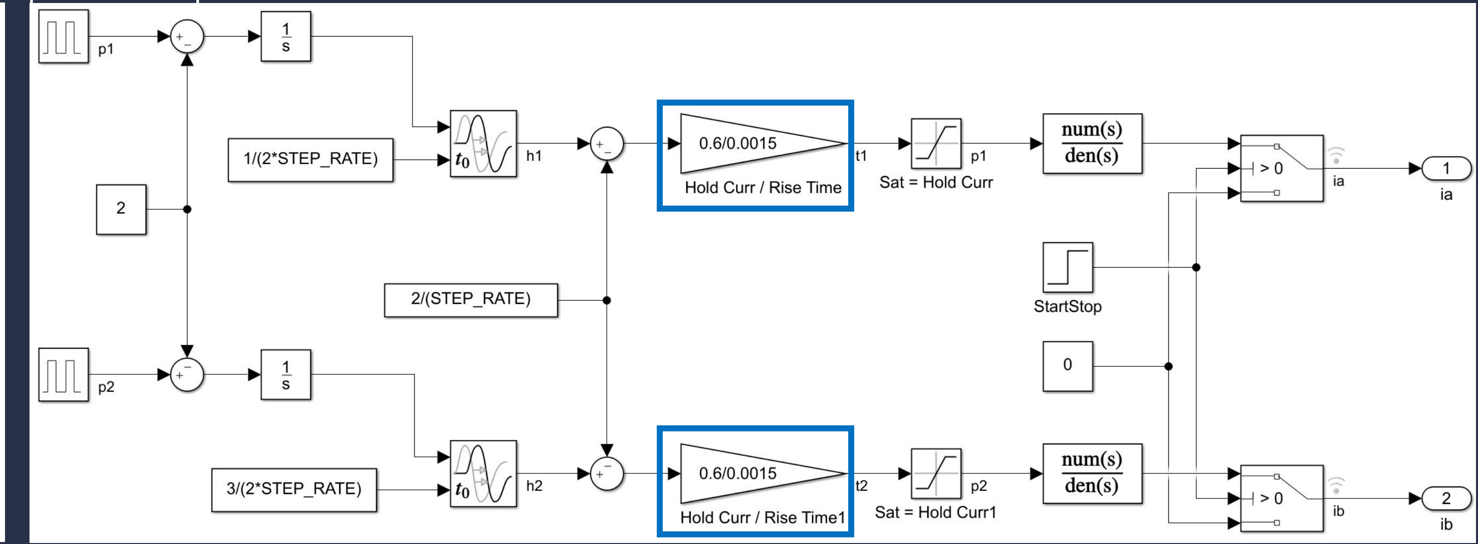
Model adaptation - *Electrical*

- Phase current was measured and ramp behavior observed
- Modeled as a clipped triangular wave

measurement



model



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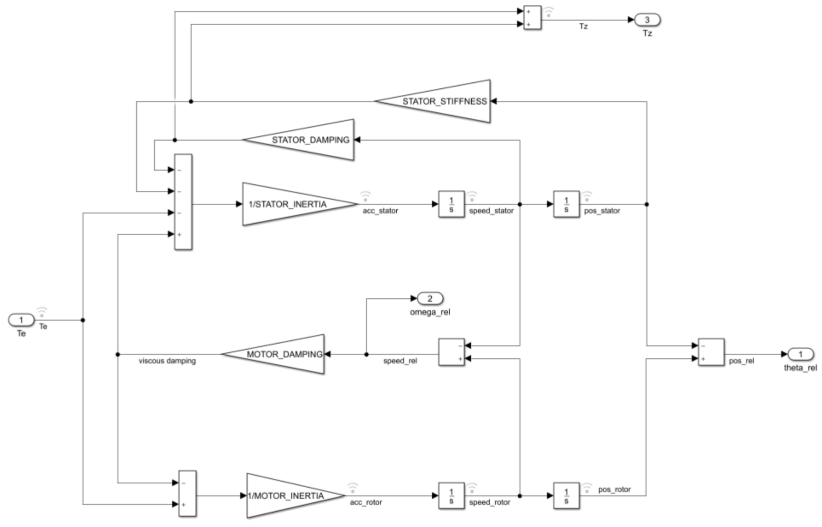
Model adaptation - *Mechanical*

- Introduction of stator dynamics (in addition to rotor dynamics)

$$J_S\ddot{\theta}_S = -T_e + C_R(\dot{\theta}_R - \dot{\theta}_S) - K_S\theta_S - C_S\dot{\theta}_S$$

$$J_R\ddot{\theta}_R = T_e - C_R(\dot{\theta}_R - \dot{\theta}_S)$$

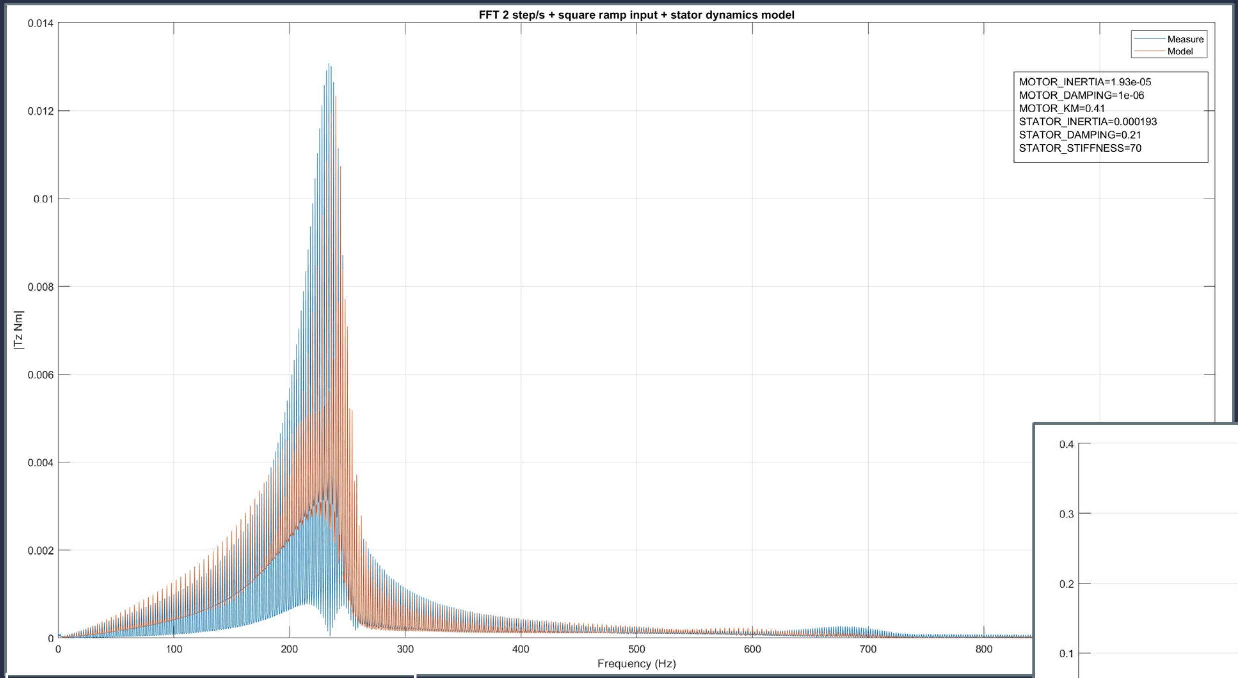


- Introduction of exported forces model (rotating unbalance)

$$F_x = M_R\left(\dot{\theta}_R^2\, cos(x + \varphi) + \ddot{\theta}_R\, sin(x + \varphi)\right)$$

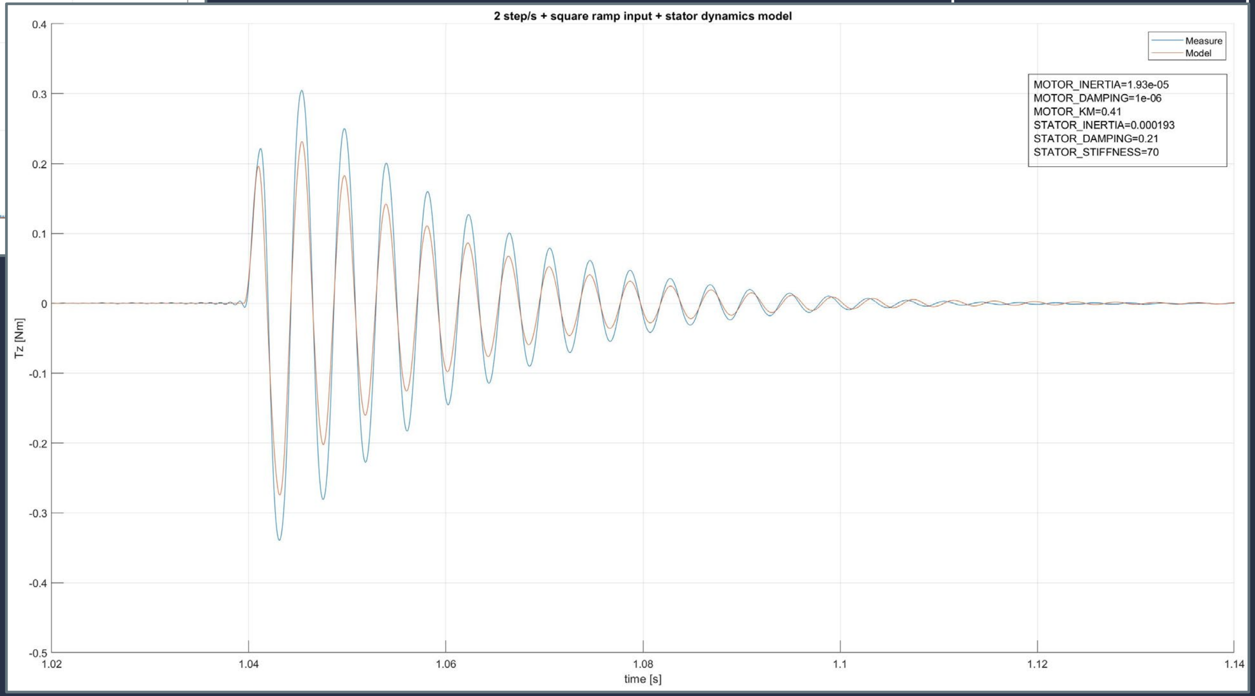
$$F_y = M_R\left(\dot{\theta}_R^2\, sin(x + \varphi) + \ddot{\theta}_R\, cos(x + \varphi)\right)$$

Results – *Torque*



Frequency domain

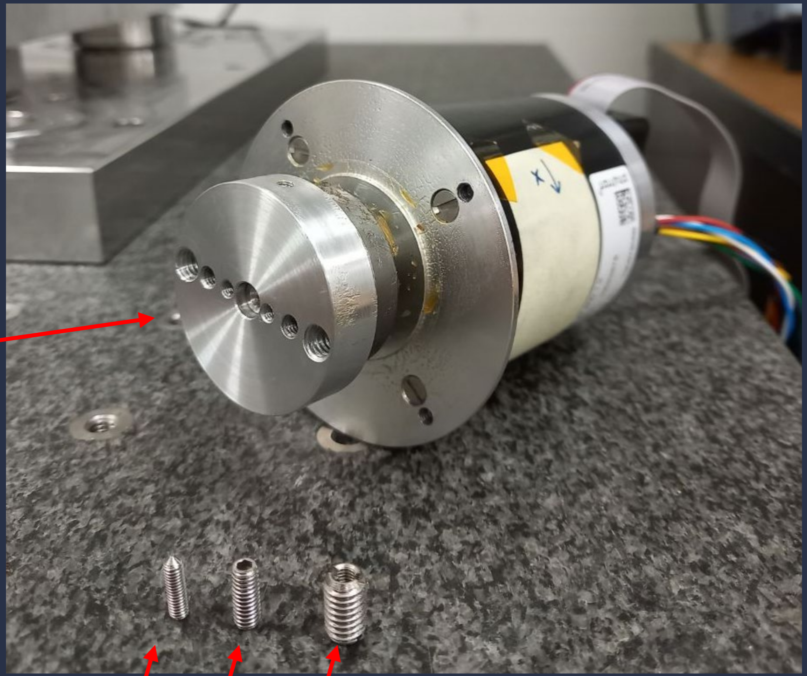
Time domain



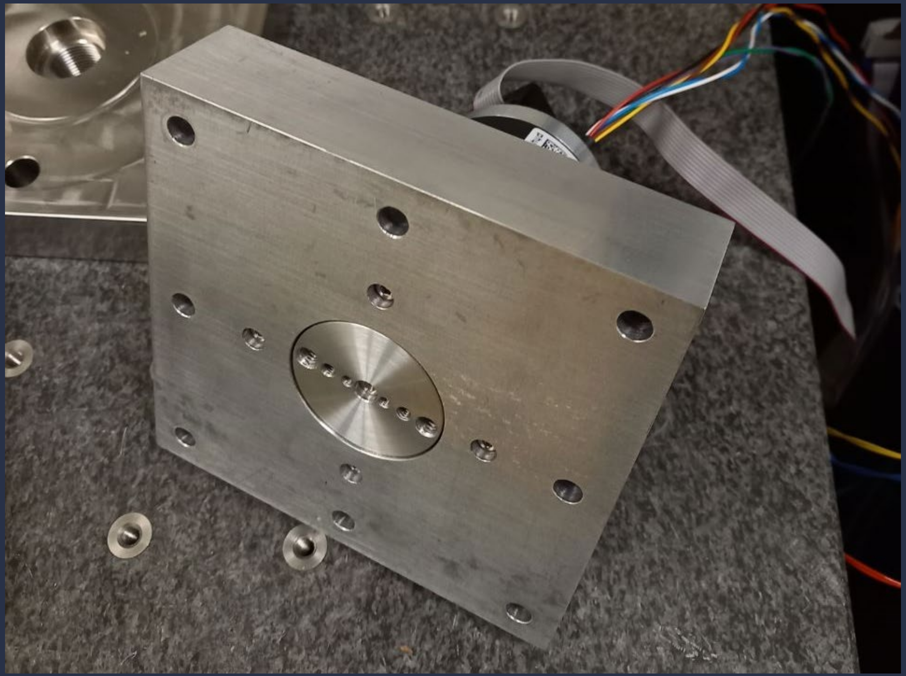
Results – *Forces*

- Measurement of controlled rotating unbalance (using screws of varying mass at varying distances from SM axis)

balanced disc

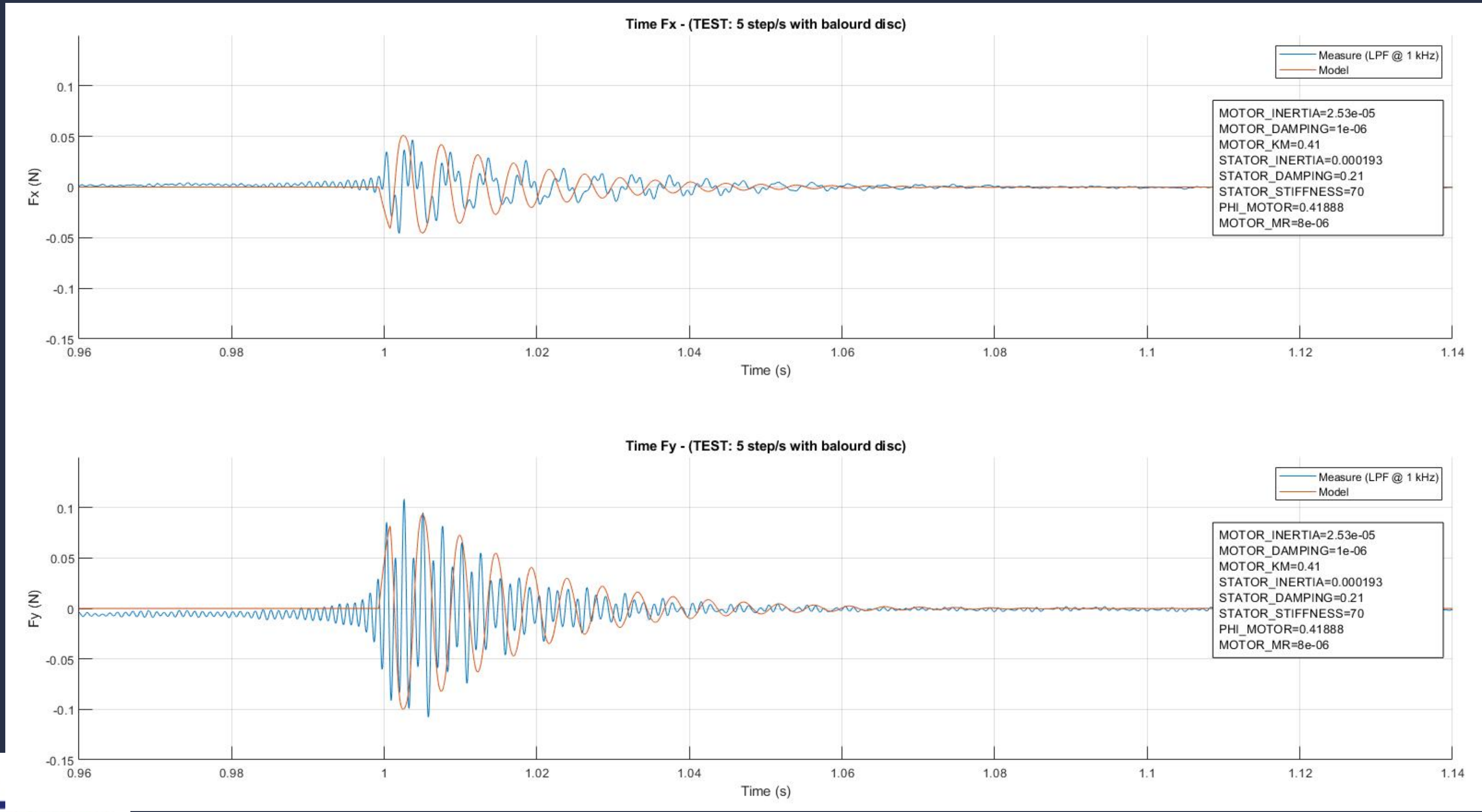


M3 *M4* *M6*



Results – *Forces*

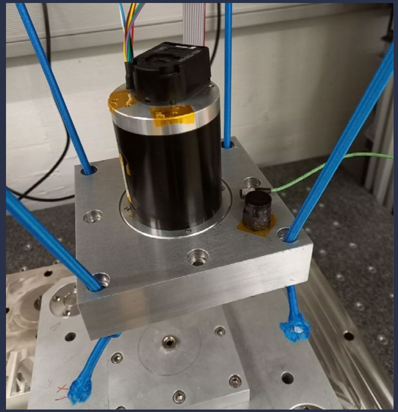
- As the higher modes are unaccounted for in the model, correlation of the model to the measured data is imprecise
- Parameters optimised for torque were kept unchanged and parameters related to rotating unbalance (*phi_motor* and *motor_mr*) were optimised



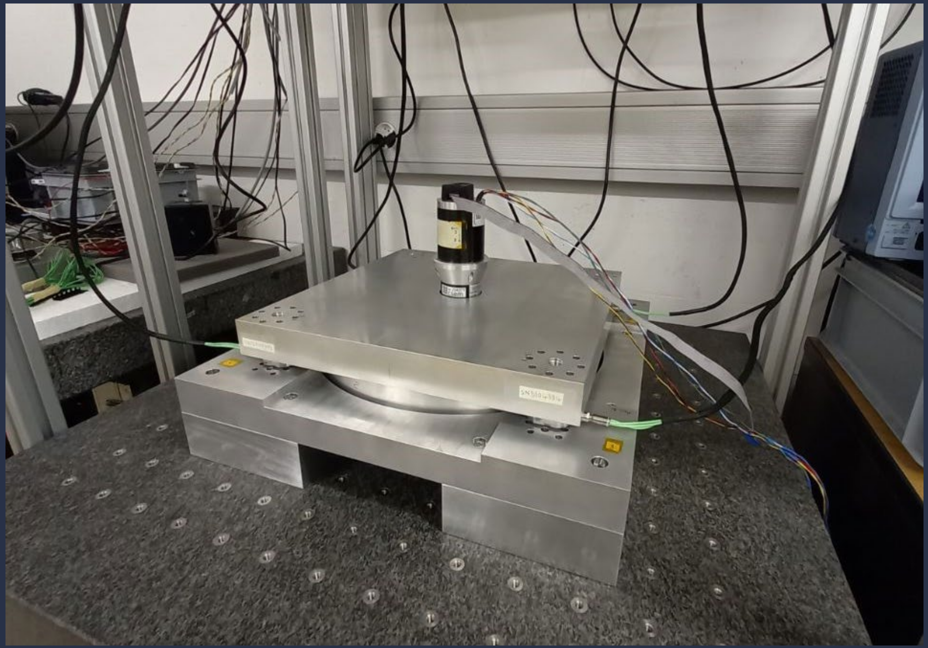
Summary of Tests

- *Torque model:* in both time and frequency (up to 1 kHz) domains, correlates well
- *Forces model:* in time domain, envelope correlates well
- *Forces model:* in frequency domain, correlates well at low frequencies

suspension test



full system with small inertia



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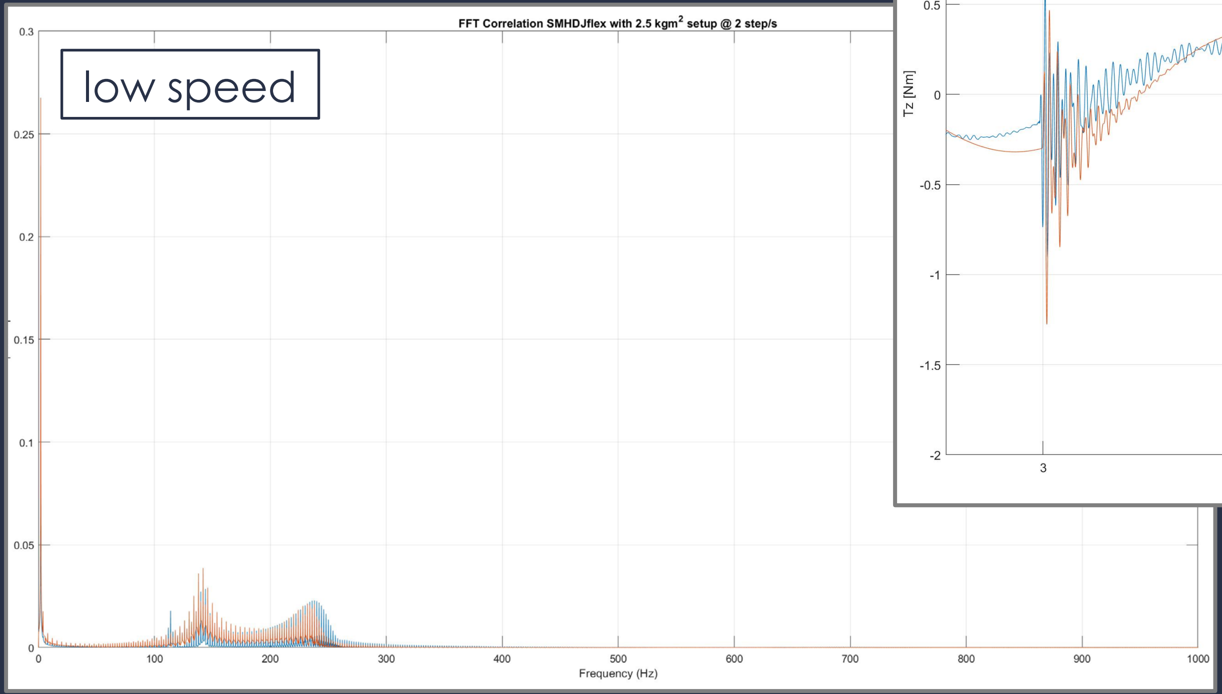
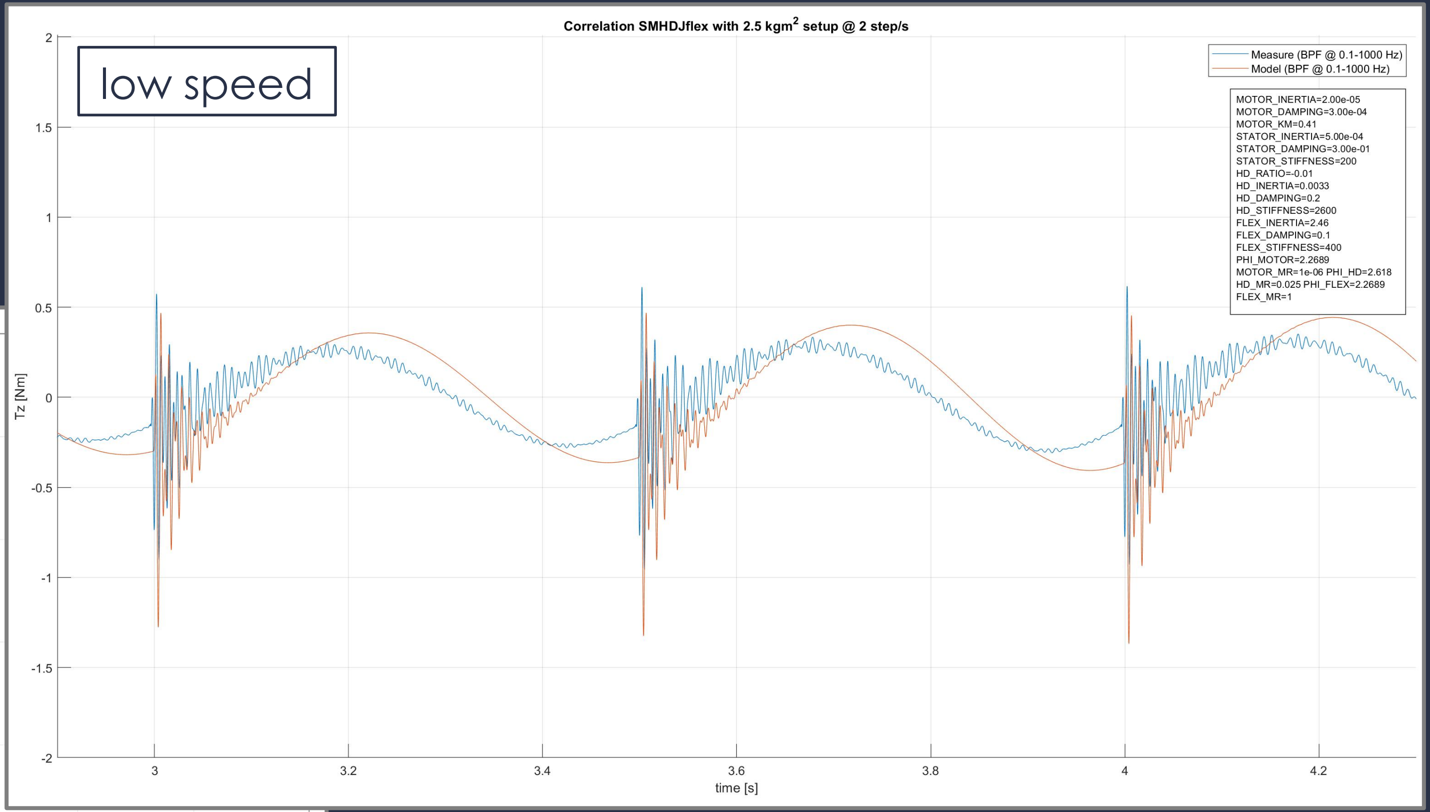
Stepper motor

Correlation: primary torque Tz (test bench #3)

FULL SYSTEM:
- with harmonic drive
- with load (large)

- *Measurement in **blue***
- *Model in **orange***





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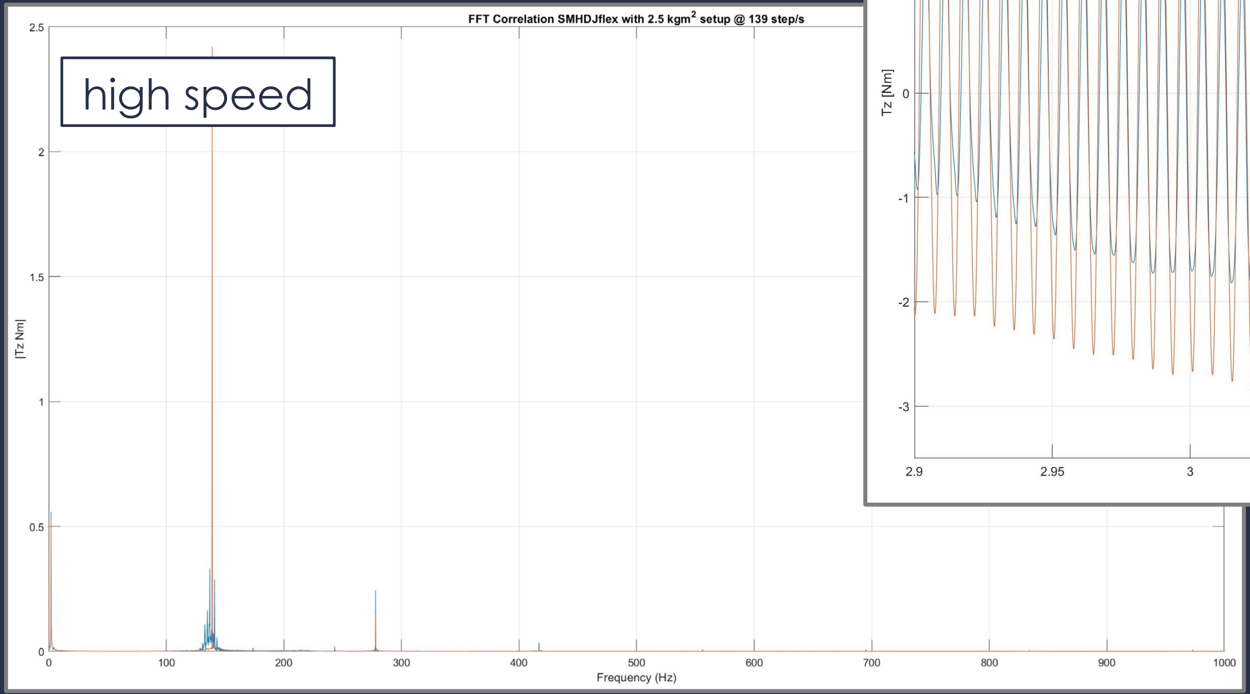
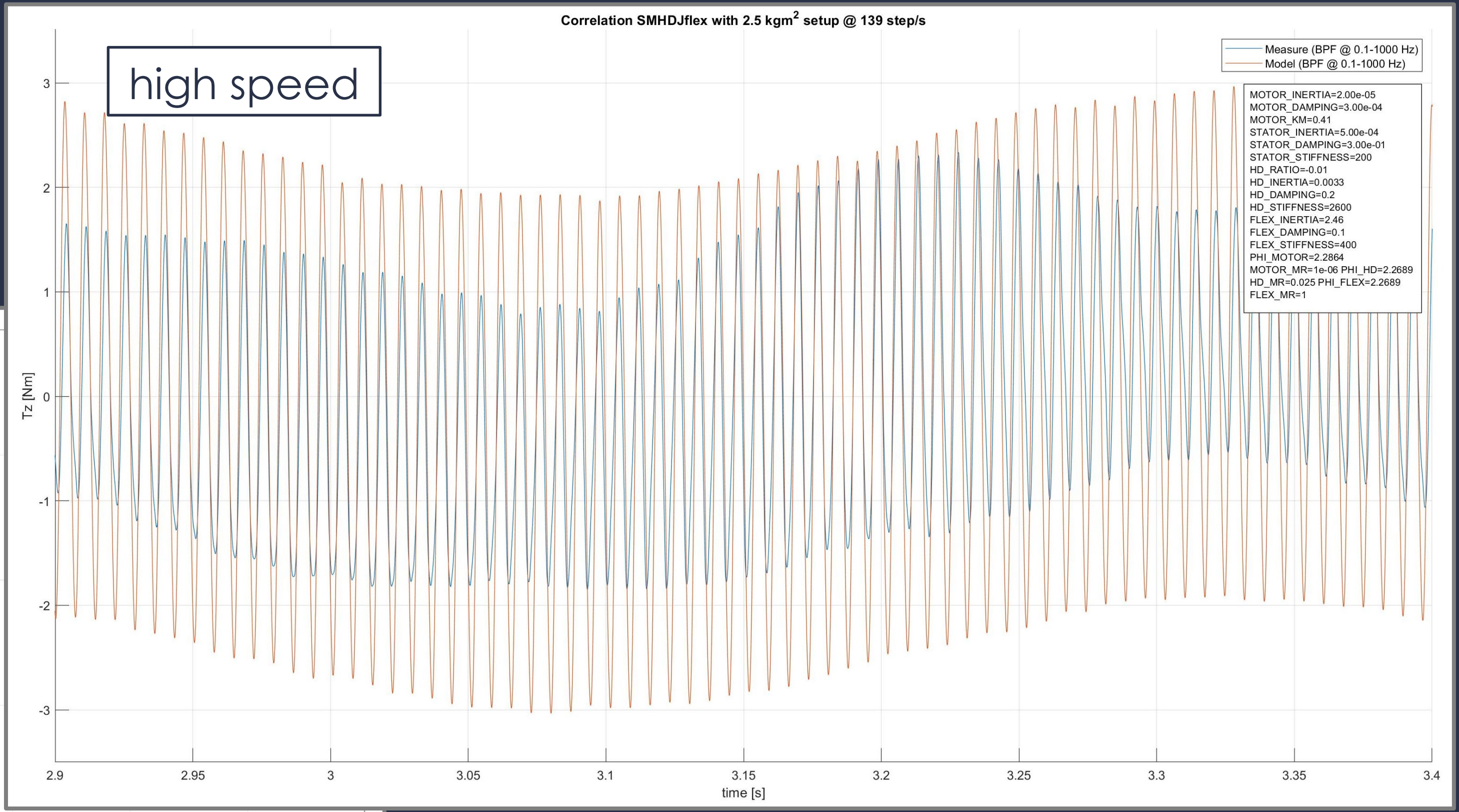




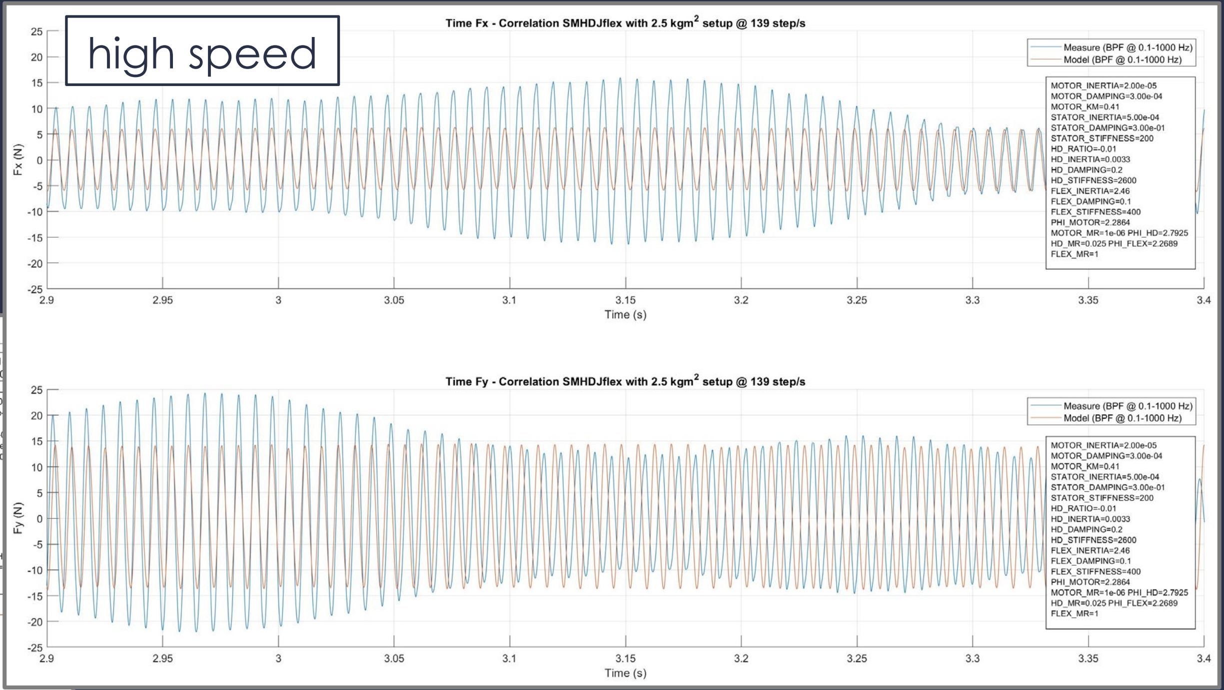
csem THALES

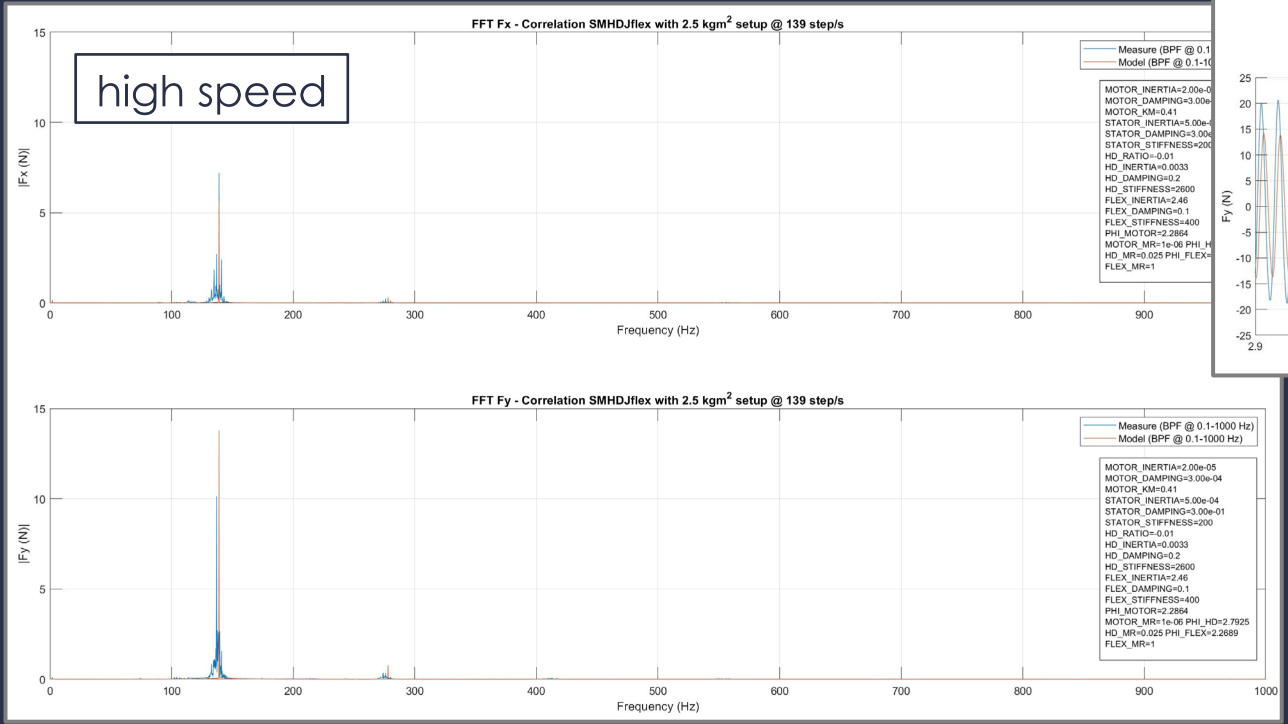
Stepper motor

Correlation: lateral forces Fx & Fy (test bench #3)

FULL SYSTEM:
- with harmonic drive
- with load (large)

- *Measurement in* ***blue***
- *Model in* ***orange***





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Stepper motor

Summary of Correlation Results

	Low speeds (<10 step/s)		High speeds (>60 step/s)	
	Torque	Forces	Torque	Forces
Test Bench #1 (only SM)	***Good***	***OK***	***Good***	***OK***
Test Bench #2 (SM+HD+J_{small})	***Good***	***OK***	***OK***	***Unsatisfactory***
Test Bench #3 (SM+HD+J_{large})	***Good***	***OK***	***OK***	***Unsatisfactory***

- *Torque correlation generally good, degrading with increasing speed and system complexity*
- *Force correlation generally OK degrading with increasing speed and system complexity*

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Conclusion & lessons learnt 1/2

- Extensive test campaign has been carried out to better understand sources of microvibration from stepper motor + harmonic drive + inertia system, whose dynamics are akin to those of a SADM

- Detailed development of multi-DoF Simulink model to predict exported microvibrations, specifically primary torque Tz and lateral forces Fx & Fy

- Correlation of model to measurements has been challenging, with error in results generally growing with increasing system complexity and step rate

- Seemingly simple system much more complex beneath the surface

Conclusion 2/2

- In the frame of micro vibration predictions, the key element is to be able to simulate acceleration and displacement of sensitive elements like telescope.
- **Globally the results match the overall tendency, but details are not captured**
- Results are generally better along Z axis
  - The structure of the telescope and the iridium case are “simpler” in the Z direction, meaning less poles and more accurate FEM explaining the slightly better prediction.
- Results show that uncorrelated FEM (not in the scope of the activity) gives only a first valid idea of micro vibration prediction with resonance frequencies most of the time off by more than 100 Hz.
- **The general idea seems promising but shall be restricted to simpler structure where a FEM correlation can be performed or used only for rough estimates.**

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Prediction in the time domain

- Task : to develop a methodology to reduce considered structure FEM model
  - Use of the CBN method of NASTRAN, subcontract to Almatech
- There is two different foreseen strategies (see Perez, J. A et al. “"Flexible Multibody System Linear Modeling for Control Using Component Modes Synthesis and Double-Port Approach “, 2016):

All in one model

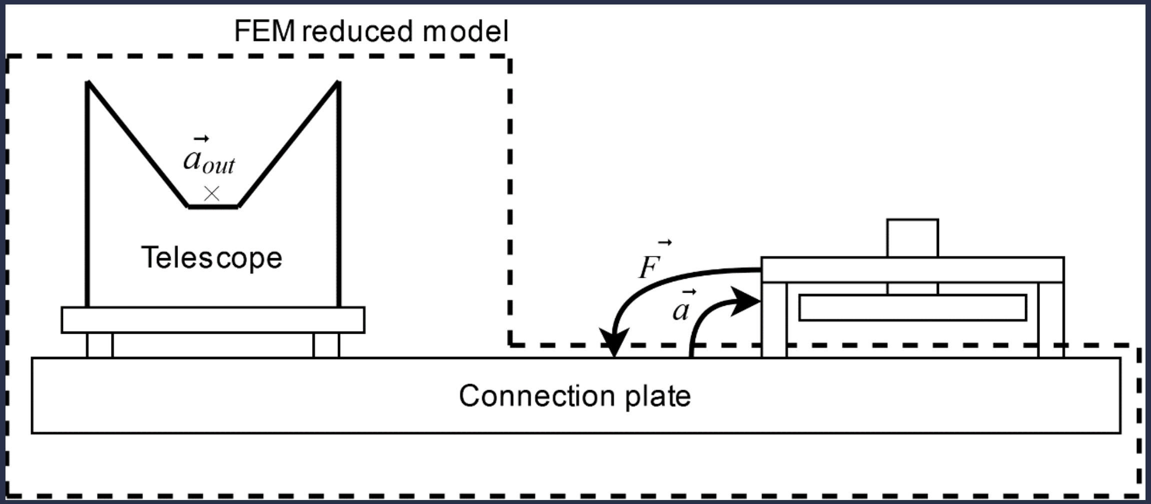
- Adding the connection plate to the telescope FEM, then performing modal reduction.
- Attachment (fixed boundary) point is the stepper and cryo cooler interfaces
- Inputs are forces
- Output point is the telescope mirror
- The output is acceleration

Dual part model

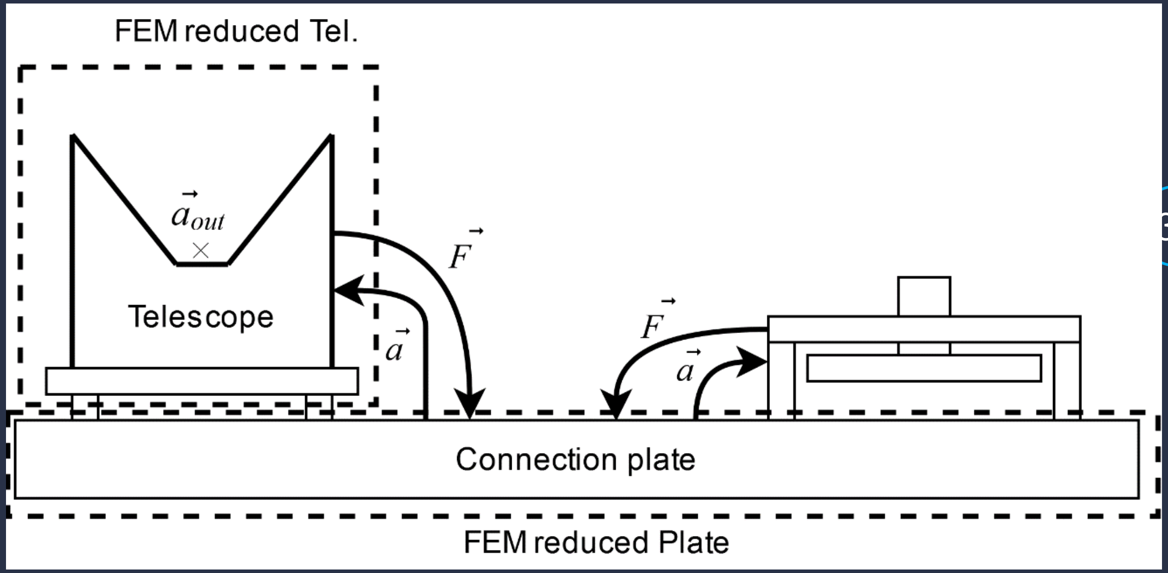
- Allows concatenating multiple elements.
- Telescope FEM is reduced alone with its defined attachments (fixed boundary). Input is acceleration at attach points, output is forces at attachment point and acceleration at mirror.
- The plate is reduced. Input is forces at attach (fixed boundary) points of stepper motor, cryo cooler and telescope, output is acceleration at attachment points.
- Full model is obtaining by connecting related I/O

Prediction in the time domain

- All in one model



- Dual part model



Prediction in the time domain– from FEM to state-space

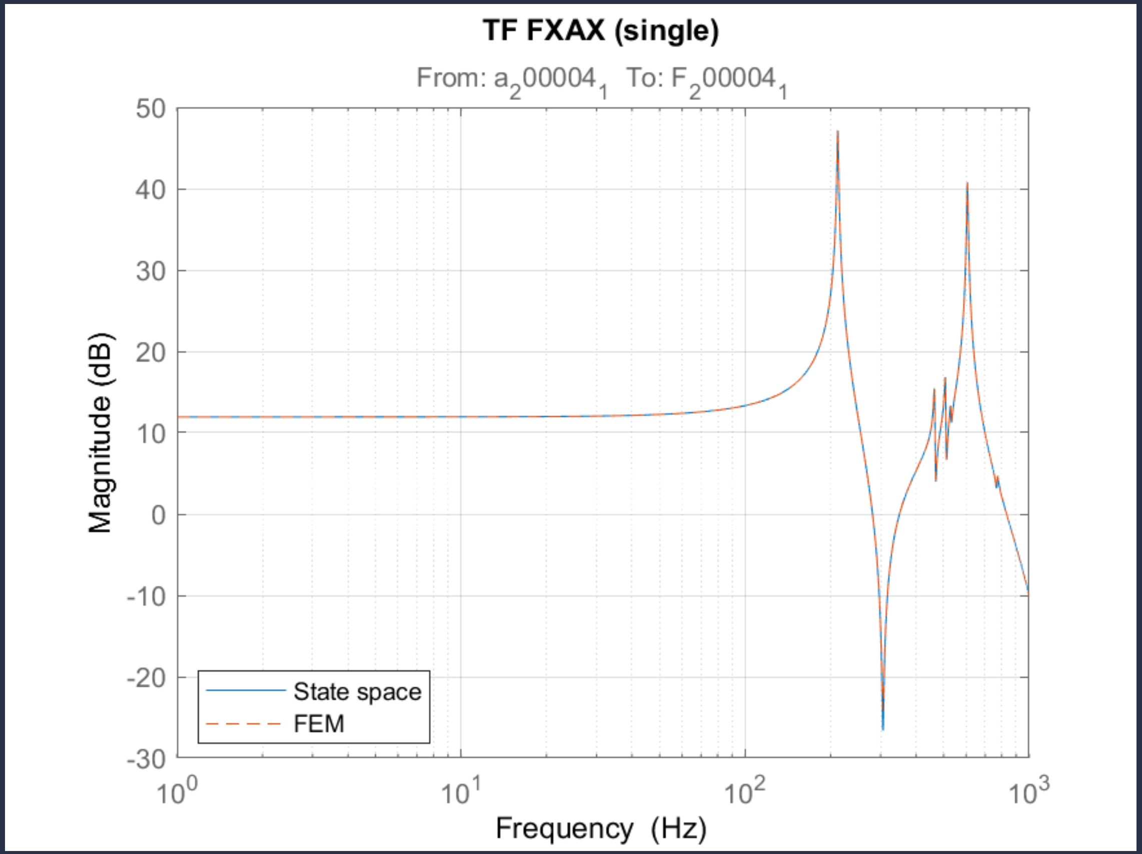
- From reduced model:

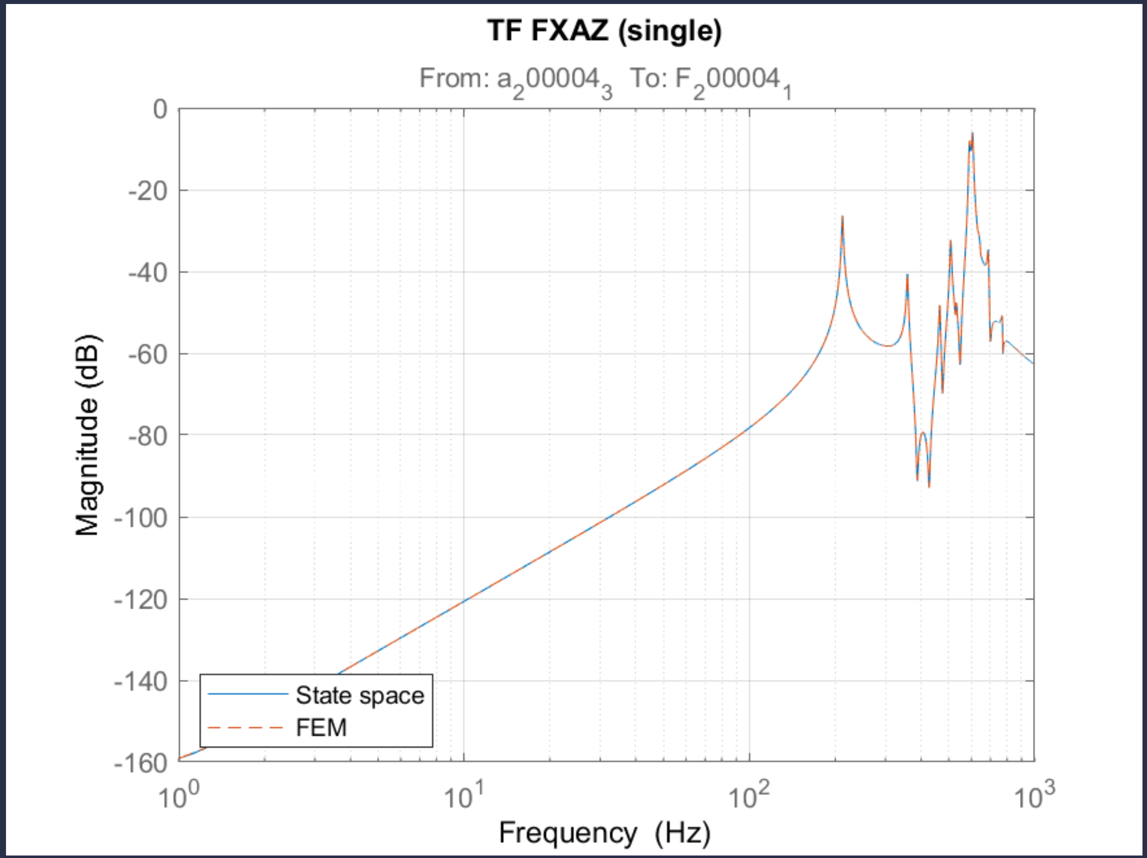
$$\underbrace{\begin{bmatrix} I_{nxn} & M_{qa} & M_{qb} \\ M_{aq} & M_{aa} & M_{ab} \\ M_{bq} & M_{ba} & M_{bb} \end{bmatrix}}_{M} \cdot \begin{bmatrix} \ddot{q} \\ \ddot{a} \\ \ddot{b} \end{bmatrix} + \underbrace{\begin{bmatrix} \omega^2 & 0 & 0 \\ 0 & K_{aa} & K_{ab} \\ 0 & K_{ba} & K_{bb} \end{bmatrix}}_{K} \cdot \begin{bmatrix} q \\ a \\ b \end{bmatrix} + \underbrace{\begin{bmatrix} 2\xi\omega & D_{qa} & D_{qb} \\ D_{aq} & D_{aa} & D_{ab} \\ D_{bq} & D_{ba} & D_{bb} \end{bmatrix}}_{KD} \cdot \begin{bmatrix} \dot{q} \\ \dot{a} \\ \dot{b} \end{bmatrix} = \begin{bmatrix} 0 \\ F_a \\ F_b \end{bmatrix}$$

- A state space is derived . Methodolgy summarized in TN3.2. 3 options studied
  - Single point – input acceleration at pt a, output forces at pt a
  - Dual port model Substructure connected to 2 structures via 1 connection point each
  - Fixed free
- To check the state space model, transfer function are compared with transfer function obtained from the full FEM model.
- The eigenvalues of the obtained state space A matrix shall be negative.

Single point model forces

From feet acceleration to feet exported forces





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Prediction in the time domain– from FEM to state-space (PM16)

- To Implement the effect of the source (stepper and cryo cooler), two terms are needed the forces & torques from the model and a set of forces and torques due to the imported acceleration (*F* is used as a vector of forces and torques):
- $F = F_{model} + F_{acc}(a)$
- If modeling ran into problems it is also possible to directly use measurements
- $F = F_{meas} + F_{acc}(a)$
- As no specific modeling of $F_{acc}(a)$ is foreseen, the following model is used:
- $F_{acc}(a) = \begin{bmatrix} 1 & 0 & 0 & 0 & ao_z & -ao_y \\ 0 & 1 & 0 & -ao_z & 0 & ao_x \\ 0 & 0 & 1 & ao_y & -ao_x & 0 \end{bmatrix} \cdot \vec{a}$

with $\overrightarrow{ao}$ being the vector from attachment point to COG of the stepper or cryo cooler.

(translation / r

Prediction in the time domain damping (PM17)

- Difference between structural and viscous damping

Structural	Viscous
$F_{D\ Struct.} = G \cdot K \cdot \cos(\omega \cdot t)$	$F_{D\ Visc.} = D \cdot \omega \cdot \cos(\omega \cdot t)$

- Usually FEM states damping as structural damping as (i stands f imaginery part):
- $M \cdot \ddot{x} = -K(1 + i \cdot G) \cdot x + F$
- With this formulation it leads to a state space of the form:

$$\begin{bmatrix} \dot{a} \\ \ddot{a} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \frac{-K(1+iG)}{M} & 0 \end{bmatrix} \begin{bmatrix} a \\ \dot{a} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{F_a}{M} \end{bmatrix}$$

Whose eigenvalues are:

- $s_1 = -a + ib$
- $s_2 = a - ib$

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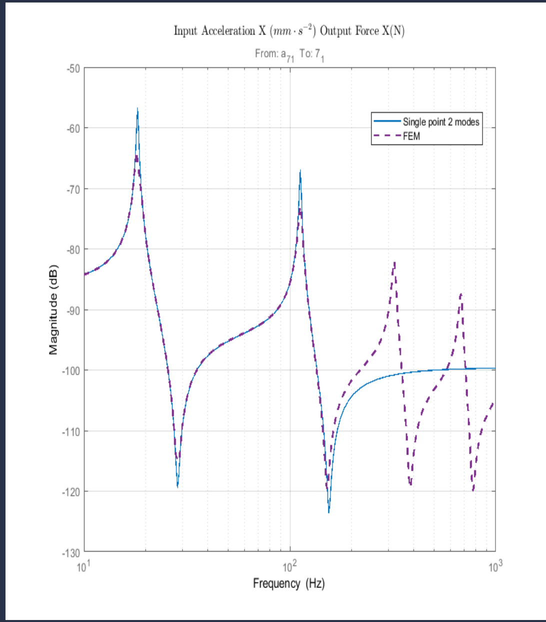
Prediction in the time domain damping

- As one of the eigen values has a positive real part, the time domain response is unbounded
- A solution is needed
  - If the damping matrix is diagonal ie with a single point reduced Newton:
  - $$\underbrace{\begin{bmatrix} E_{nxn} & M_{qa} \\ M_{aq} & M_{aa} \end{bmatrix}}_{M} \cdot \begin{bmatrix} \ddot{q} \\ \ddot{a} \end{bmatrix} + \underbrace{\begin{bmatrix} \omega^2 & 0 \\ 0 & 0 \end{bmatrix}}_{K} \cdot \begin{bmatrix} q \\ a \end{bmatrix} + \underbrace{\begin{bmatrix} G\omega^2 & 0 \\ 0 & 0 \end{bmatrix}}_{D} \begin{bmatrix} \dot{q} \\ \dot{a} \end{bmatrix} = \begin{bmatrix} 0 \\ F_a \end{bmatrix}$$
  - D matrix is replaced by: $\underbrace{\begin{bmatrix} G \cdot \omega & 0 \\ 0 & 0 \end{bmatrix}}_{D}$ for viscous damping



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Agenda

- Project introduction, structure and organization – CSEM
- Stepper motor modelling and correlation – CSEM
- Cryo cooler motor modelling and correlation – TAS
- Time domain summation methodology – CSEM
- Frequency domain summation methodology– TAS
- Test results - CSEM / TAS
- Conclusions

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Improve

- Final test:
  - Main goal, validate the whole chain:
    - (Source model) replaced by shaker
    - Propagation model
    - Telescope model
- 3 step experiment consisting of:
  - Structure Only, iridium case
  - Structure + sensitive load (iridium case + DSS)
  - Structure + sensitive load (iridium case + DSS) with several perturbation sources in parallel
    - Mounting two shakers one at stepper location the other @ cryo location
    - A sum of sinuses was be injected on each shaker

Simplified testing techniques

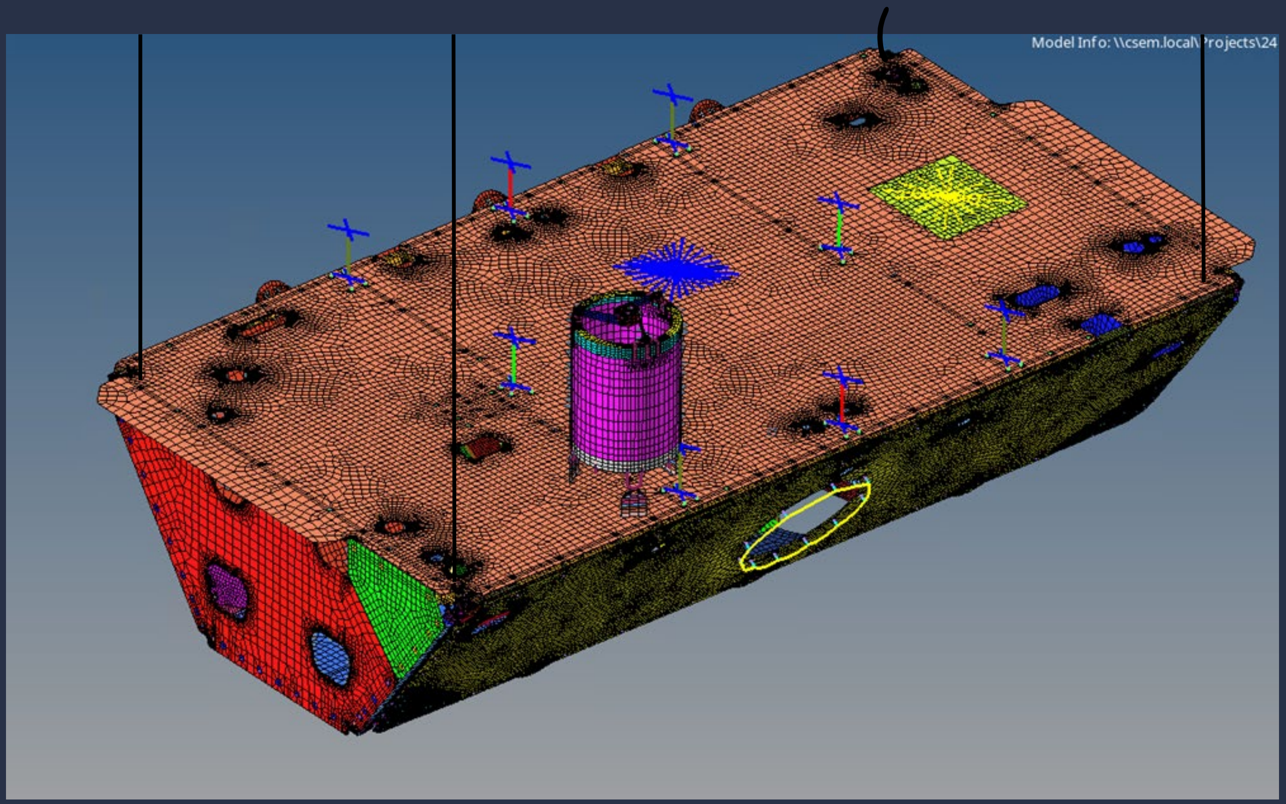
- Literature search has been performed on testing techniques
  - Almost everybody uses rigid mounting of setup on Kistler table
  - Whole setup being decoupled from ground through heavy marble and pneumatic dampers
  - There is one facility at Estec that uses active decoupling
    - Rising performance in the low frequency range
  - For more realistic reconstruction of exported forces a suspended test configuration is able to recover the dynamic mass contribution
    - Dynamic mass improve the computation of exported forces when couples to a structure.

Example of instrumentation

- Structure + DSS tests
  - Mounting a known perturbation source on stepper and cryo cooler location. (shaker)
  - Mounting force sensor between shaker and structure (TBC)
  - Mounting accelerometer @ Telescope primary and secondary mirrors
  - Measuring transfer function from source to telescope primary and secondary mirrors
    - Compare it with FEM reduced model
    - Transfer function measured will be from X,Y,Z to X,Y,Z (9 TF)
    - Transfer function involving rotation and torques won't be measured

Setup

- Irridium case suspended on hoisting lines to recreate a free free behaviour
- Acquisition system:
  - Accelerometers PCB 356
  - Force sensors Kistler
  - LMS acquisition platform



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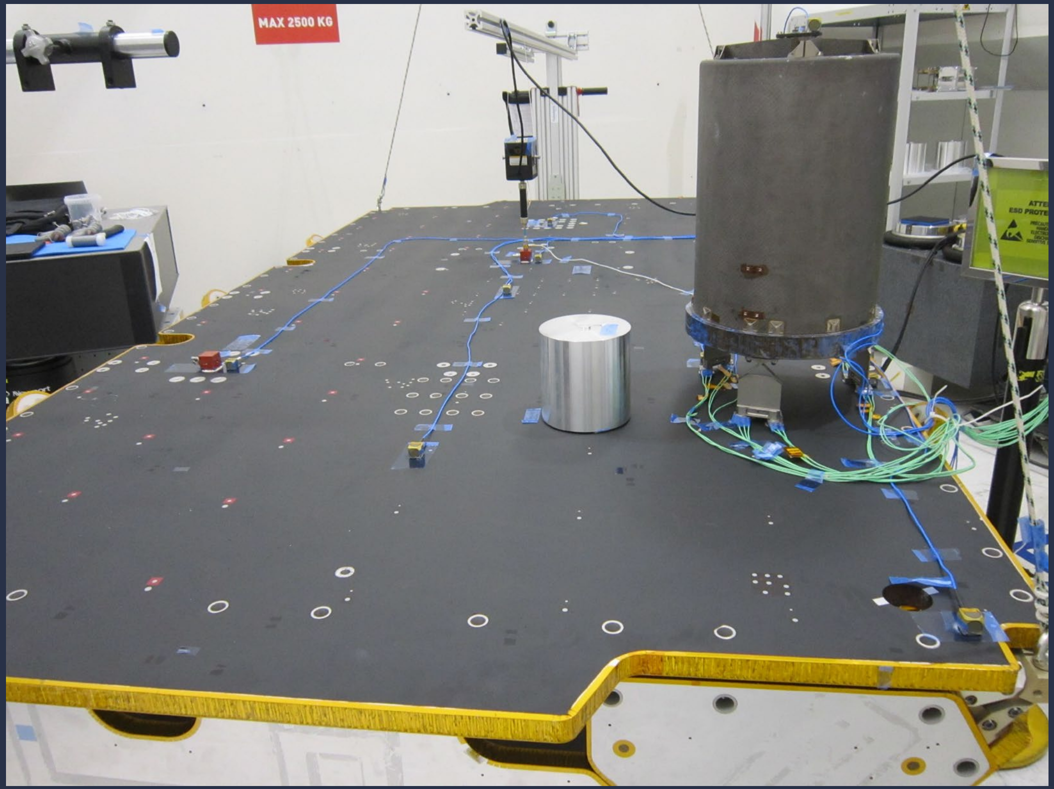
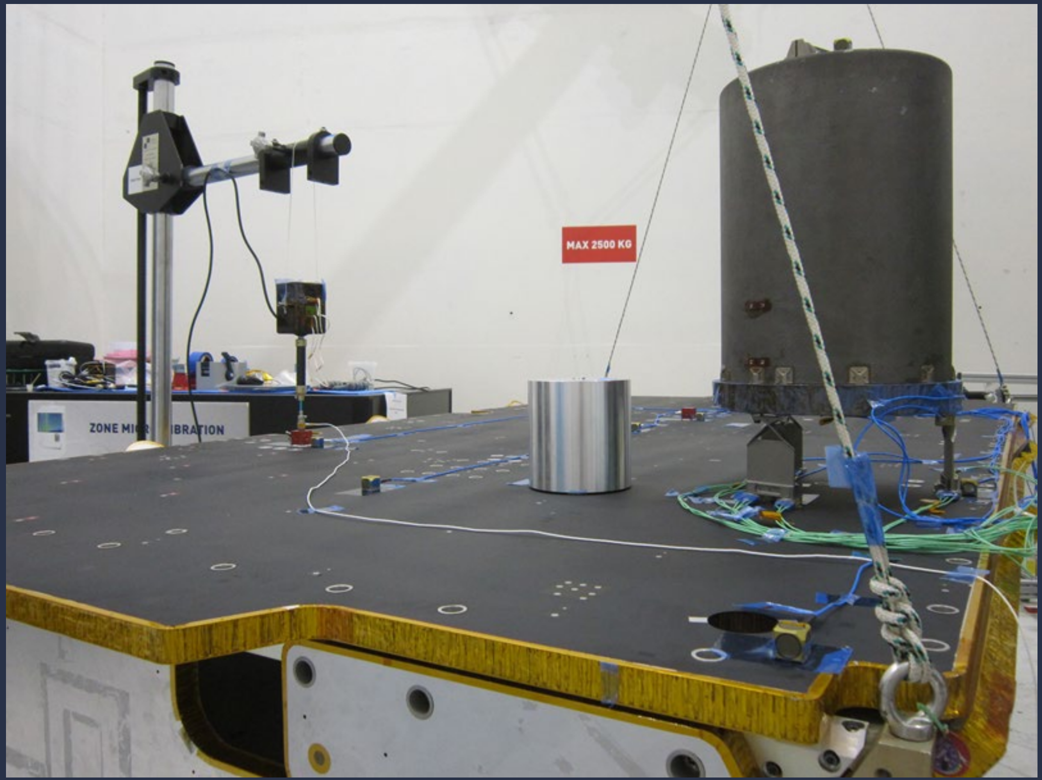
Setup

- Final tests

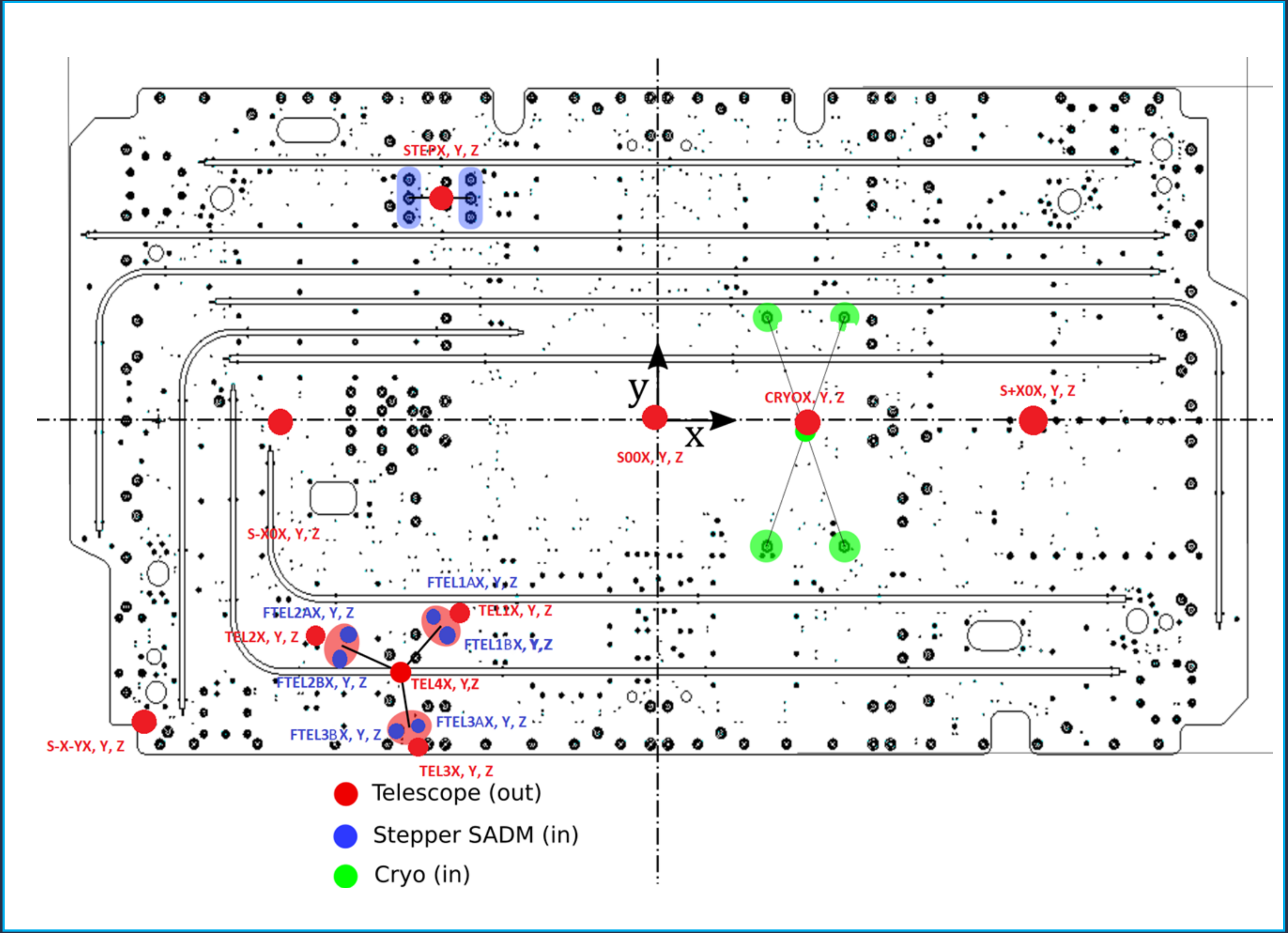




Final tests

Accelerometers locations

- Blue = Stepper (SADM)
- Green = cryocooler
- Red = DSS
- Telescope mounted with force sensor at interface with top panel



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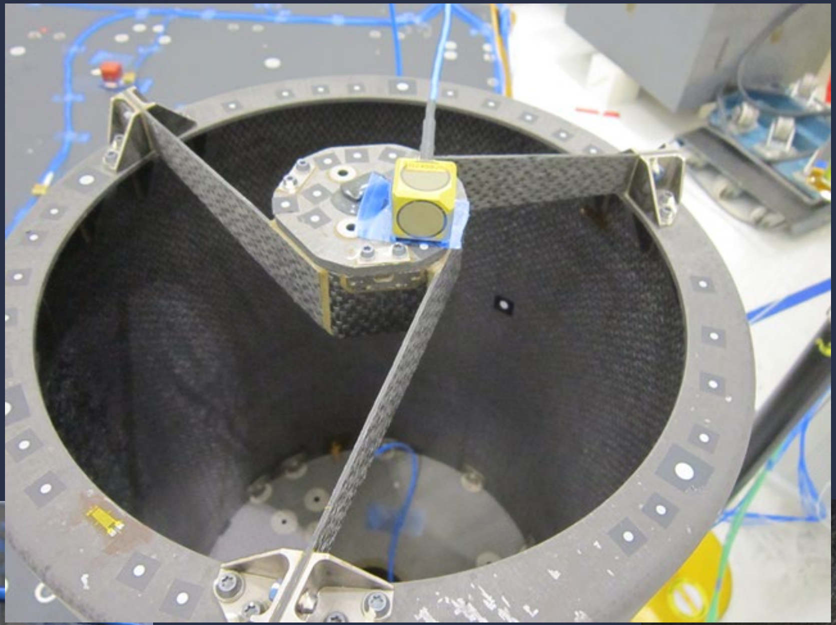
Accelerometers location telescope details

TEL4



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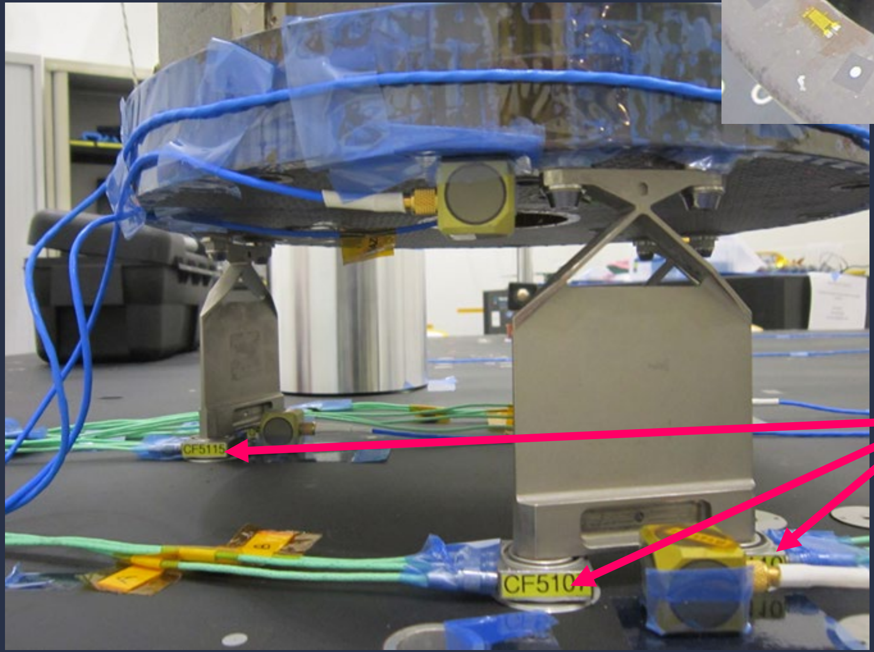
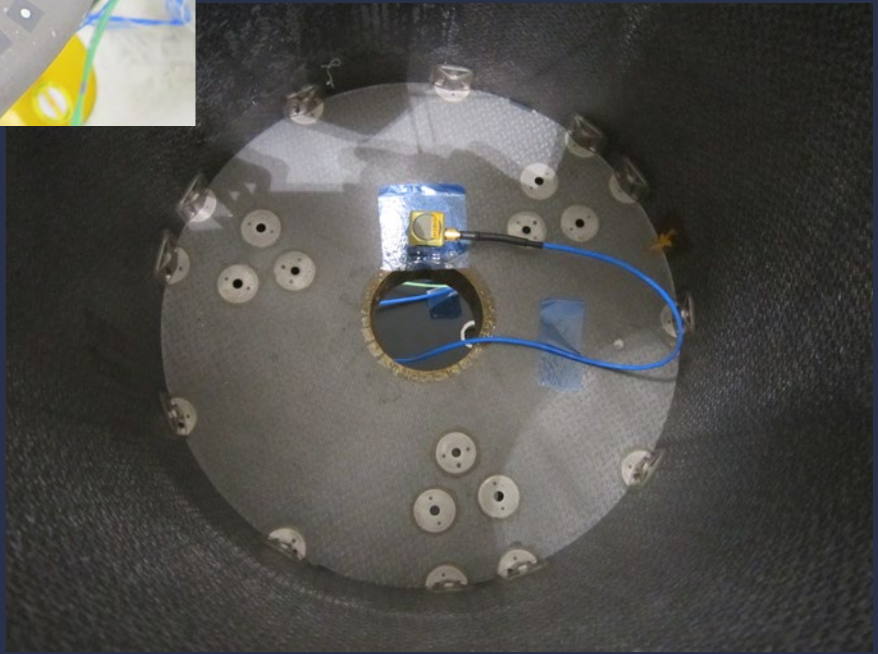


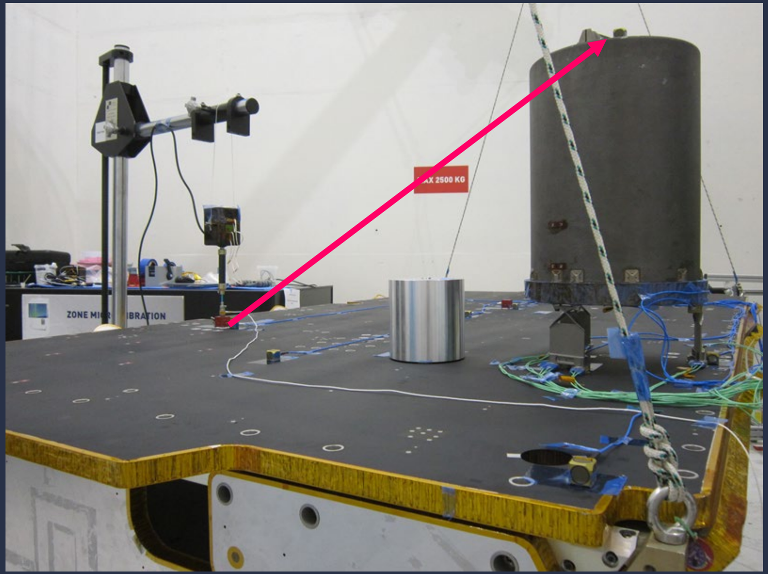
6*Force sensors

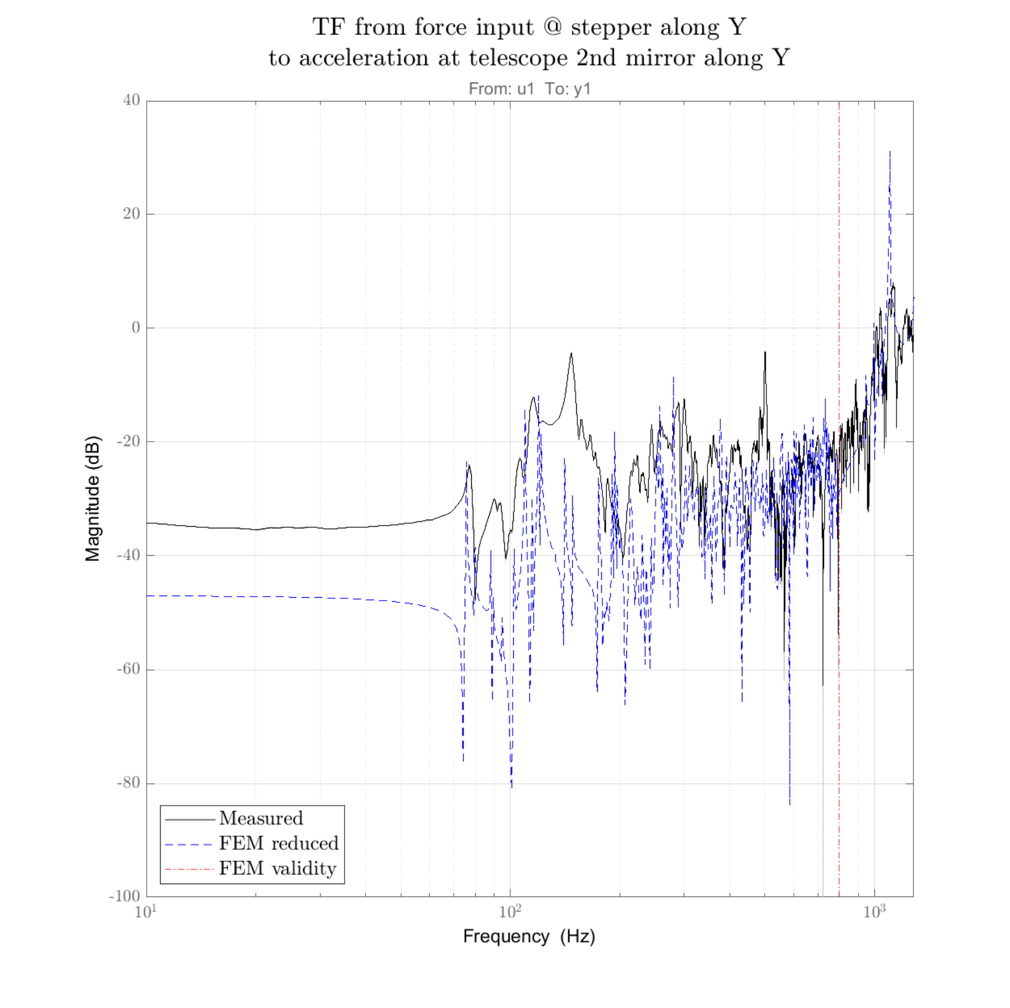
TEL5



Example: Structure + DSS

- From force at stepper location to acceleration at secondary mirror
- Axis Y





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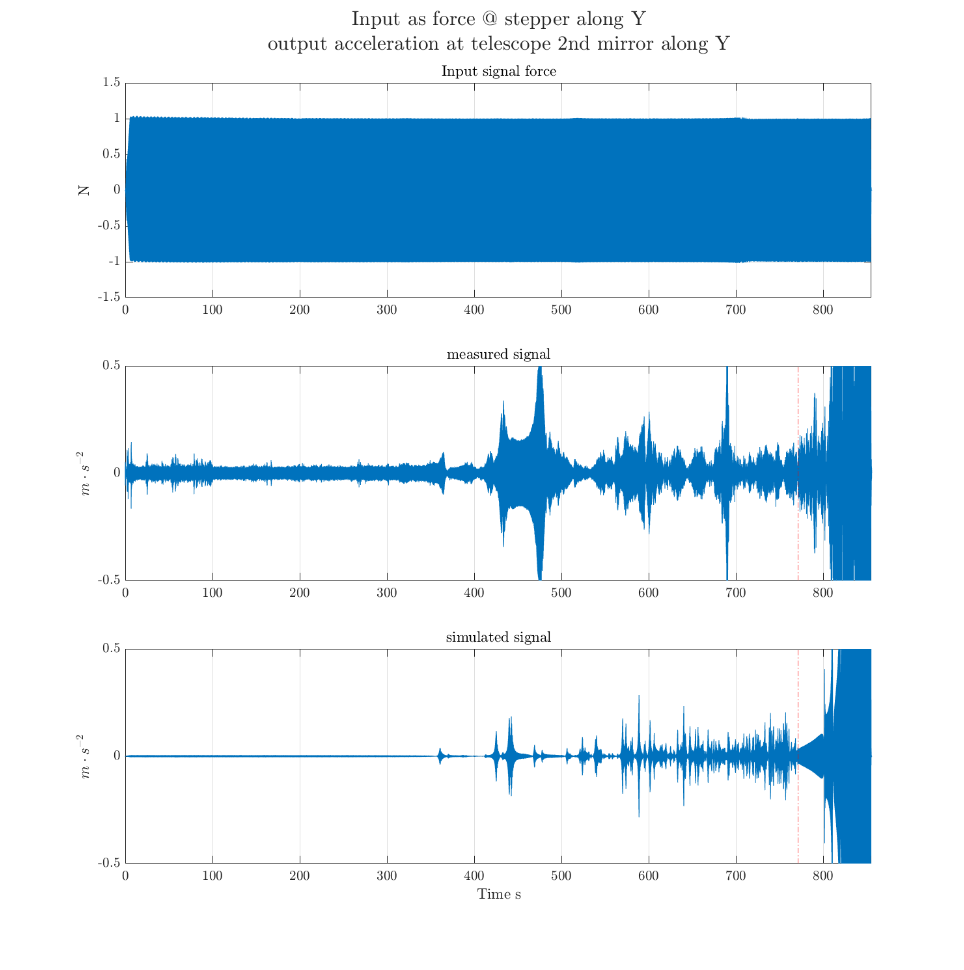
Example: Temporal domain with structure + DSS

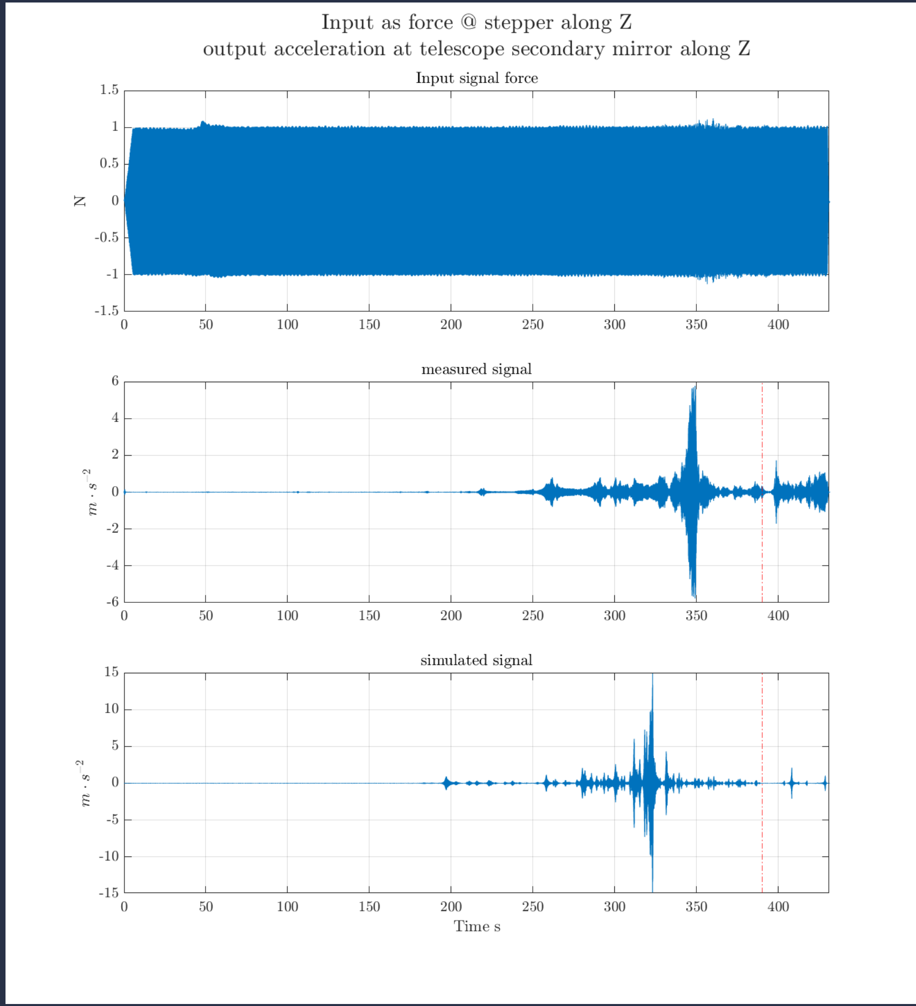
- From stepper force to 2nd ary mirror (input 1 N sinesweep 10 → 1280 Hz)



Y

Measure

Simulation



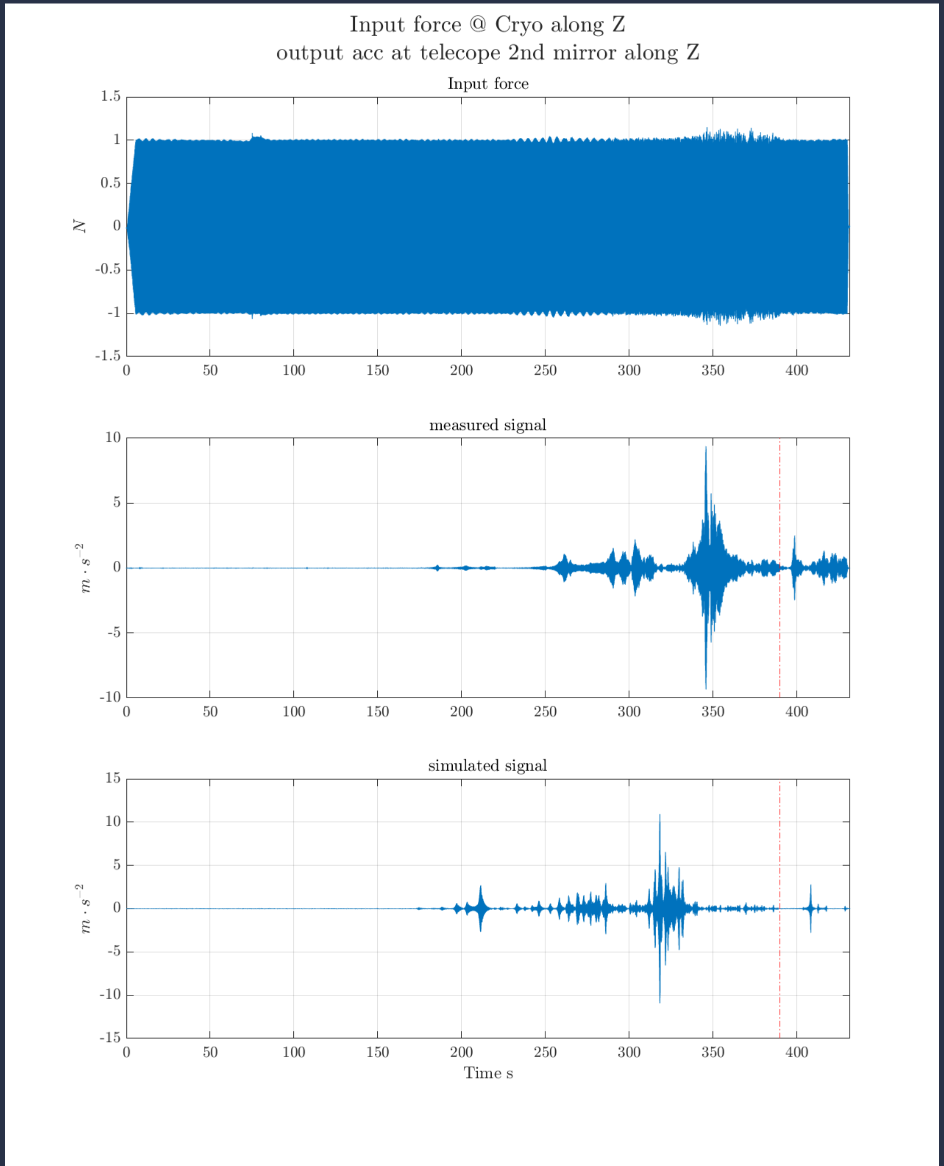
Z

Temporal domain with DSS (input 1 N sinesweep 10 → 1280 Hz)

- From Cryo force to 2nd ary mirror
- Z axis

Measure

Simulation



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Conclusion

- In the frame of micro vibration predictions, the key element is to be able to simulate acceleration and displacement of sensitive elements like telescope.
- **Globally the results match the overall tendency, but details are not captured**
- Results are generally better along Z axis
  - The structure of the telescope and the iridium case are "simpler" in the Z direction, meaning less poles and more accurate FEM explaining the slightly better prediction.
- Results show that uncorrelated FEM (not in the scope of the activity) gives only a first valid idea of micro vibration prediction with resonance frequencies most of the time off by more than 100 Hz.
- **The general idea seems promising but shall be restricted to simpler structure where a FEM correlation can be performed or used only for rough estimates.**

Thank you for your attention!