Super-Attenuator Design Concept Integrating an Active Platform and an Inverted Pendulum

Thomas Giordano
Precision Mechatronics Laboratory

March 26, 2025

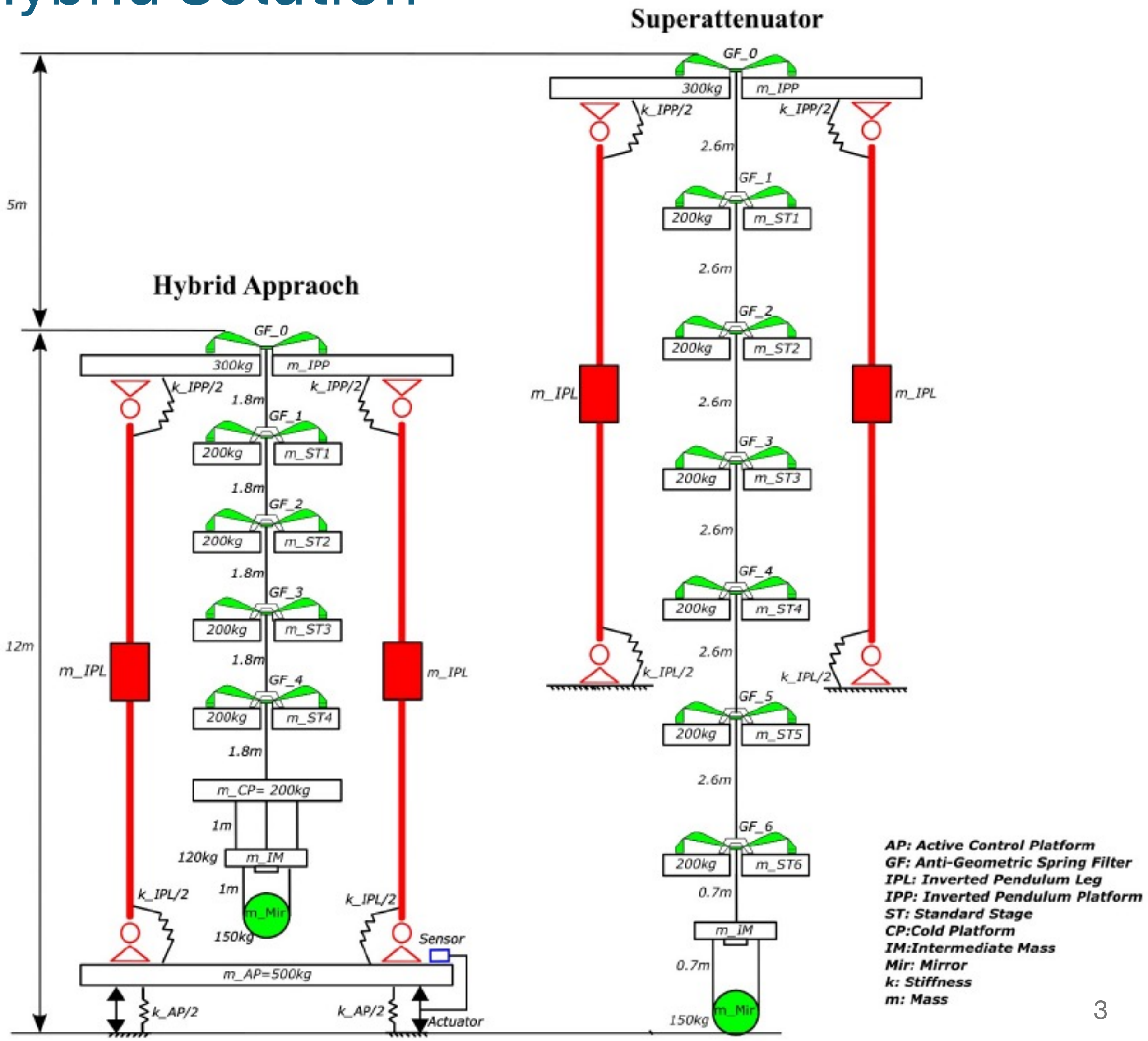
Contents

Introduction

From the 17m Superattenuator to a Hybrid Solution

Hybrid approach = fewer stages

Reduce height of attenuation chain

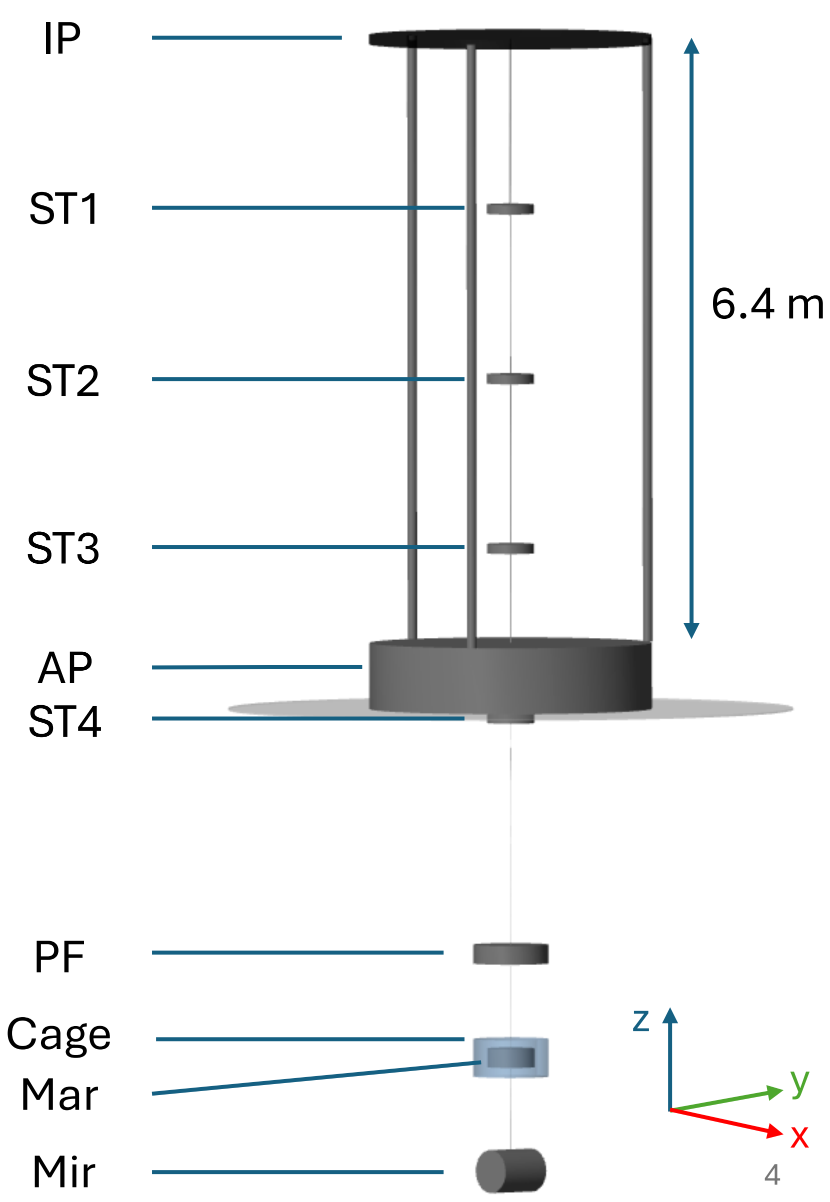


Model Overview

- Features
  - Integration of both an Active Platform (AP) and an Inverted Pendulum (IP)
  - Four additional stages (ST1 → ST4) between IP and PF
  - Functional height: 12 m

- Modeling Approach
  - Software: Simscape
  - Payload from Baseline Design with:
    - Single wire connecting two bodies, attached to CoM
    - Vertical stiffness computed for the correct number of wires
    - Motivated by the development of an analytical model

      → Easier to consider all wires at CoM



Model Parameters

Optimization of Masses and Lengths of Suspension Chain

- Find the optimal length and mass of ST1 → ST4 to minimize longitudinal transmissibility (T2100287)

- Fixed parameters:

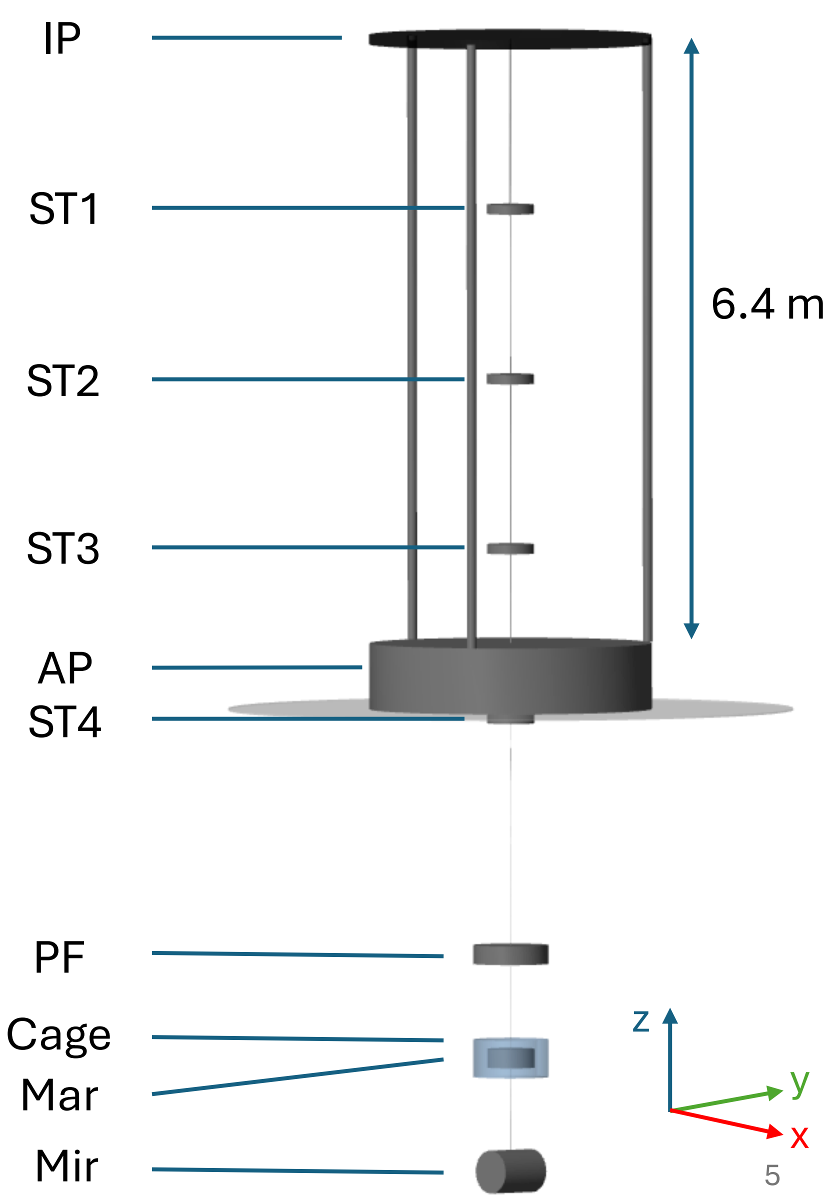
  - $l_{\mathrm{ST4-PF}} = 2.5$ m
  - $l_{\mathrm{PF-Cage}} = 0.9$ m
  - $l_{\mathrm{PF-Mar}} = 1.1$ m
  - $l_{\mathrm{Mar-Mir}} = 1.2$ m
  - $m_{\mathrm{PF}} = 300\ \mathrm{kg}$
  - $m_{\mathrm{Cage}} = 200\ \mathrm{kg}$
  - $m_{\mathrm{Mar}} = 183\ \mathrm{kg}$
  - $m_{\mathrm{Mir}} = 183\ \mathrm{kg}$

- Geometric progression for masses:

$$m_n = (1-\rho)\rho^{n-1} M_{\mathrm{tot}}$$

$$\rho = \left(\frac{m_{\mathrm{PF}} + m_{\mathrm{Cage}} + m_{\mathrm{Mar}} + m_{\mathrm{Mir}}}{M_{\mathrm{tot}}}\right)^{\frac{1}{N-1}}$$

$$M_{\mathrm{tot}} = \sum_{n=1}^{N} m_n = 1900\ \mathrm{kg}$$



Model Parameters

- For lengths:

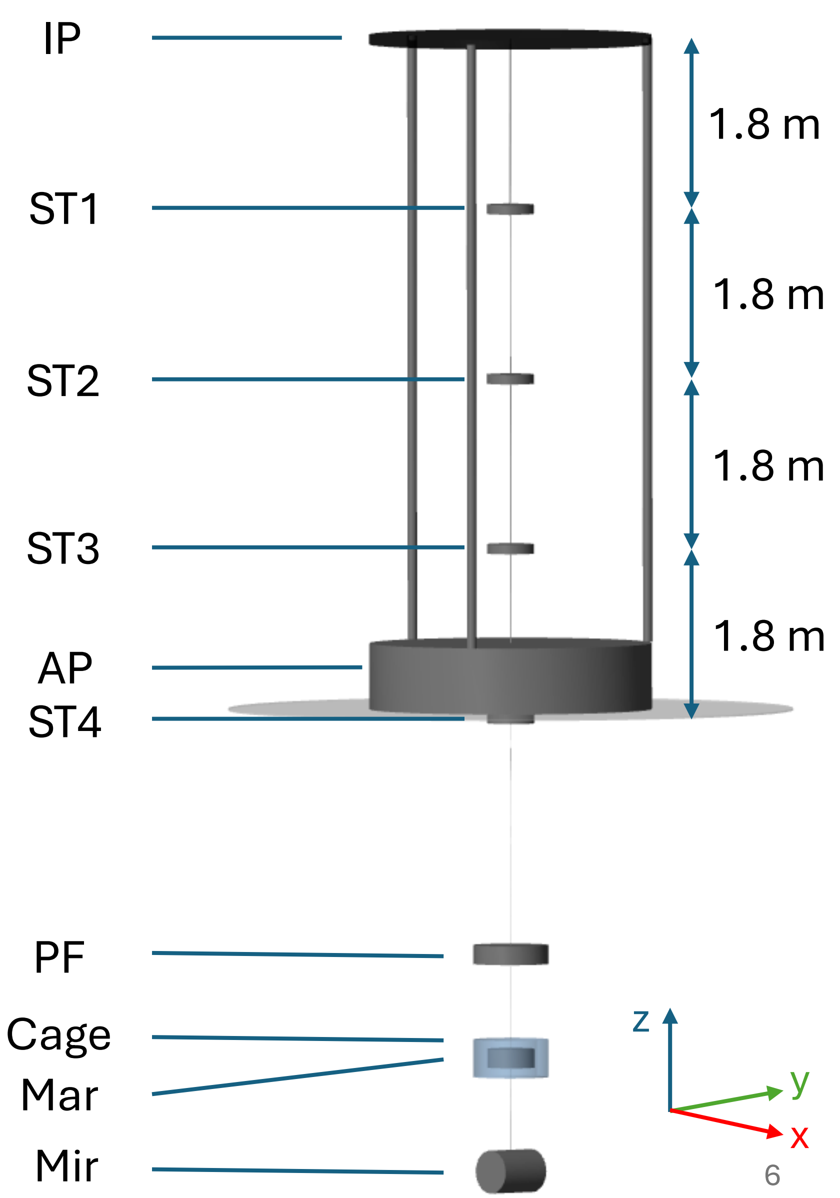
$$l_{\mathrm{IP-ST1}} = l_{\mathrm{ST1-ST2}} = l_{\mathrm{ST2-ST3}} = l_{\mathrm{ST3-ST4}}$$

$$= \frac{12 - l_{\mathrm{ST4-PF}} - l_{\mathrm{PF-Mar}} - l_{\mathrm{Mar-Mir}}}{4}$$

$$= \mathbf{1.8\ m}$$

Current masses and Inertias

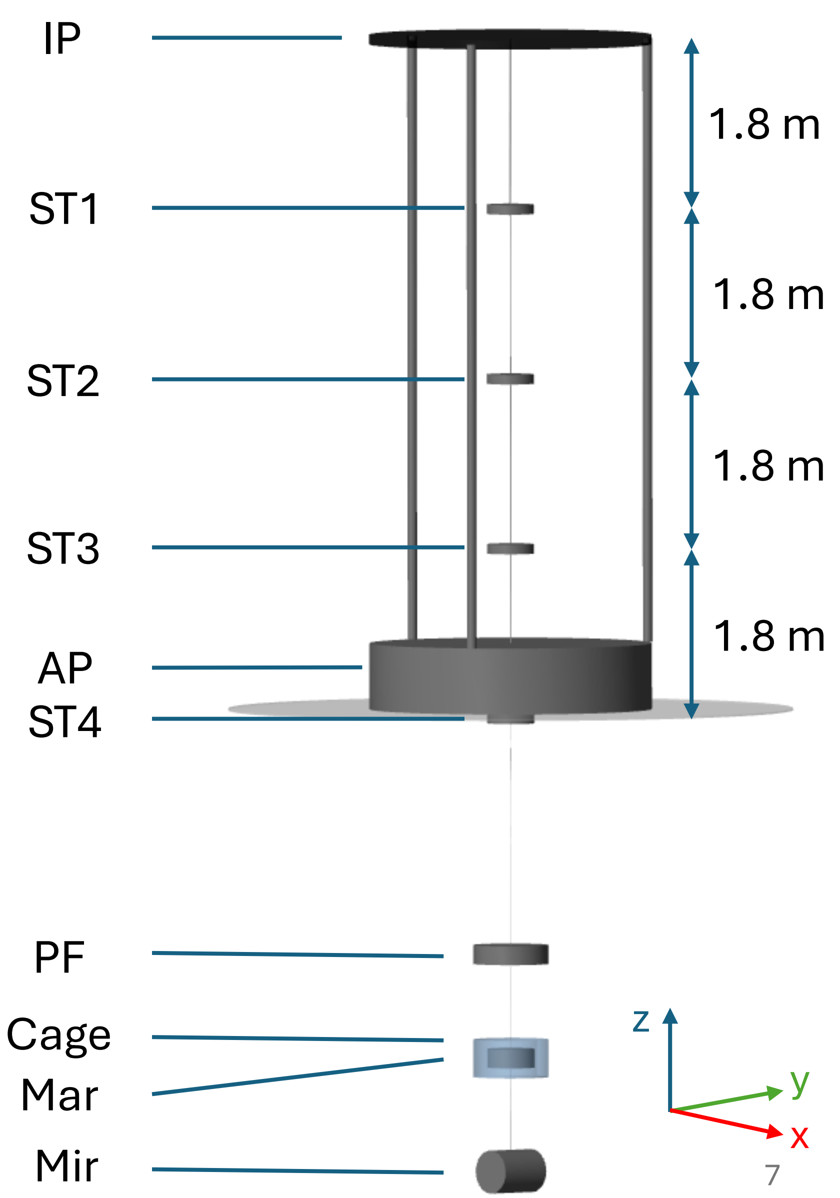
Body	Mass [kg]	I_{xx}, I_{yy} [kg m²]	I_{zz} [kg m²]
AP	2500	1508	2812
IP	500	282	562
ST1	339	5.6	10.6
ST2	278	4.6	8.7
ST3	229	3.8	7.2
ST4	188	3.1	5.9



Model Parameters

Stiffnesses of Different Elements

From Body	To wire/flexure	Anti-Spring	k_x, k_y [N/m]	k_z [N/m]	k_r [Nm/rad]
GND	GND - AP	no	10^5	10^5	$3 \cdot 10^5$
AP	AP - IP Legs	no	∞	∞	$6 \cdot 10^4$
IP Legs	IP Legs - IP	no	∞	∞	$6 \cdot 10^4$
IP	IP - ST1	yes	∞	10^3	10^{-3}
ST1	ST1 - ST2	yes	∞	10^3	10^{-3}
ST2	ST2 - ST3	yes	∞	10^3	10^{-3}
ST3	ST3 - ST4	yes	∞	10^3	10^{-3}
ST4	ST4 - PF	yes	∞	10^4	10^{-3}



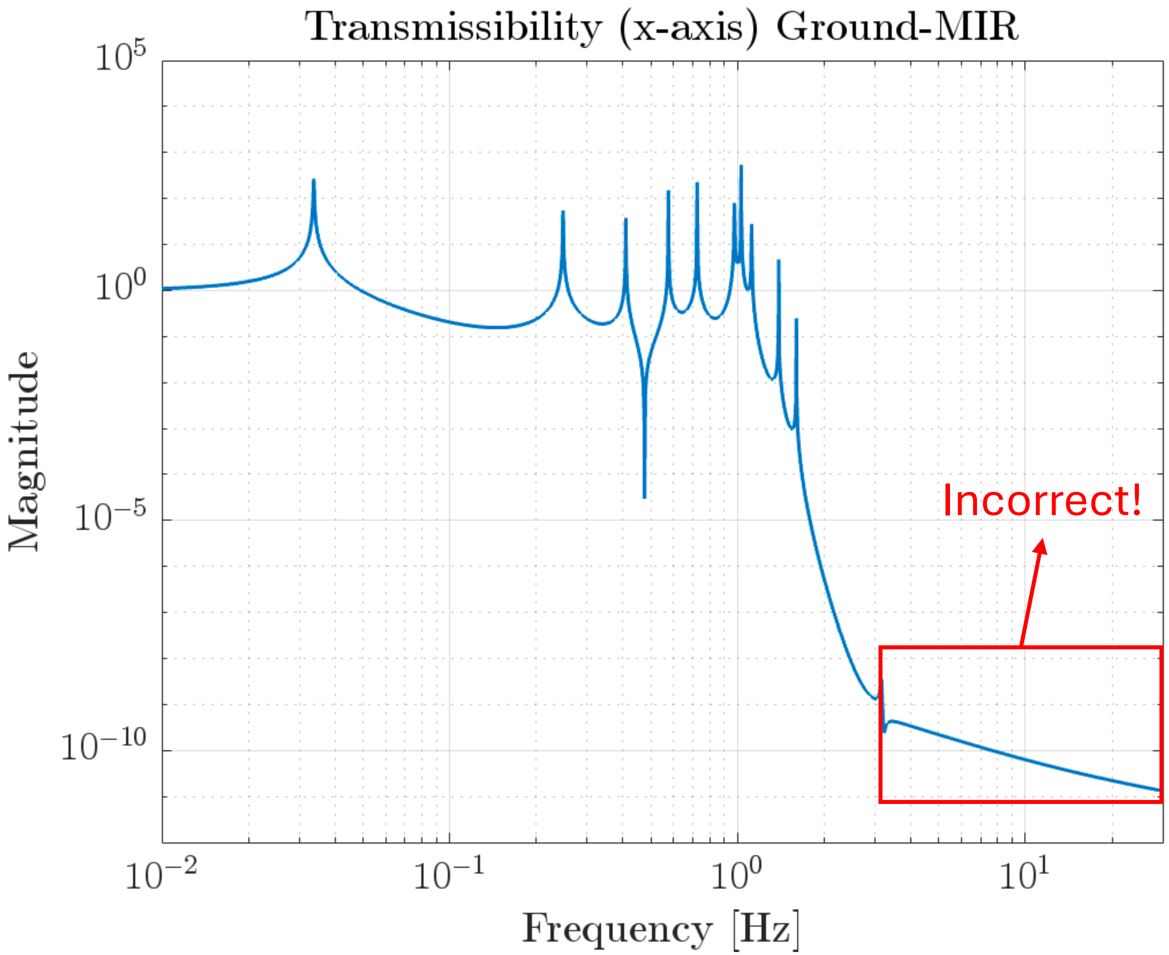
Linearization with Simscape

- For some reasons that we do not fully understand, the linearization of the simscape model introduces errors for $f > 2$ Hz
- Problems for closed-loops and strain requirements

→ Incorrect behaviour after 2 Hz

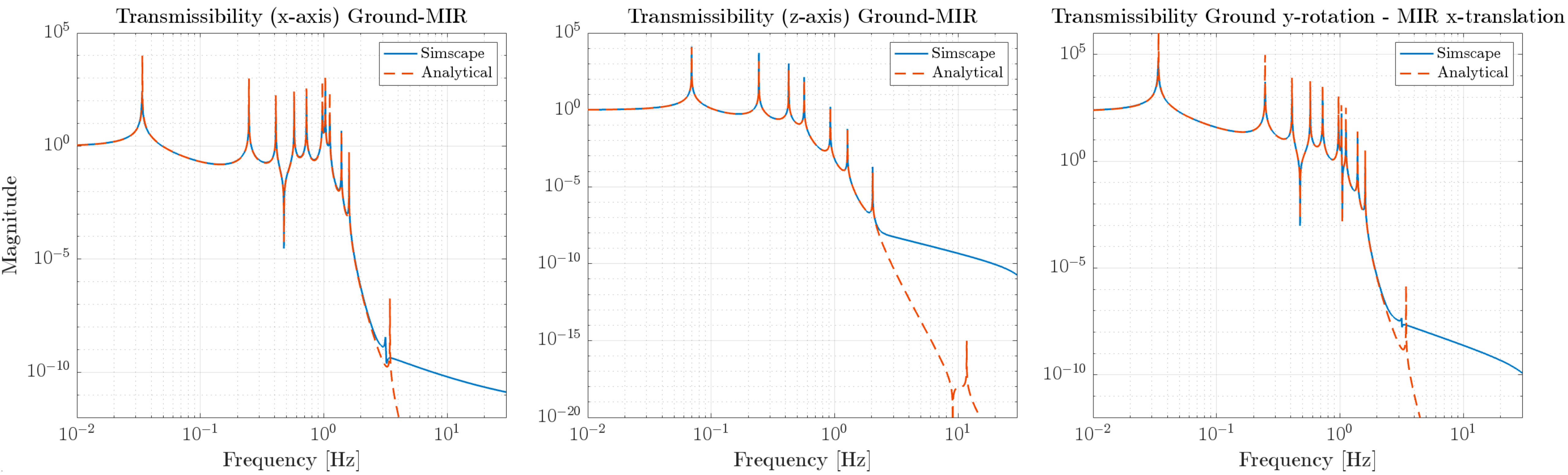
- Analytical model built with the following assumptions:
  - IP legs massless
  - Vertical modes decoupled from other diections
  - All wires connected to CoM

→ Correct shape after 2 Hz



Comparison with Analytical Model

Open-Loop Transmissibilities to Mirror (Horizontal, Vertical and Tilt-to-Horizontal)



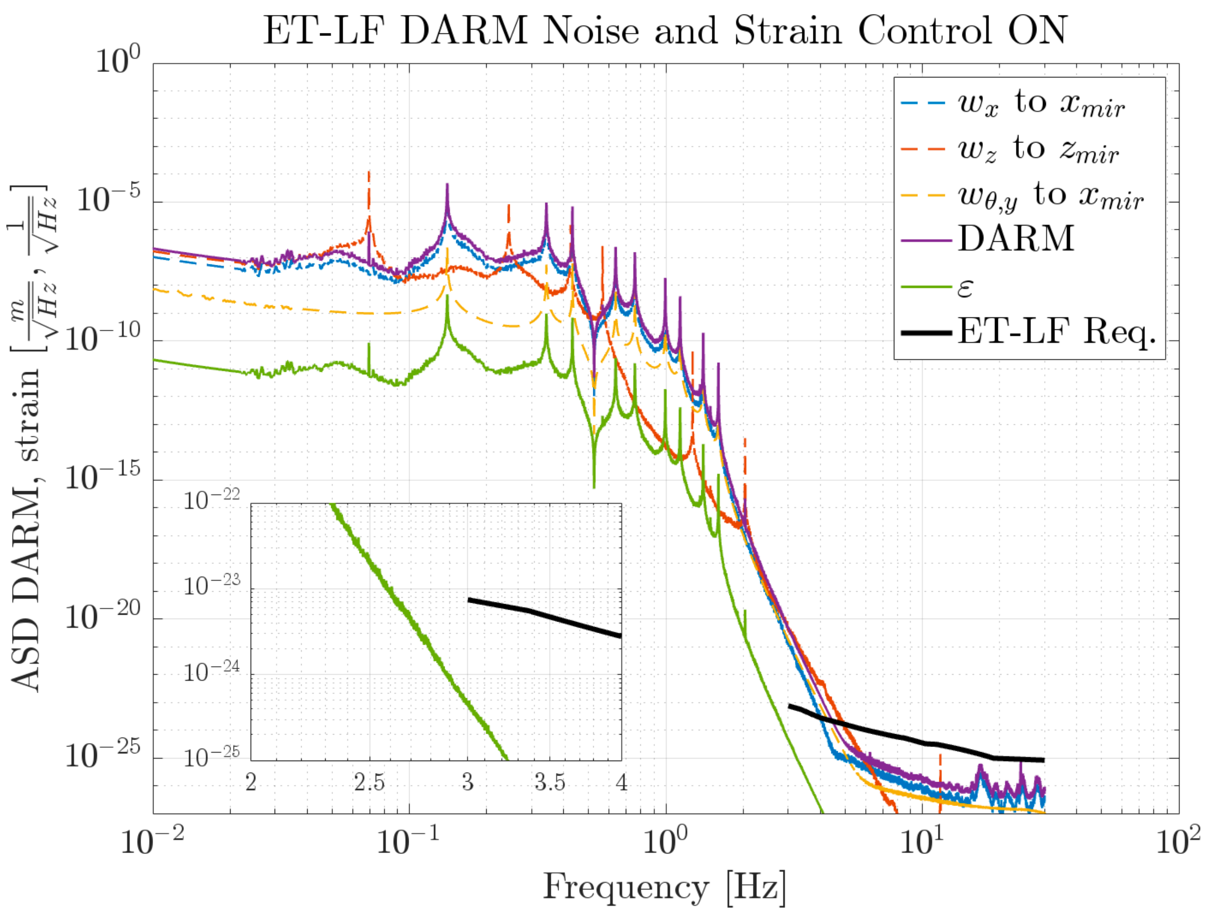
Analytical model provides the correct shape after 2 Hz

DARM and Strain

Response to Ground Motion of the Analytical Model using the LNGS Spectra

- Closed-loop transmissibilities for
  $x_{\text{gnd}} \to x_{\text{mir}}$, $y_{r\,\text{gnd}} \to x_{\text{mir}}$ and $z_{\text{gnd}} \to z_{\text{mir}}$
- DARM computed using a vertical to horizontal cross coupling coefficient $\frac{1}{300}$
- Strain computed using a 10 km arm length

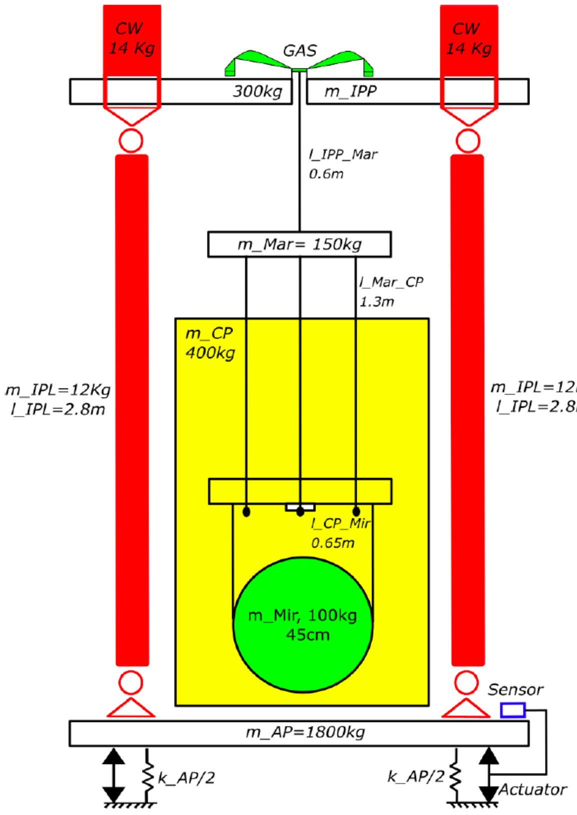
Strain satisfying the requirements at 3 Hz



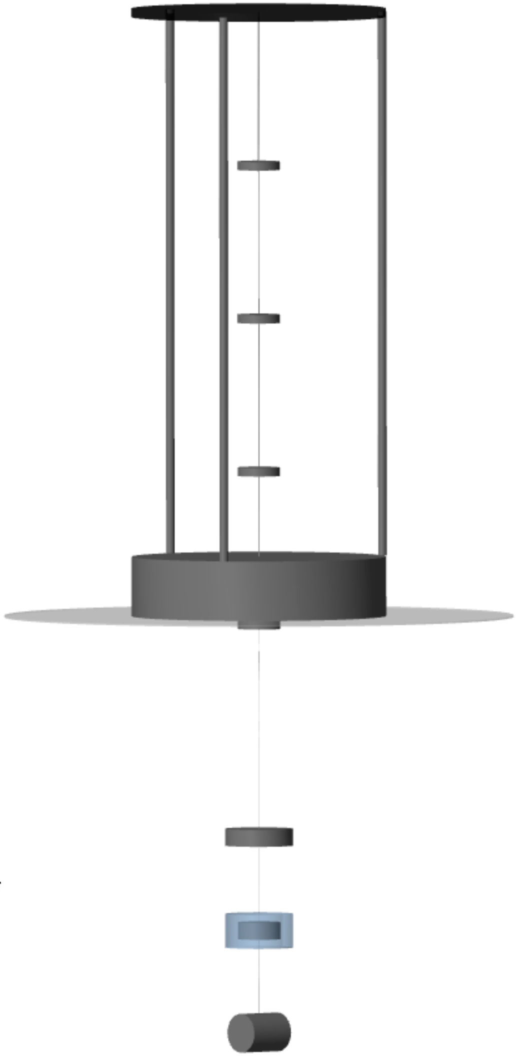
E-TEST

Suspension Model → Bridge between E-TEST & ET

E-TEST (4.5m)

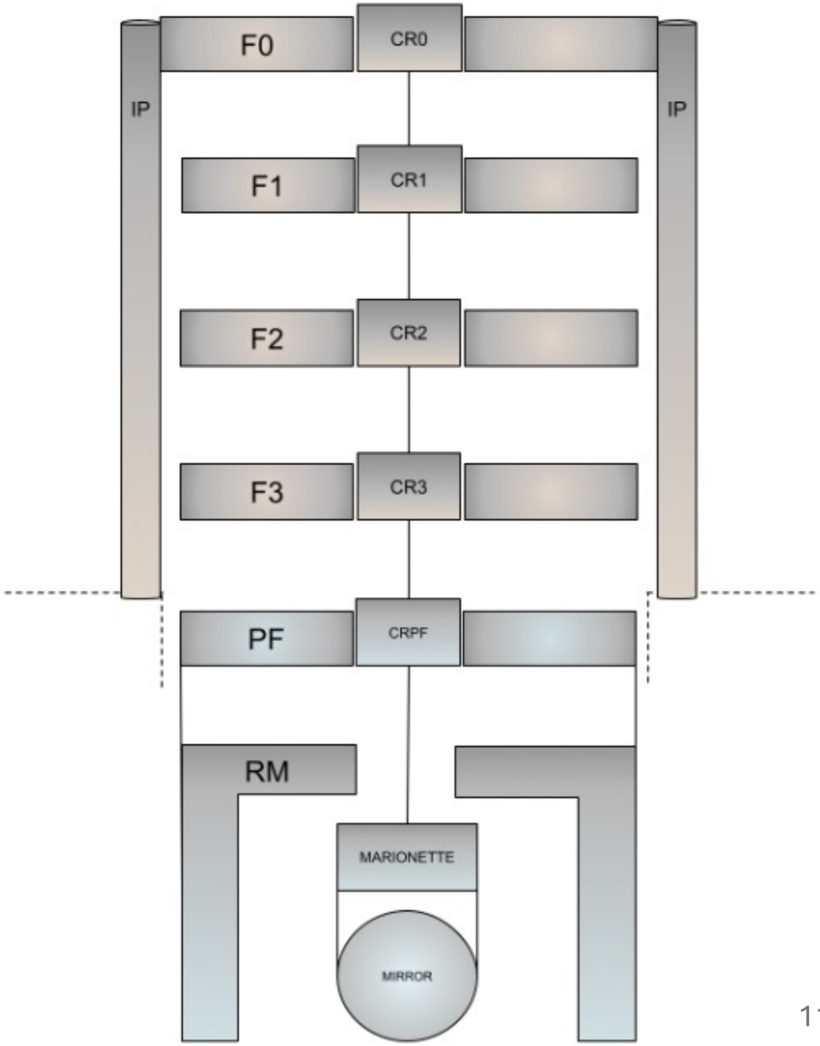


Model (12m)

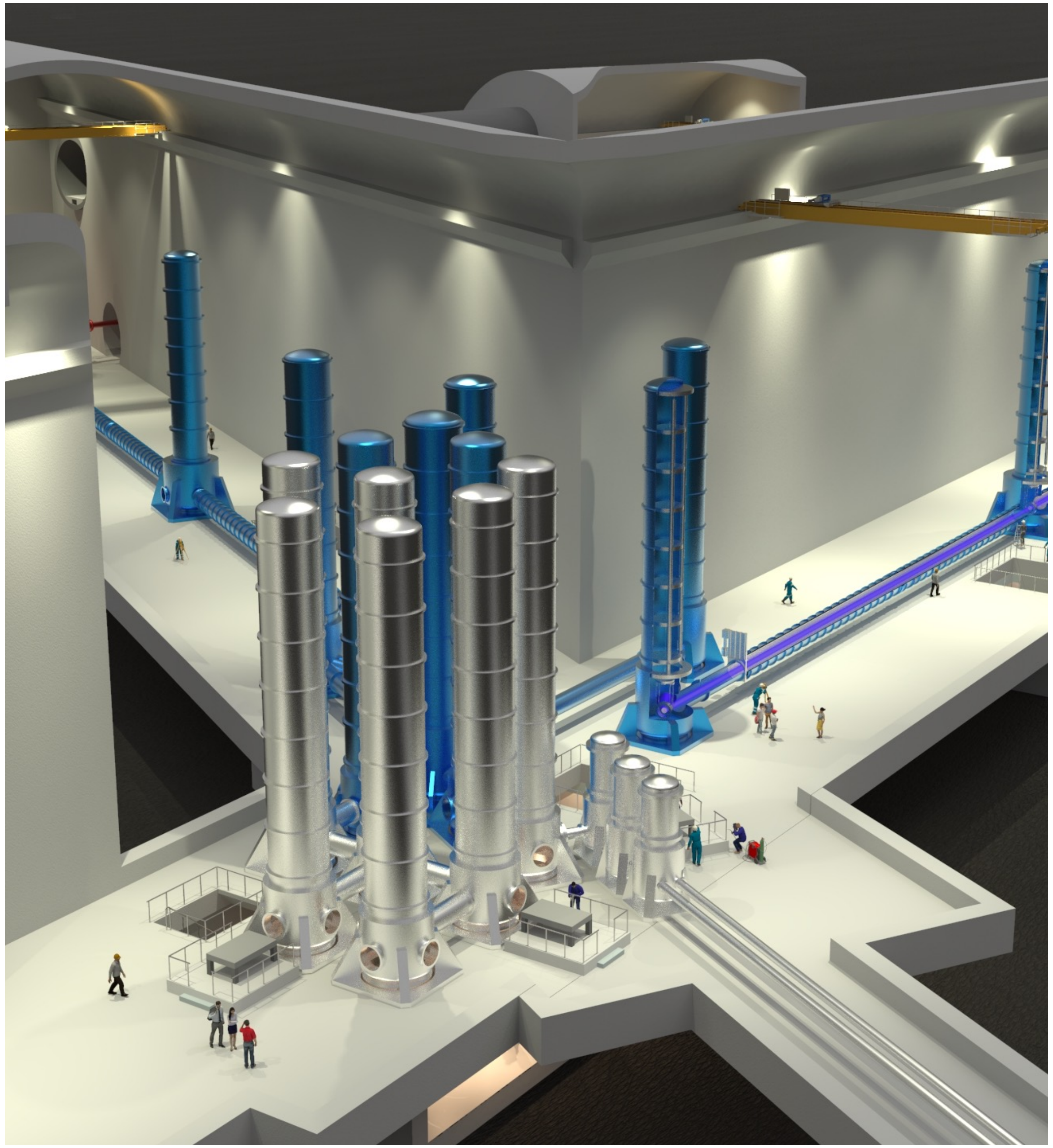


Abbreviation:
AP: Active Inertial Platform
GAS: Geometric Anti-Spring
IPL: Inverted Pendulum Leg
IPP: Inverted Pendulum Platforr
Mar: Marionette
CP:Cryostat+Cold Platform
Mir: Mirror
k: Stiffness
m: Mass
CW: Counter Weight

Reference Solution (17m)



E-TEST Objectives

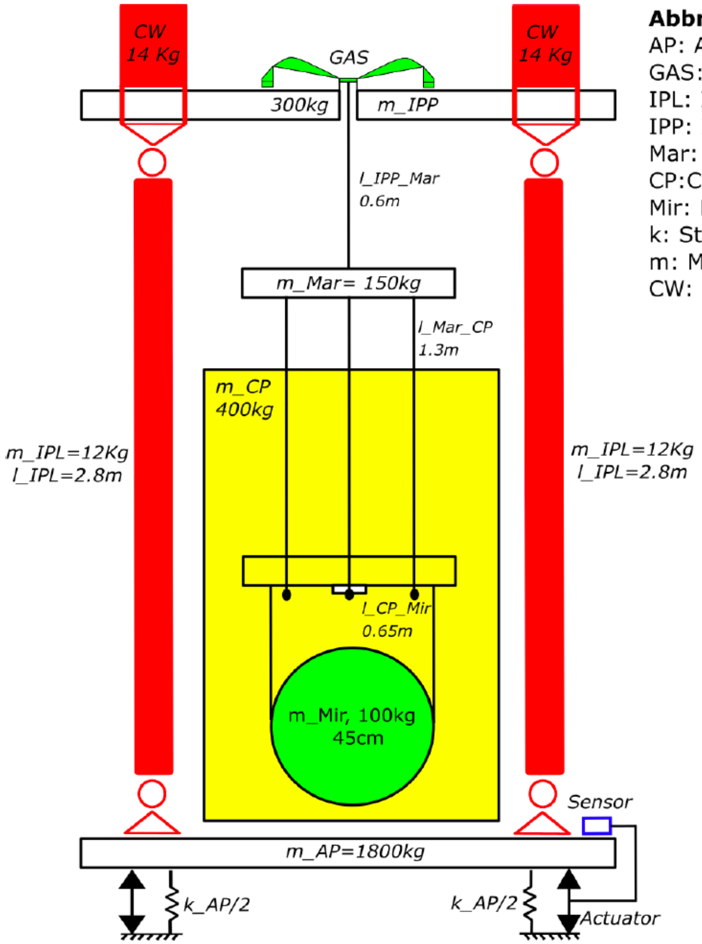


- Large mirror (100 Kg)
- Cryogenic temperature (10-20 K)
- Isolated at low frequency (0.1-10 Hz)
- Compact suspension (4.5 meters)

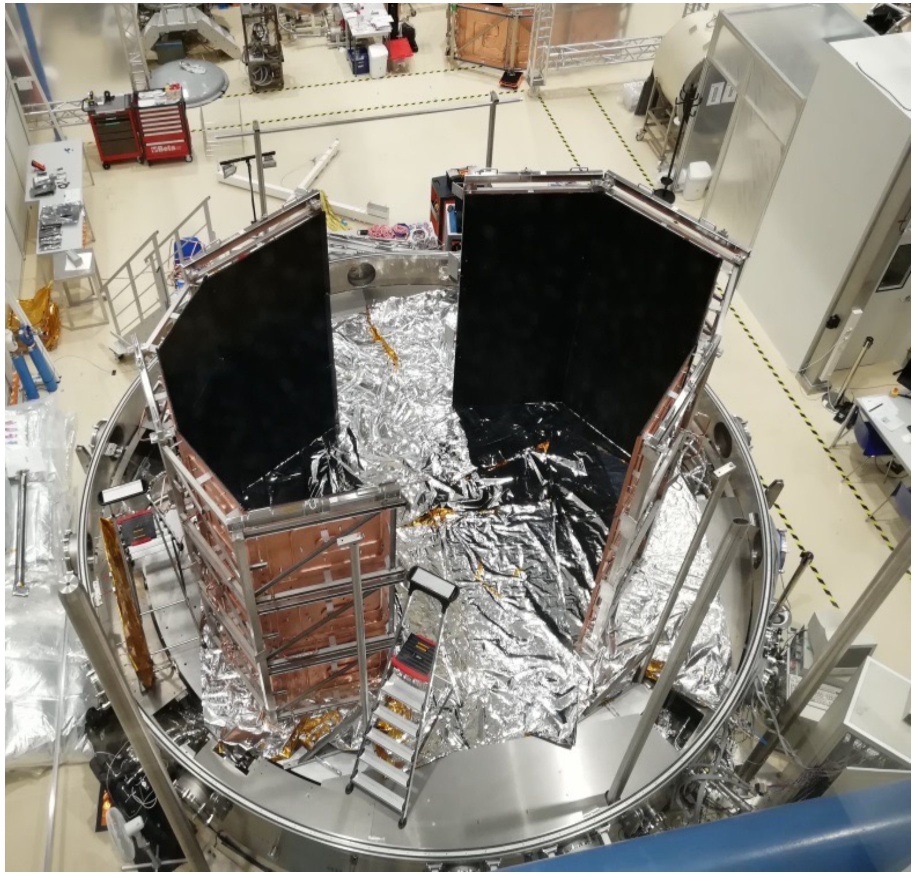
E-TEST feasibility strategy

E-TEST is a project funded by the Interreg Euregio Meuse-Rhine and ET2SME consortium, which allow us to capitalize on existing infrastructure at Centre Spatial Liège (CSL) for the construction of the facility.

E-TEST: How It Started



Abbreviation:
AP: Active Inertial Platform
GAS: Geometric Anti-Spring
IPL: Inverted Pendulum Leg
IPP: Inverted Pendulum Platform
Mar: Marionette
CP:Cryostat+Cold Platform
Mir: Mirror
k: Stiffness
m: Mass
CW: Counter Weight



Hybrid (active + passive) isolation

Radiative cooling

Liège Space Center

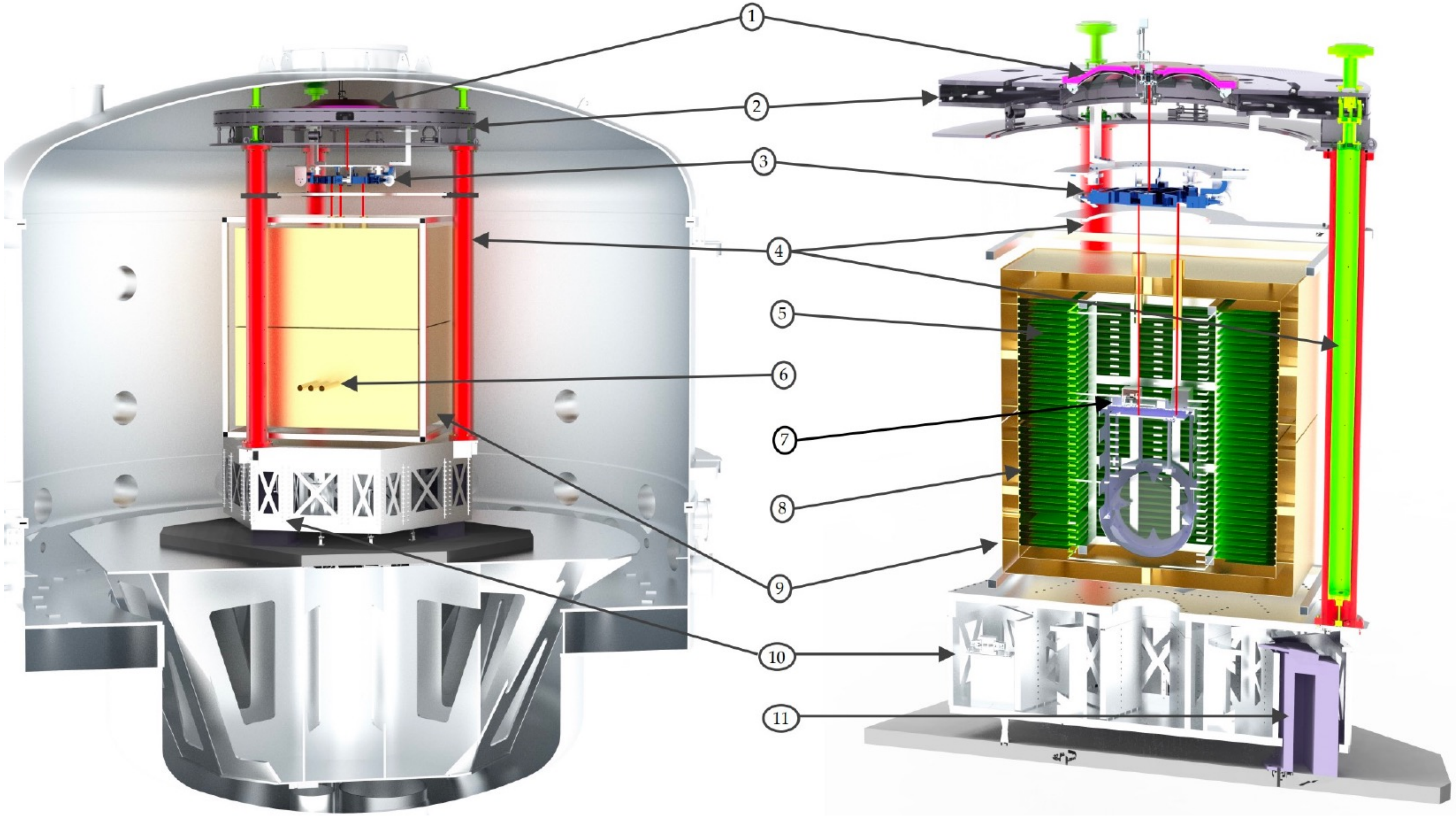
From Design Concept to Technical Drawings

- Vibration Isolator

1) GAS filter
2) IP platform
3) Marionette
4) IP legs
10) Active platform

- Cryogenic Payload

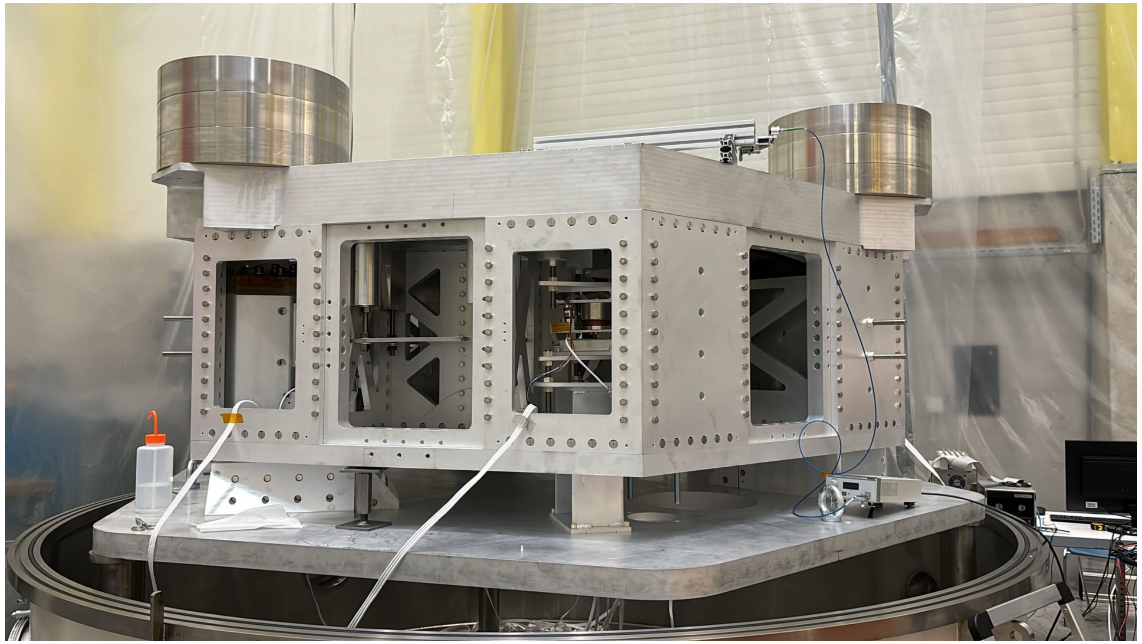
5) Heat exchanger and cold platform
7) 25K inner thermal shield
8) 80K outer thermal shield

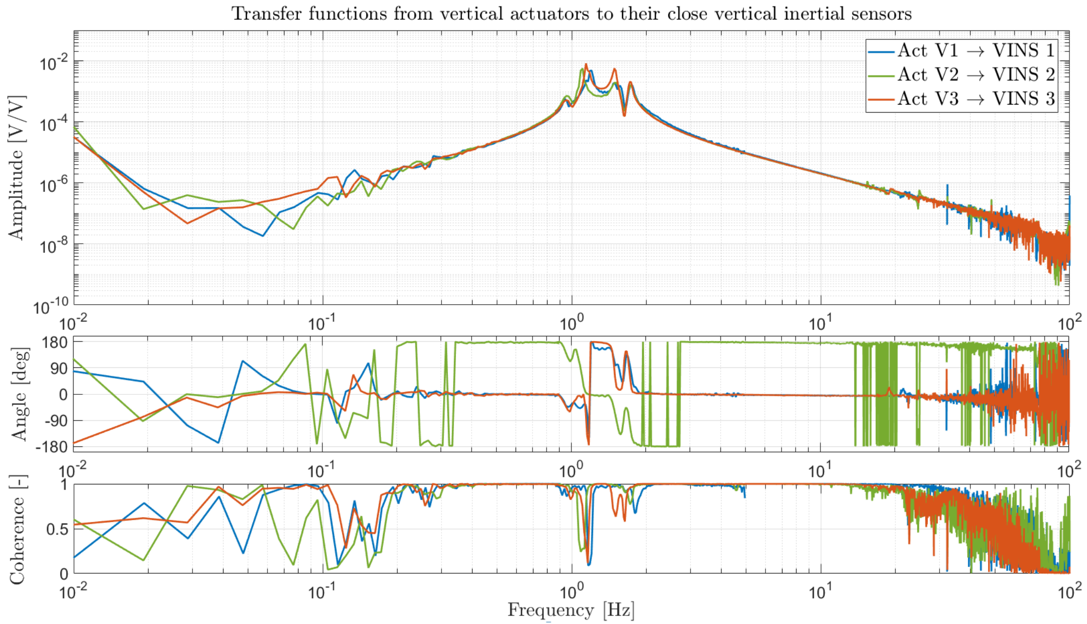


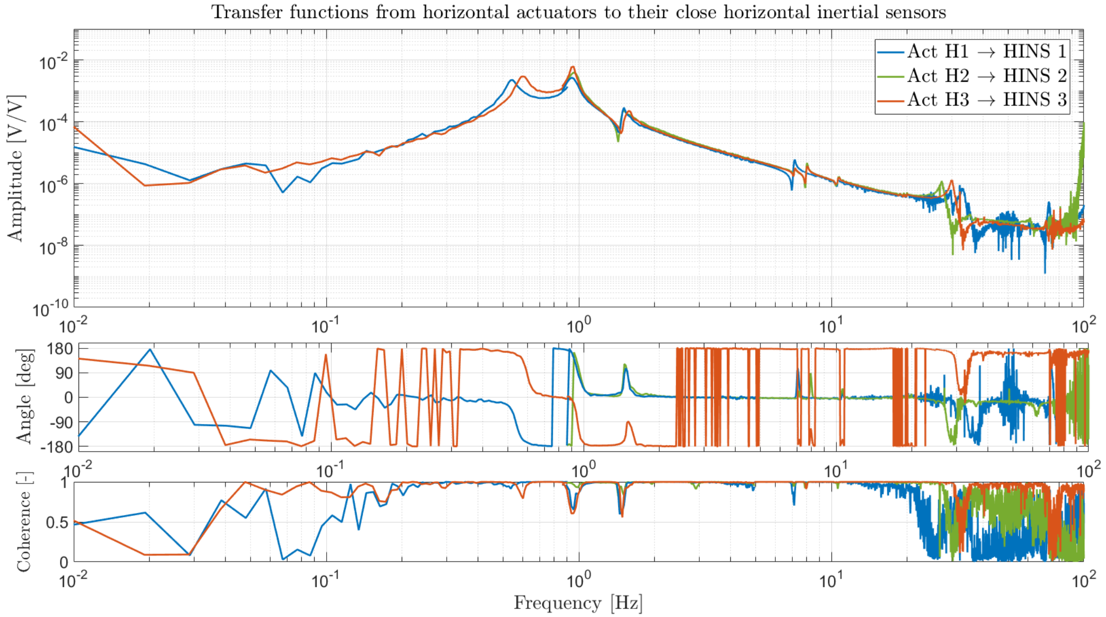
Low-Frequency Active Isolation

E-TEST Active Platform

Contact : Haidar Lakkis (ULiege)
mhlakkis@uliege.be





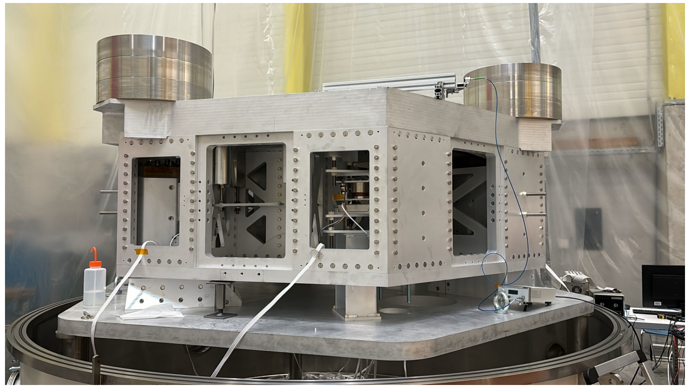


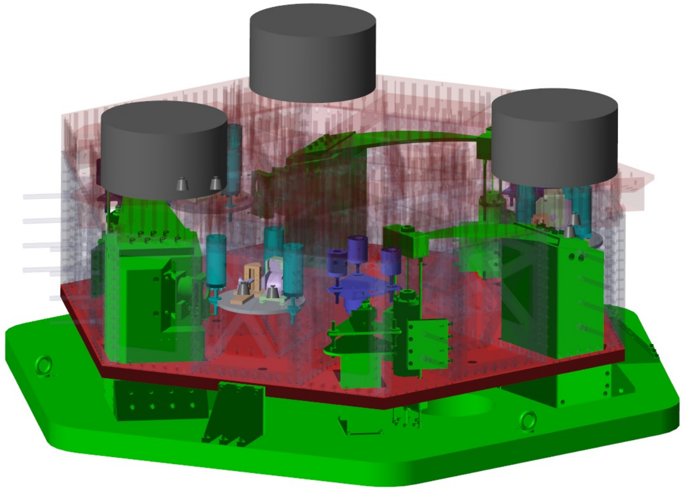
- Low-frequency Active Isolation
  - Locking platform with the ground at low frequency using BOSEMs (below 0.1 Hz)
  - Inertial control at mid frequencies (0.1 Hz to 10 Hz)

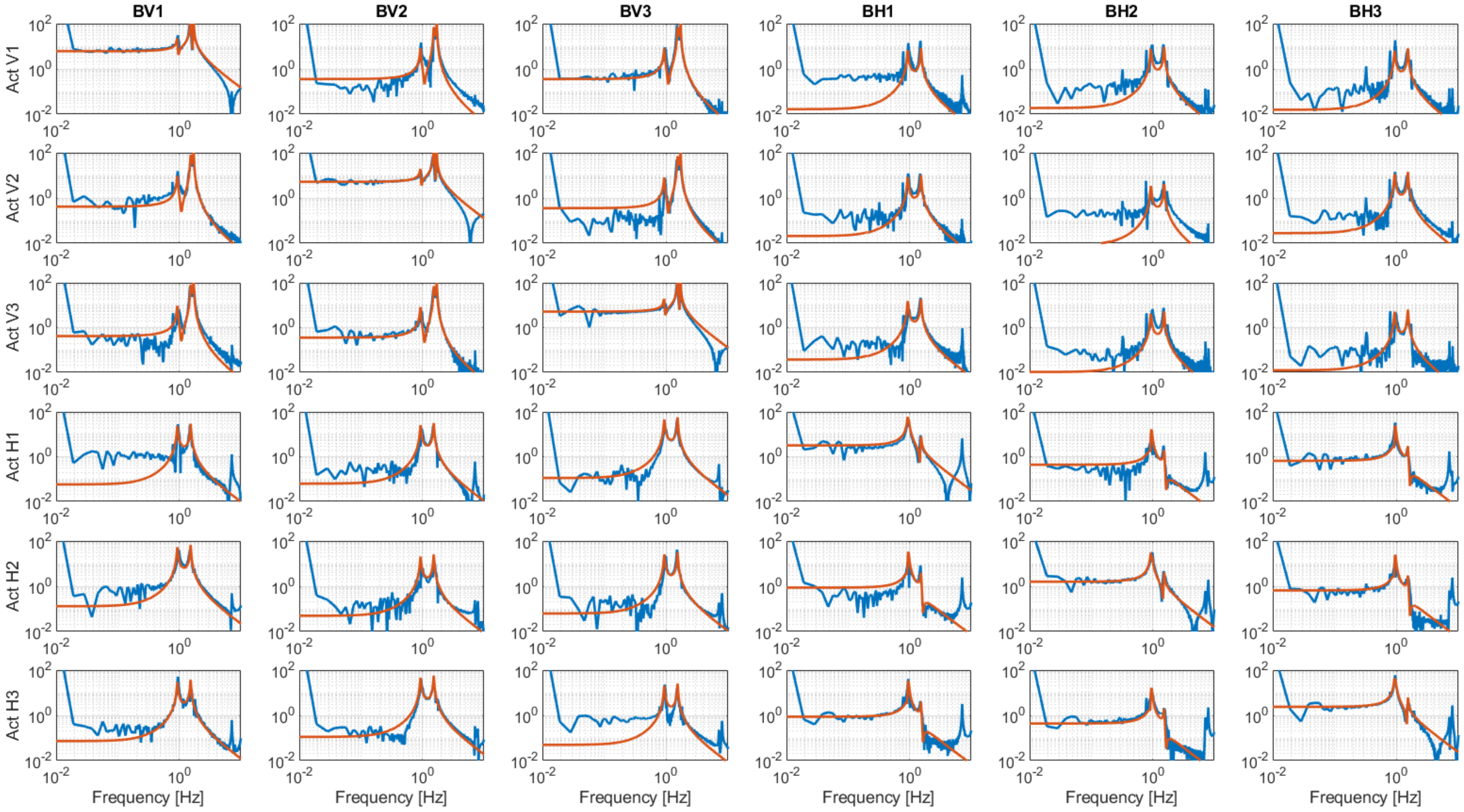
Low-Frequency Active Isolation

From Modelling to Experimental Data

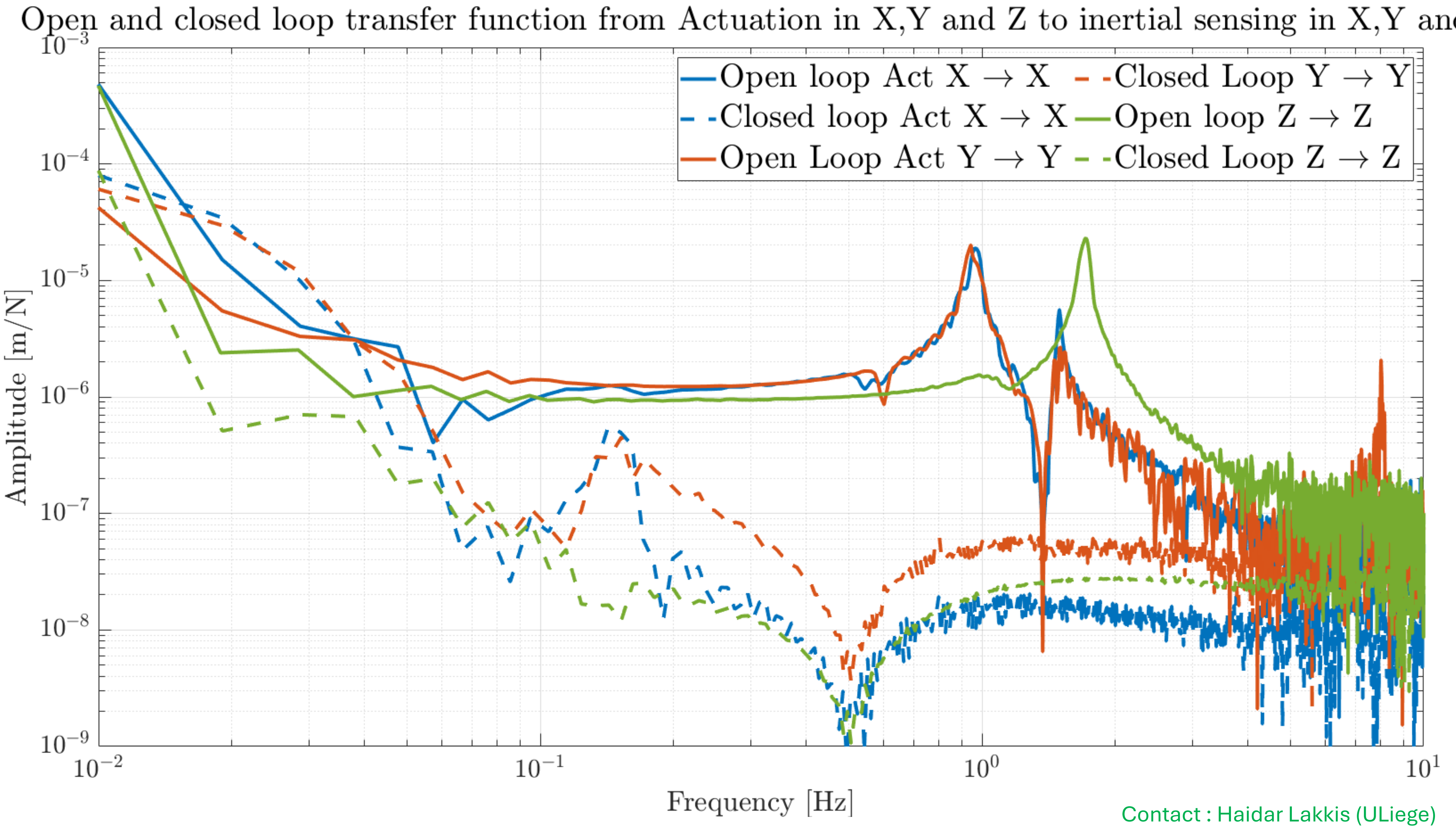
Contact : Haidar Lakkis (ULiege)
mhlakkis@uliege.be







Low-Frequency Active Isolation



Contact : Haidar Lakkis (ULiege)
mhlakkis@uliege.be

Summary and Plan

ET-LF Model

- Characteristics
  - Integration of both an AP and an IP
  - Functional height: 12 m
  - Simscape and analytical
    - ➢ Wires at CoM
    - ➢ $m_{\mathrm{IPL}} = 0$ kg
- Satisfies ET-LF strain requirements at 3 Hz
- Next steps:
  - Comparison of payload resonance frequencies with Octopus
  - Taking $m_{\mathrm{IPL}} \neq 0$ in analytical model

Summary and Plan

E-TEST

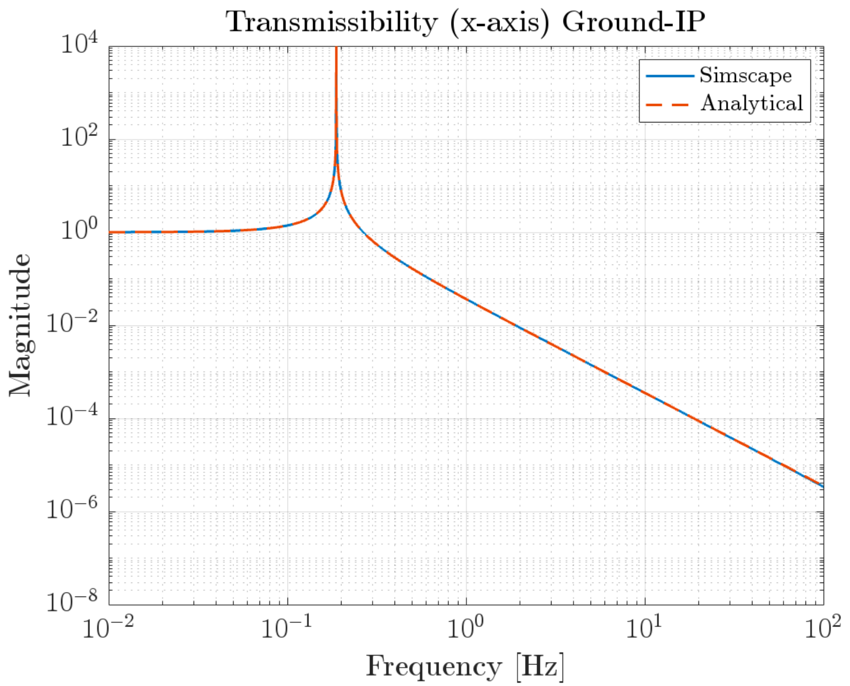
- 2023: 1st run with fully assembled prototype
  - 100 kg test-mass
  - Low frequency seismic isolation
  - Radiative cooling strategy
- 2024-2025
  - 100 kg Si mirror being polished
  - Improvement of sensors
  - Control strategies

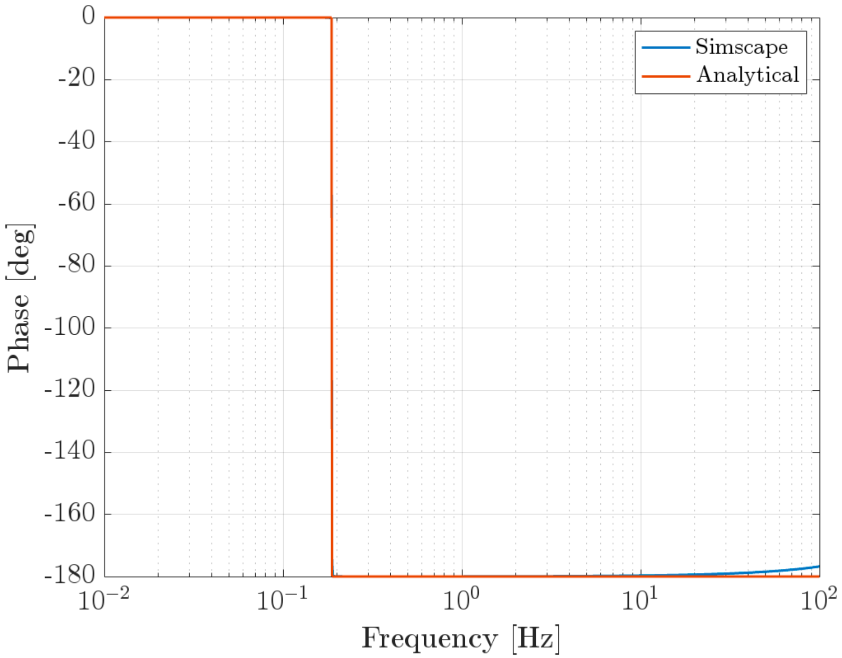
E-TEST becomes CRISTAL

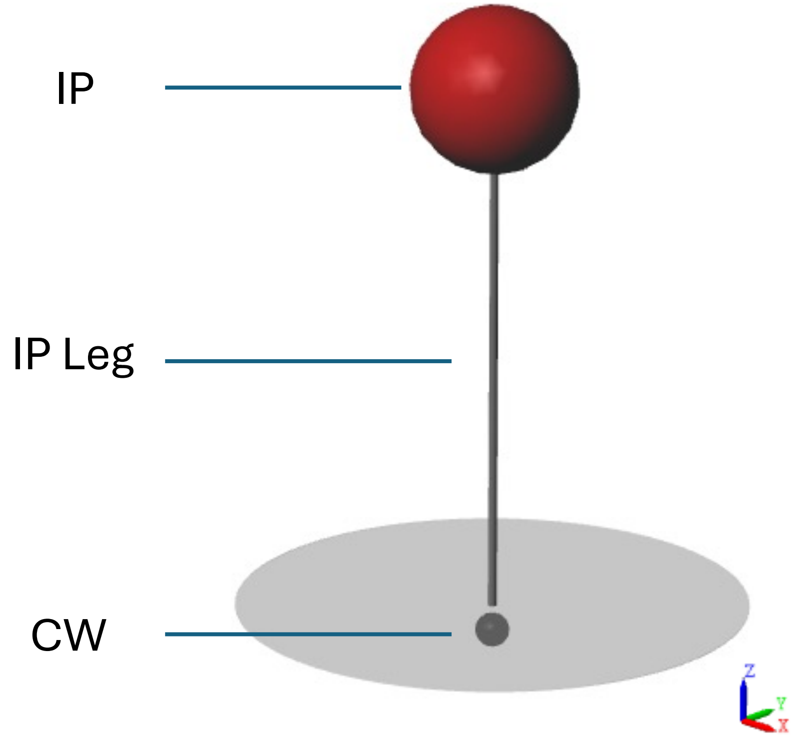
Appendix

Simple Inverted Pendulum & Percussion Point Effect

- Assumptions:
  - ➢ IP and counter weight (CW) are point masses
  - ➢ IP Leg has a mass and an inertia
- First, consider $m_{\mathrm{IPL}} = 0$ kg and no CW



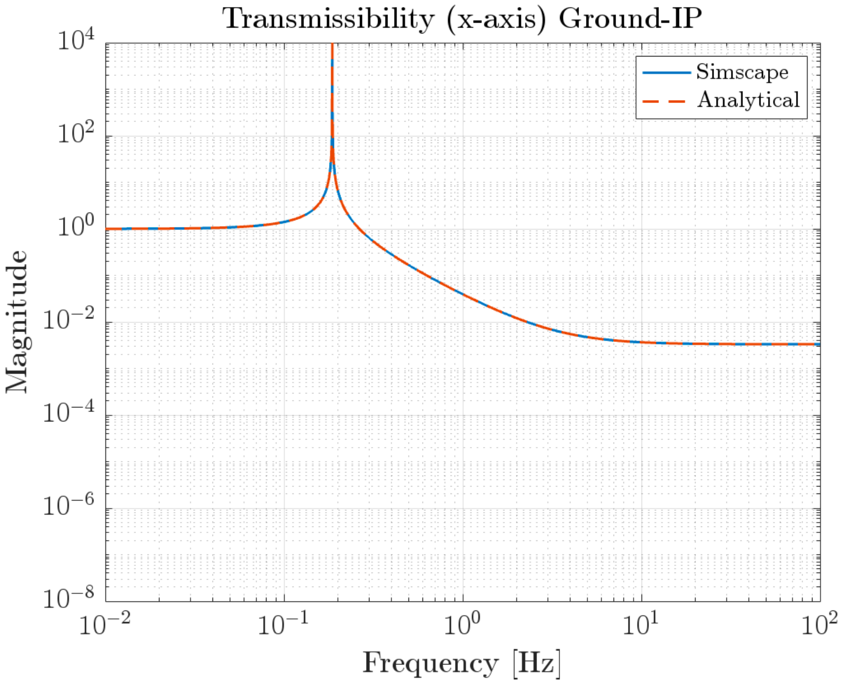


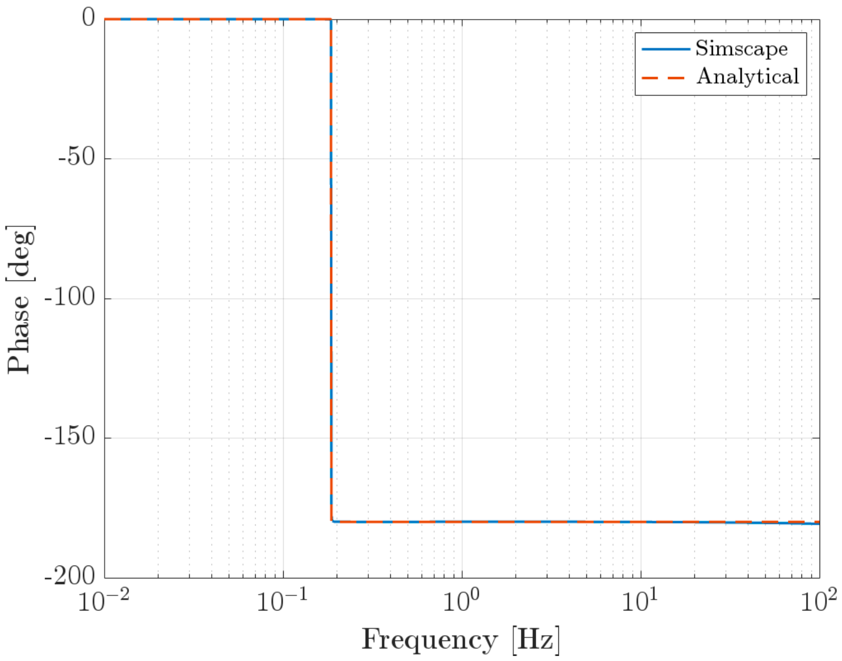


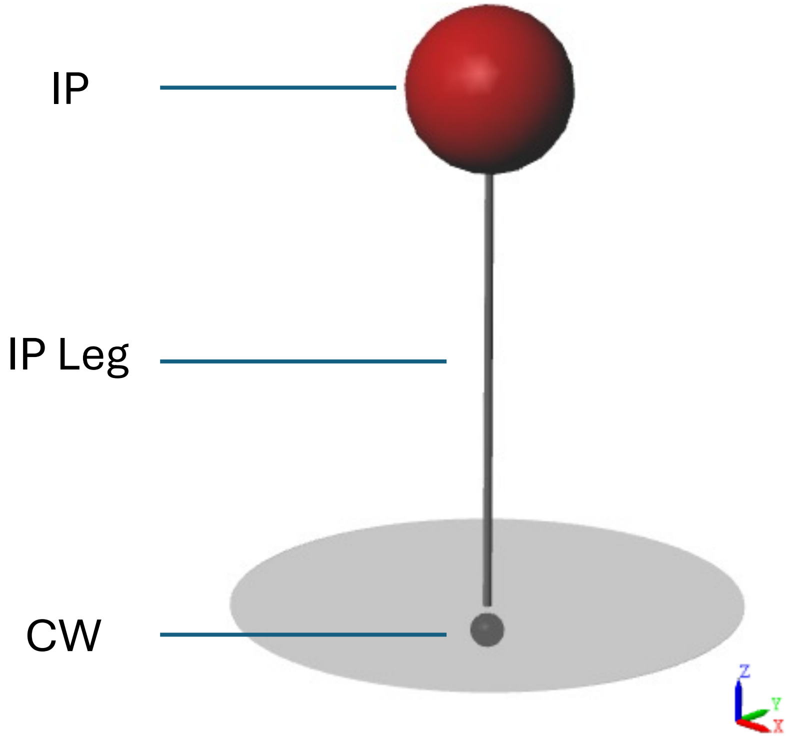
Appendix

Simple Inverted Pendulum & Percussion Point Effect

- Assumptions:
  - IP and counter weight (CW) are point masses
  - IP Leg has a mass and an inertia
- Then, consider $m_{\mathrm{IPL}} = 10$ kg and no CW







Appendix

Simple Inverted Pendulum & Percussion Point Effect

- Assumptions:
  - IP and counter weight (CW) are point masses
  - IP Leg has a mass and an inertia
- Finally, consider $m_{\mathrm{IPL}} = 10$ kg a proper CW