Progress on the overall modelling of cryogenic payload

Pinto M., Majorana E., Ruggi P.

Outline

Open issues discussed at last Elba workshop, finally tackled (some of them still on-going)

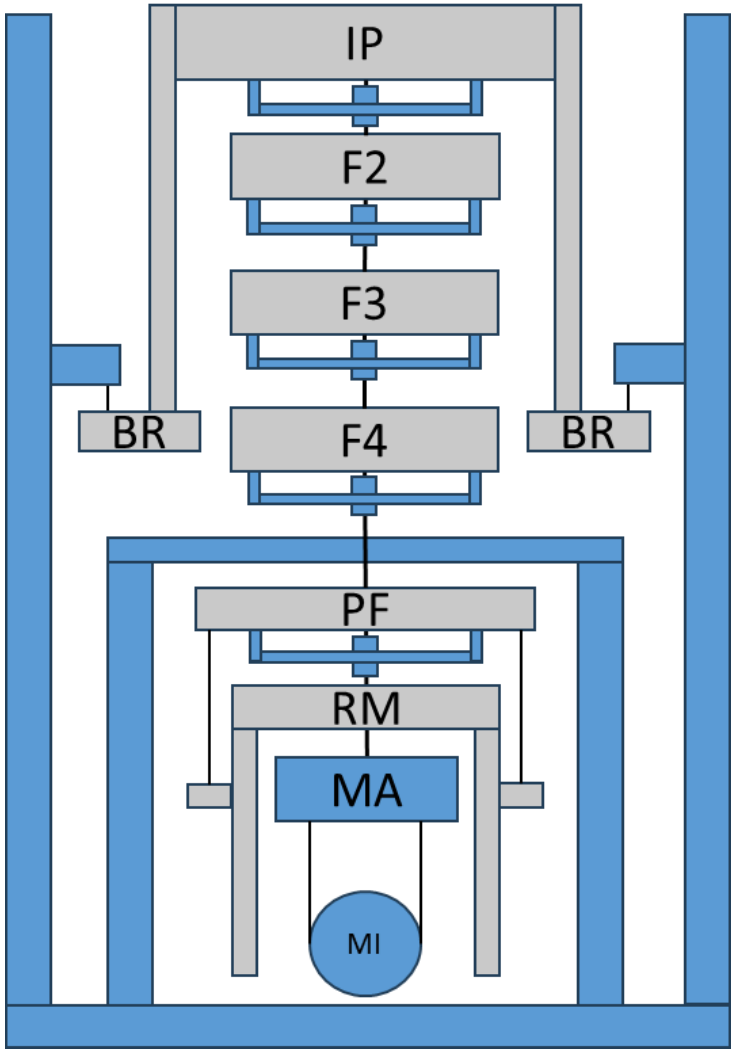
- Update of angular control and angular noise budget;
- Radiation pressure contribution;
- Single wire solution for PF suspension (time domain analysis VS PF oscillation);
- DAC noise budget for locking force actuation;

Outcome: Overall requirements extraction, for a given proper methodology in terms of control strategy.

Open points and next steps:

- VERTICAL control and attenuation
- Heat link implementation.

Case of study: Baseline 12m Suspension and Cryo-PAY model

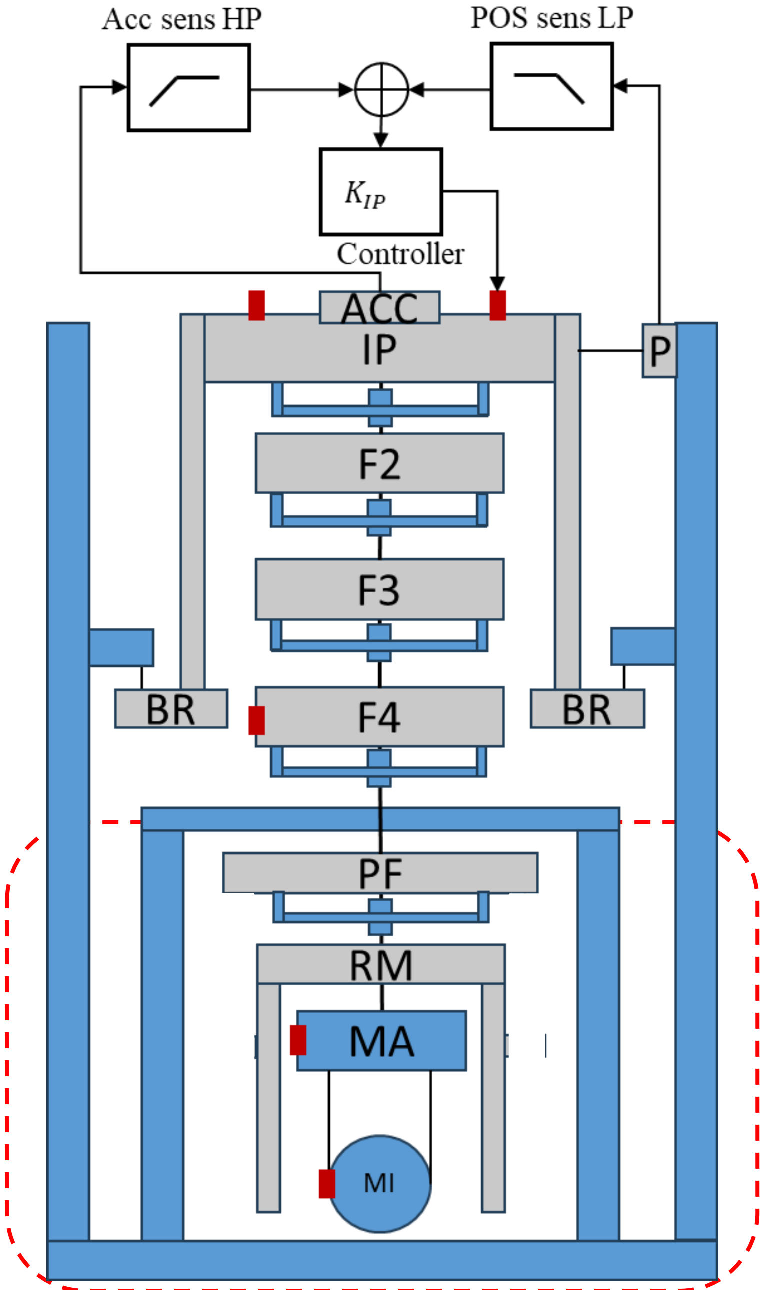


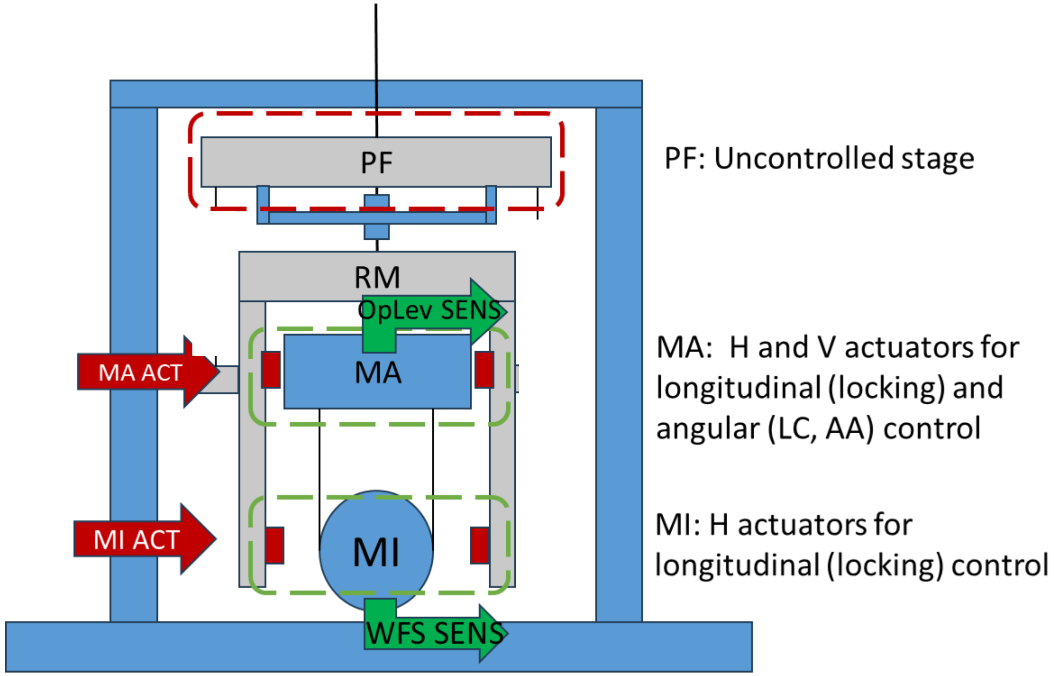
Baseline solution** for the single cavern option + Cryo-PAY (seed parameters) have been taken as case of study.

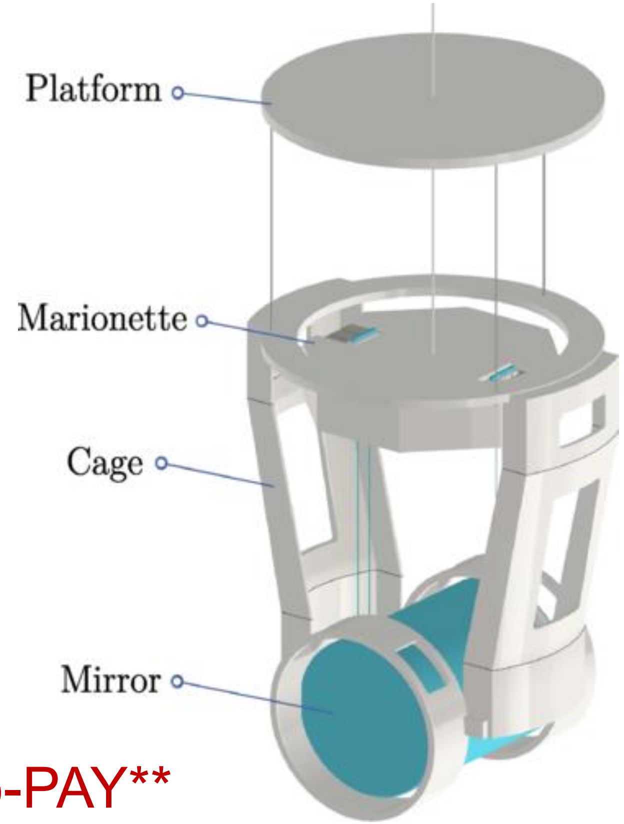
Body	MASS (KG)	IXX (KGM^2)	IYY (KGM^2)	IZZ (KGM^2)
MIRROR (MI)	183	3.6	3.6	4.6
MARIONETTE (MA)	183	5.7	11.2	5.7
REACTION MASS (RM)	200	44	30	46
PLATFORM (PF)	300	18	34	18
CROSSBAR PF (CRPF)	5	0.5	0.5	1.0
FILTER 4 (F4)	367	25	50	25
CROSSBAR F4 (CR4)	4.8	0.16	0.15	0.33
FILTER 3 (F3)	514	30	60	30
CROSSBAR F3 (CR3)	8	0.16	0.15	0.33
FILTER2 (F2)	726	30	60	30
CROSSBAR F2 (CR2)	8	0.16	0.15	0.33
FILTER 0 (F0)	1013	50	100	50
CROSSBAR F0 (CF0)	20	0.40	0.40	0.60

- ** Trozzo, Spada, Ruggi, Pinto, Lucchesi, Losurdo - *A Superattenuator for the ET-LF Test Masses*. II. Workshop on ET-LF TM Tower Integration March 25 – 27, 2025.
- ** Spada, Losurdo, Lucchesi, Pinto, Ruggi, Trozzo - *Feasibility and Compliance Study for the Seismic Isolator of Low-Frequency Einstein Telescope Test Masses*. GR24/Amaldi16 Conference Proceedings.

Topic 1: angular control of the cryo-payload and implication on the design



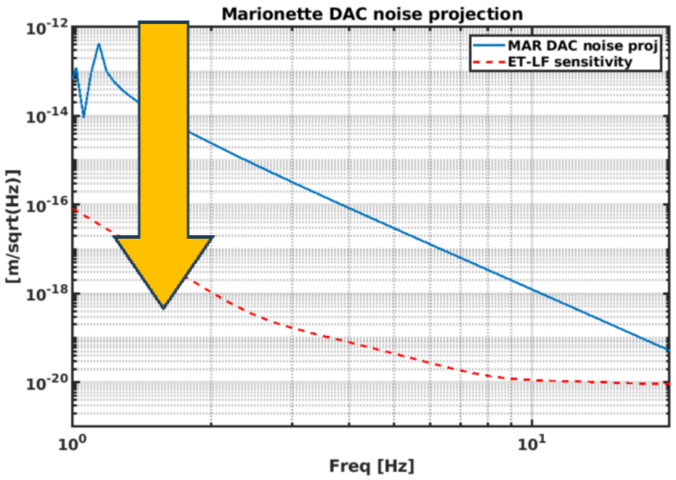




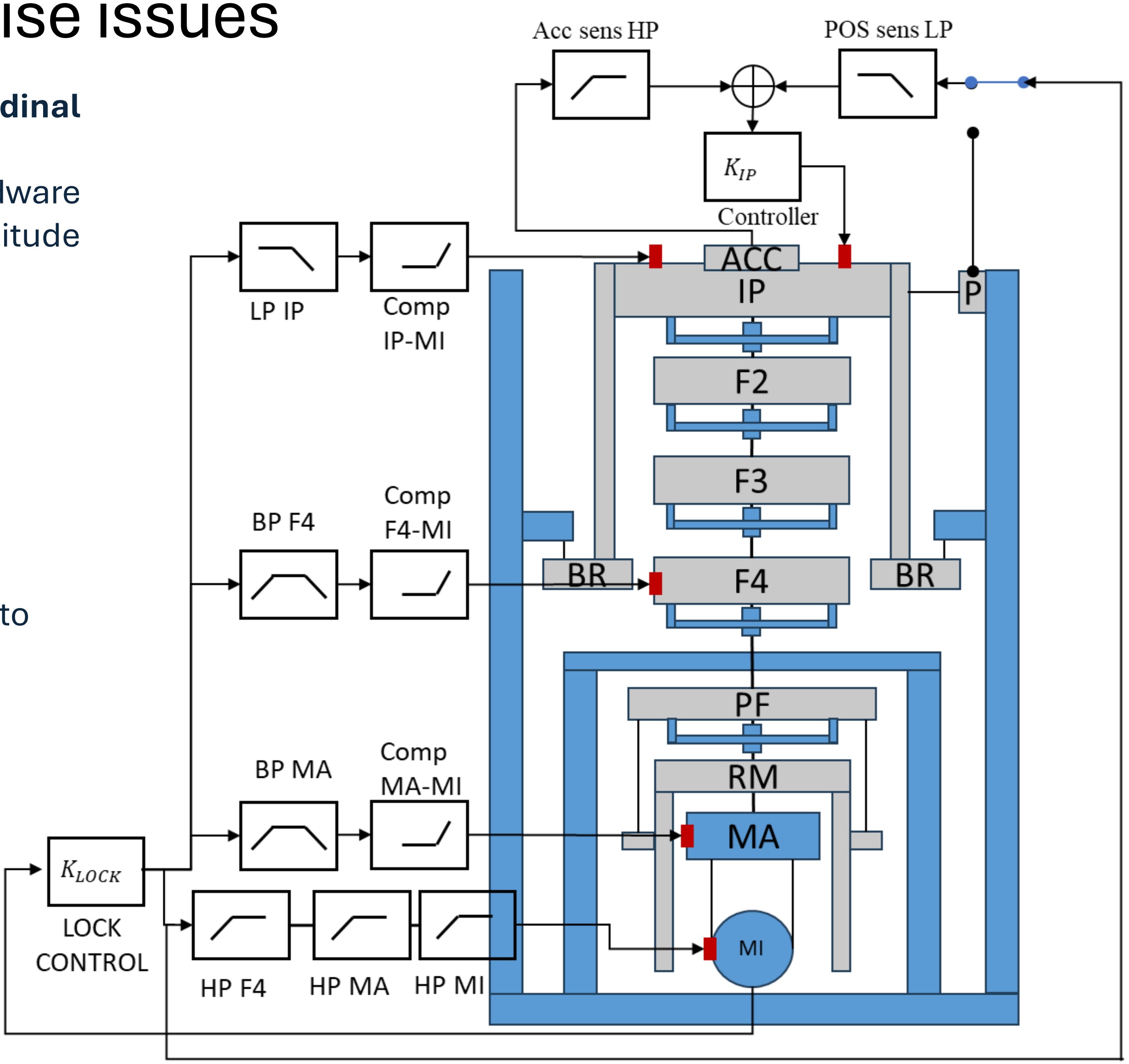
- Case of study: baseline solution + Cryo-PAY**
- **Basic ID control** strategy.
- Angular control using **OpLev** and **WFS** ("soft" mode on OpLevs)
- **No actuation neither on the PF, nor on the RM(cage), relevant not to add further components into the cryostat**

❑ ** Koroveshi, Busch, Majorana, Puppo, Rapagnani, Ricci, Ruggi, Grohmann - *Cryogenic payloads for the Einstein Telescope: Baseline design with heat extraction, suspension thermal noise modeling, and sensitivity analyses.* Phys. Rev. D 108, 123009

Topic 2: Multi-stages longitudinal Hierarchical Control to address the actuation noise issues



- Need to tackle the **longitudinal actuation noise budget**;
- With the current DAC hardware we are few orders of magnitude far from the requirements;



- Low-noise actuation strategy is needed: (**Hierarchical control***);
- Strategy already proven to be effective and stable on Virgo ITF**.
- Updated measurement of ground TILT*** noise at LNGS available to test the strategy.

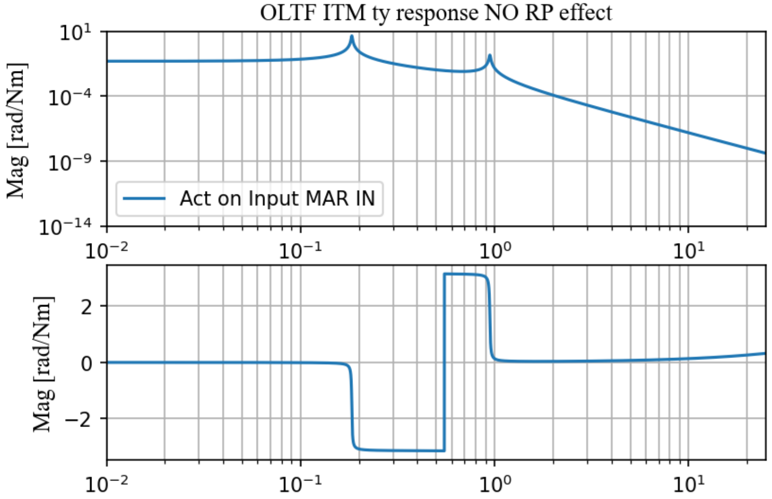
- * Ruggi, Pinto, Majorana, Losurdo - *Considerations on the control strategy for the ET-LF superattenuator:* ET-0527A-24*;*
- ** Ruggi, Pinto, Majorana, Losurdo - *Modelling further advancement of Virgo-like seismic isolation system towards ET-LF design:* 3rd ET annual meeting, Warsaw Nov,13th 2024 ET-0637A-24*;*
- *** Naticchioni, Trozzo, Ricci M., Pirro, Majorana, Di Giovanni - *Low frequency noise measurements at LNGS & tilt estimation* - ET-0434A-25

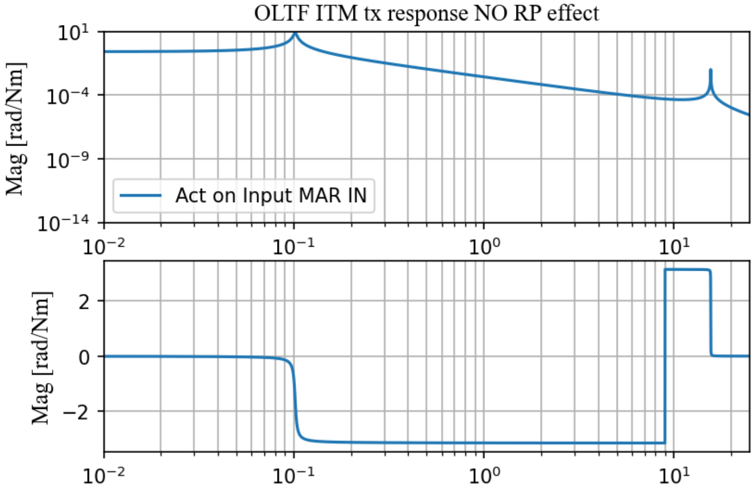
Angular control of the Cryo-Payload

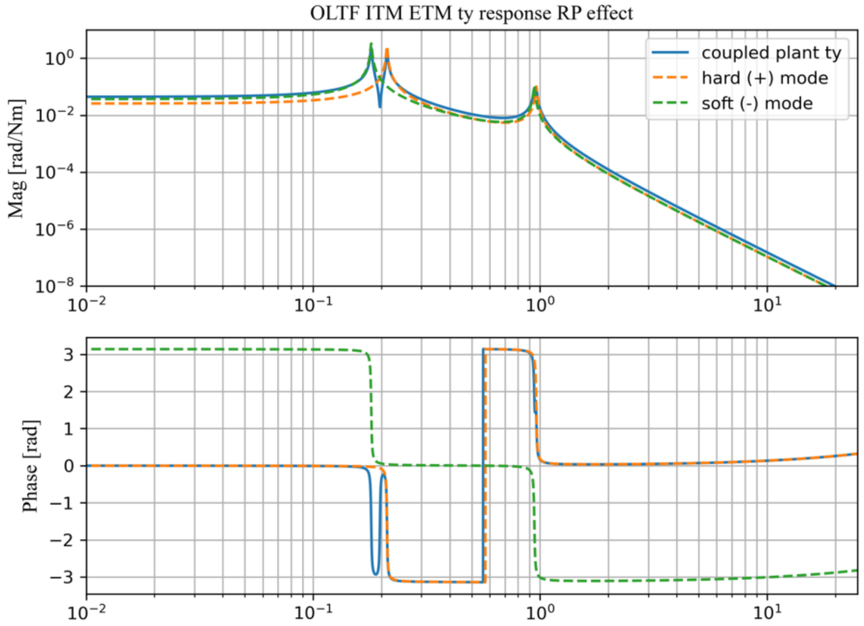
Effect of radiation pressure – negligible for LF?

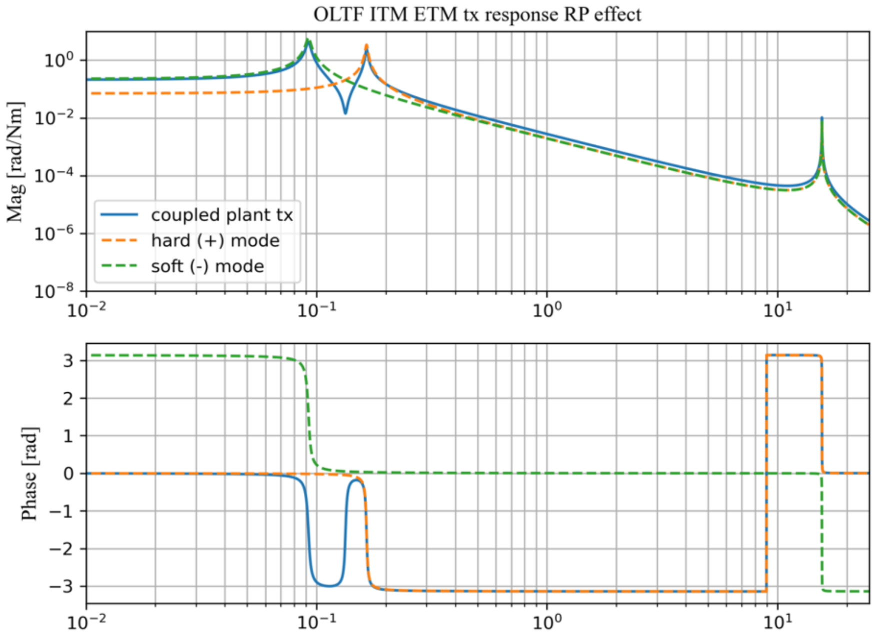
- P=18kW (3 W input)
- RoC = 5580m
- g = 0.65
- L=10070m

Effect of RP is very marginal. Consideration made so far on the control noise within detection band are VALID.
Few modifications on the control filters to adapt the plant changes could be made.

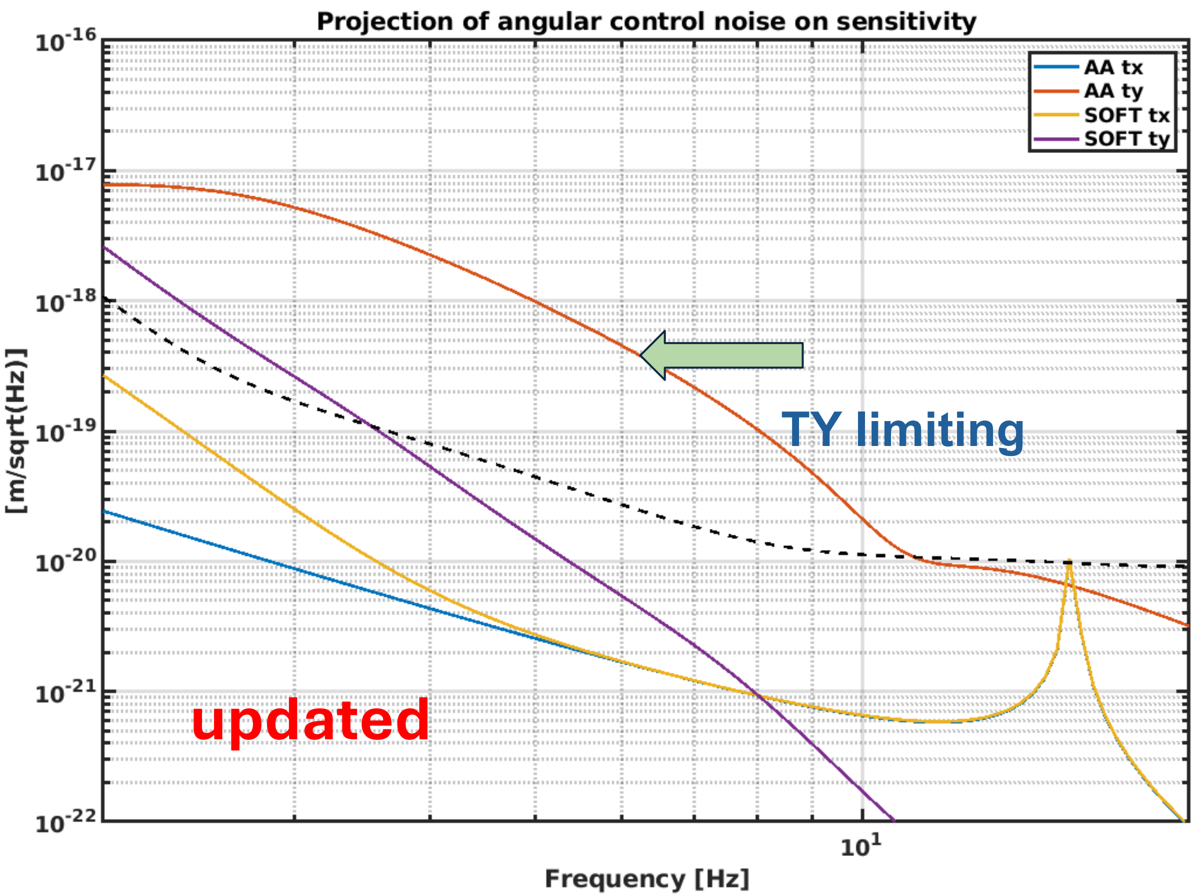








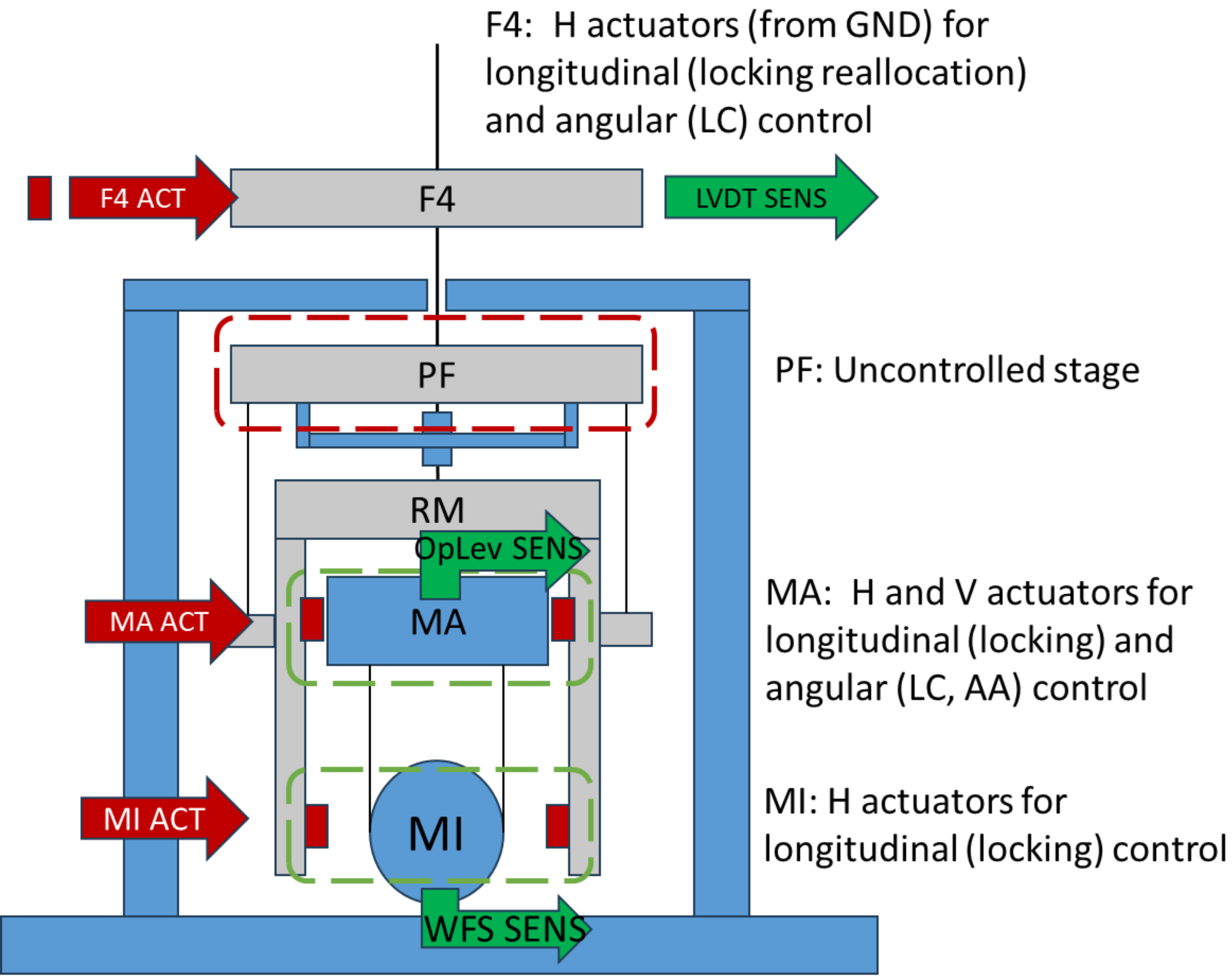
Recap of angular noise budget and Concluding Remarks



- YAW AND PITCH TFs are significantly different due to the intrinsically different structure

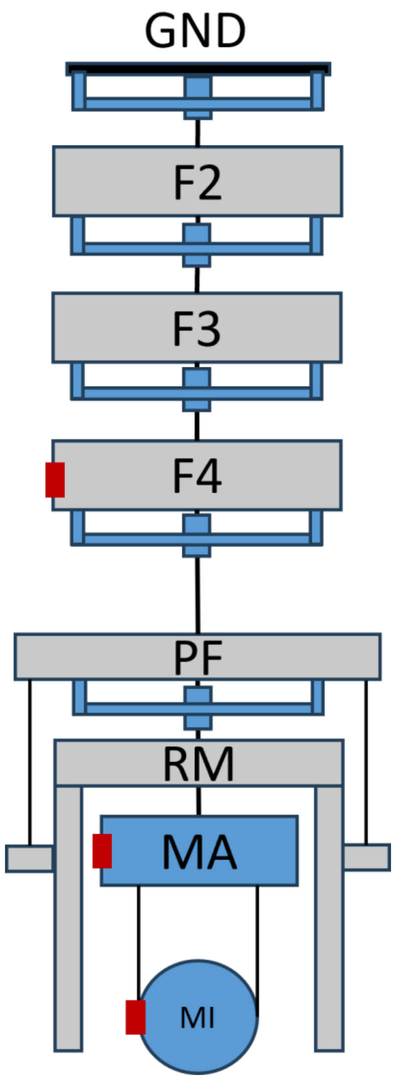
- Results reported here enhance the plausible **limitations coming from the angular control noise**;
- Results are preliminary, we are interested in the 'order of magnitude' gap WRT the sensitivity requirements.
- The methodology enlightens the **'knobs' on which the design effort be focused:** hardware noise, control strategy, control design…
- This can be used as a tool in order to **derive requirements** on the performance of the hardware (sensors and actuators) in order to reach the sensitivity goals.
- Additionally this could also drive the **optimal choice for the mechanical design** of the suspension elements (SA & Cryo-PAY) and their control strategy.

Payload control: ty control of the last attenuation stage



- Leaving the PF totally uncontrolled, could be potentially risky.
- If one of the low-freq rotational modes gets excited, it could take a very long time to naturally damp it.
- Given the constraints of the design of the cryostat, a possibility to damp the low frequency yaw modes of the PF and the payload is explored.
- TY control of the last attenuation stage of the suspension, i.e. the Filter 4 has been designed and simulated.
- This possibility copes with the 'necessity' to install actuators on this stage to apply the foreseen longitudinal locking hierarchical control strategy.

Payload control: time domain analysis



- Extraction of the inertia matrix M, stiffness matrix K and losses matrix D from the mechanical model.
- Development of a reduced state space model of the suspension: only TY DoF; TOP stage is modeled as an equivalent rigid ground.
- Implementation of the angular controls of the payload and F4 ctrl within a MIMO formalism control matrix C.
- Stability, time response and coexistence of the different controls is evaluated.

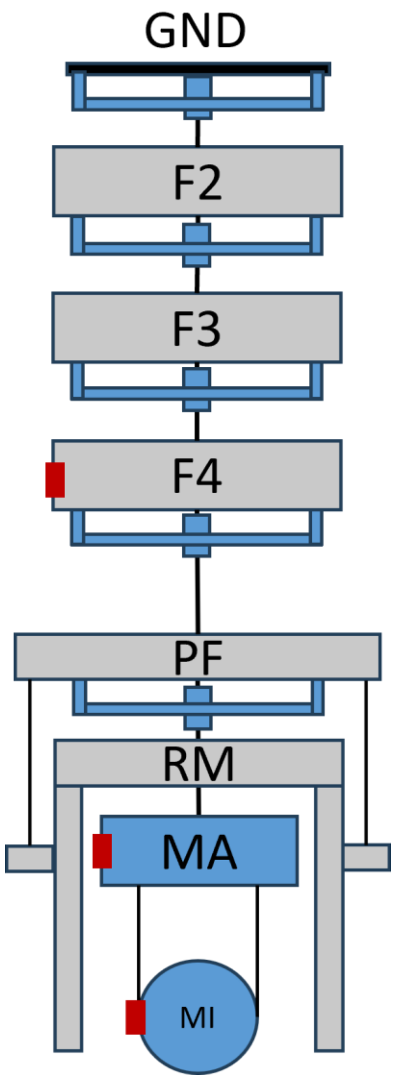
$$\dot{x} = A \cdot x + B \cdot u$$

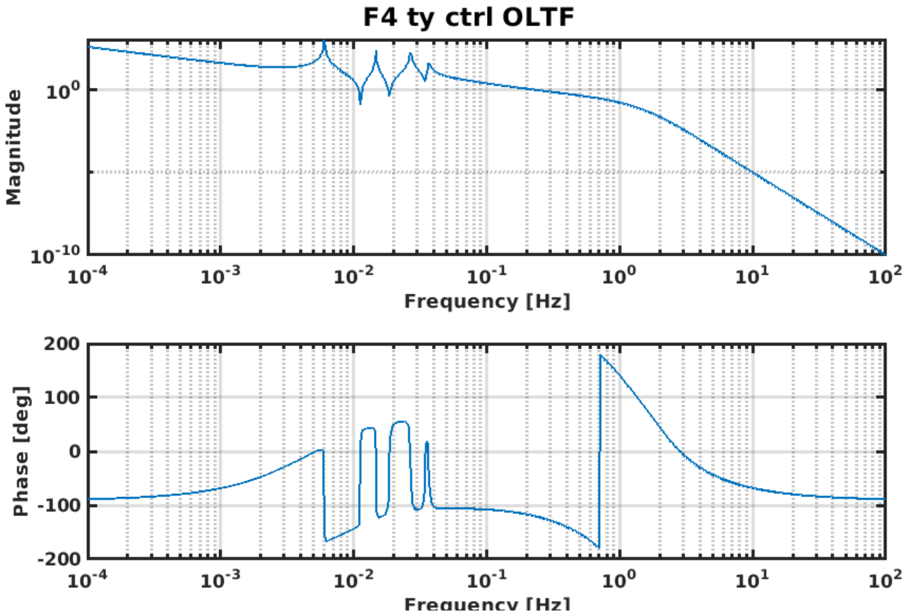
$$\begin{Bmatrix} \dot{\theta} \\ \ddot{\theta} \end{Bmatrix} = \begin{bmatrix} o & I \\ -M^{-1} \cdot K & -M^{-1} \cdot D \end{bmatrix} \cdot \begin{Bmatrix} \theta \\ \dot{\theta} \end{Bmatrix} + \begin{bmatrix} 0 \\ M^{-1} \end{bmatrix} \cdot u$$

$$u = -C \cdot x = -\left[0, \quad \frac{c_i(s)}{s}\right] \cdot \begin{Bmatrix} \theta \\ \dot{\theta} \end{Bmatrix}$$

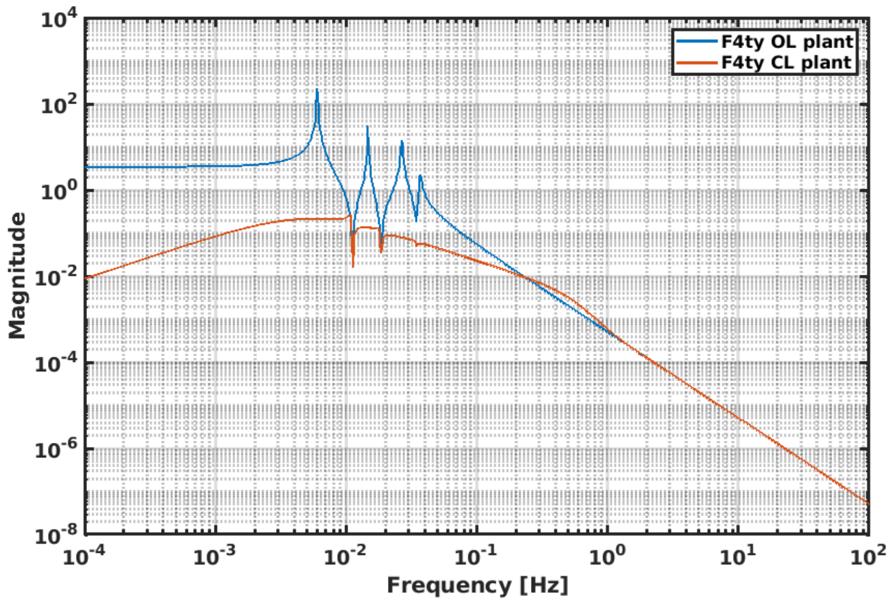
$$\frac{\theta}{F} = (s \cdot I - A)^{-1} \cdot B$$

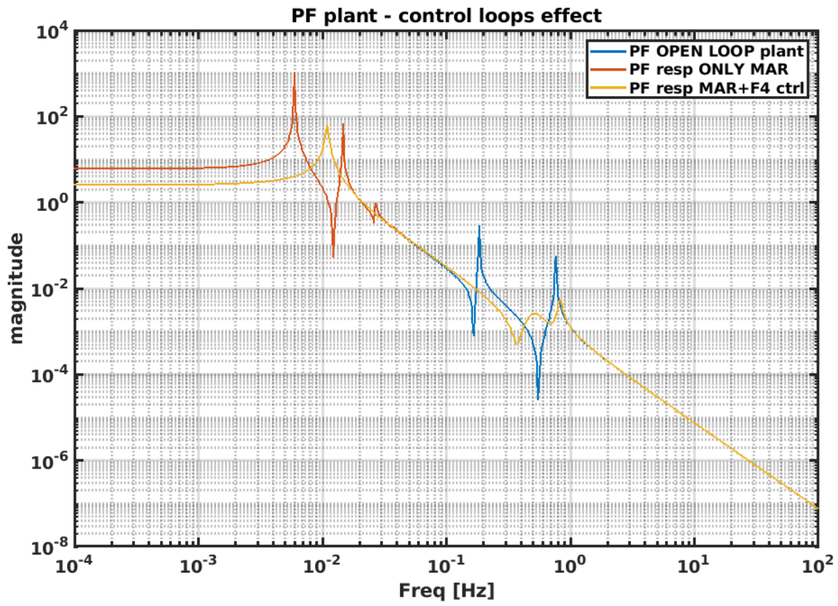
Payload control: time domain analysis





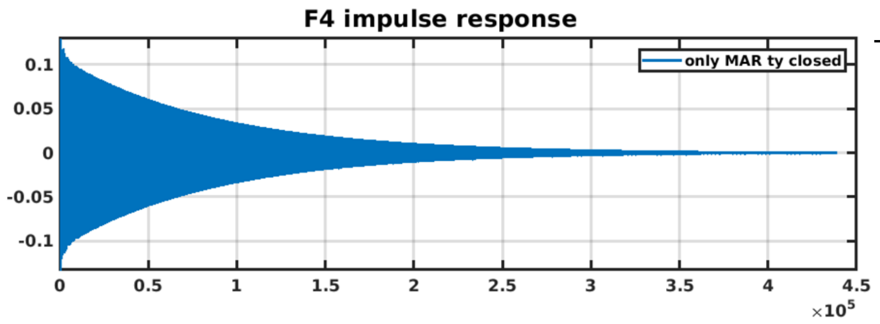
- F4 control (with integral action) is developed. Low bandwidth control (200 mHz).
- Noise coupling to the TM residual motion is negligible.
- Closed-loop plant of the PF is evaluated depending on the hierarchy of the implemented control.



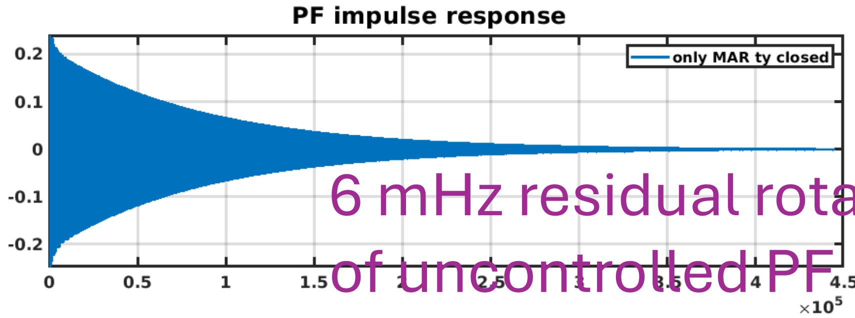


Payload control: time domain response

Impulse response of the MIMO closed loop system has been analyzed. Results report the time scales needed to reach a reduction of the amplitudes of the oscillations down to the 2% of the initial values.

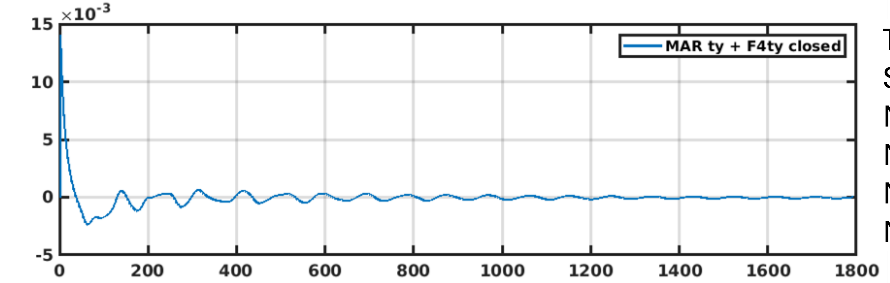


TransientTime: 832.13
SettlingTime: 1689.56
Min: -0.002326
MinTime: 63.48
Max: 0.0140
MaxTime: 1.20

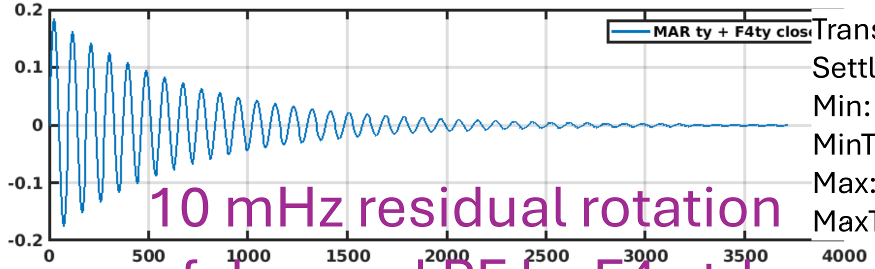


TransientTime: 42583.45
SettlingTime: 56925.68
Min: -0.247
MinTime: 123.75
Max: 0.233
MaxTime: 216.56

6 mHz residual rotation of uncontrolled PF



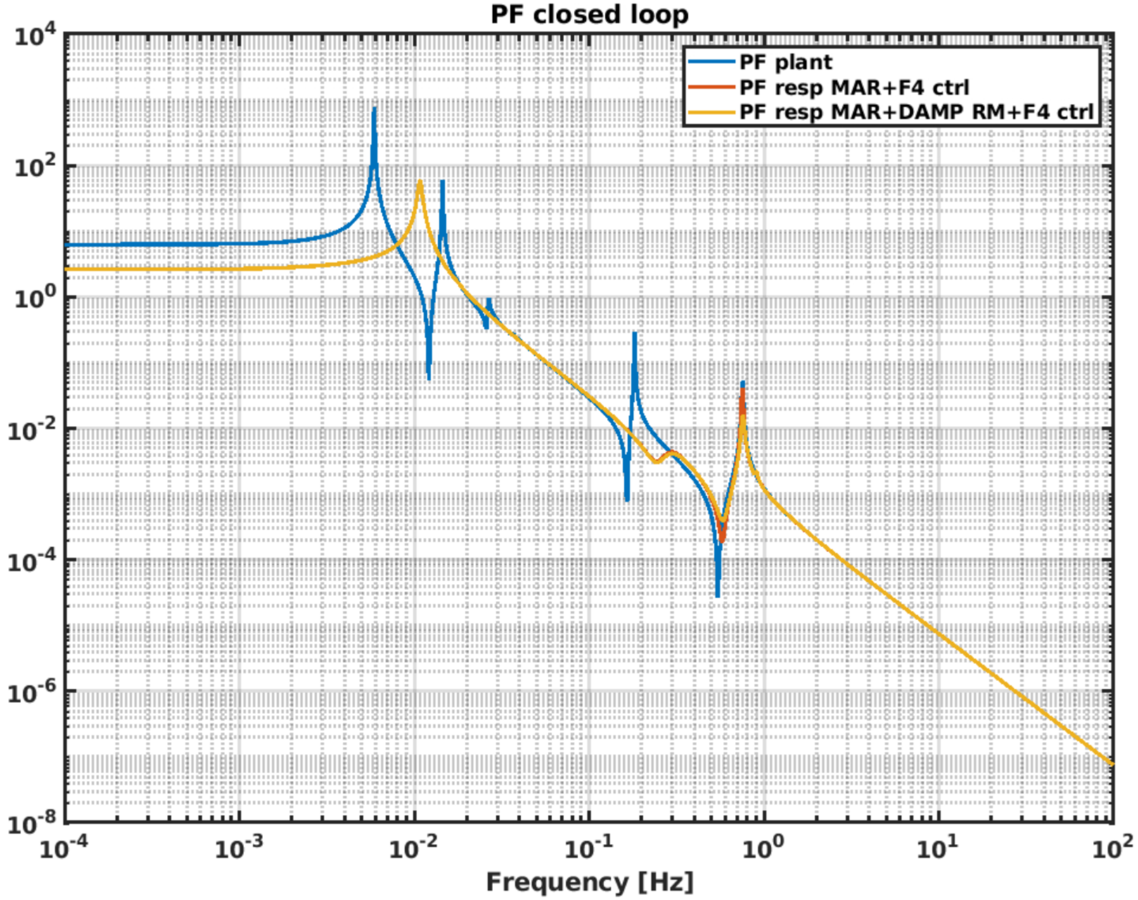
TransientTime: 41573.15
SettlingTime: 55645.13
Min: -0.137
MinTime: 105.90
Max: 0.132
MaxTime: 200.81



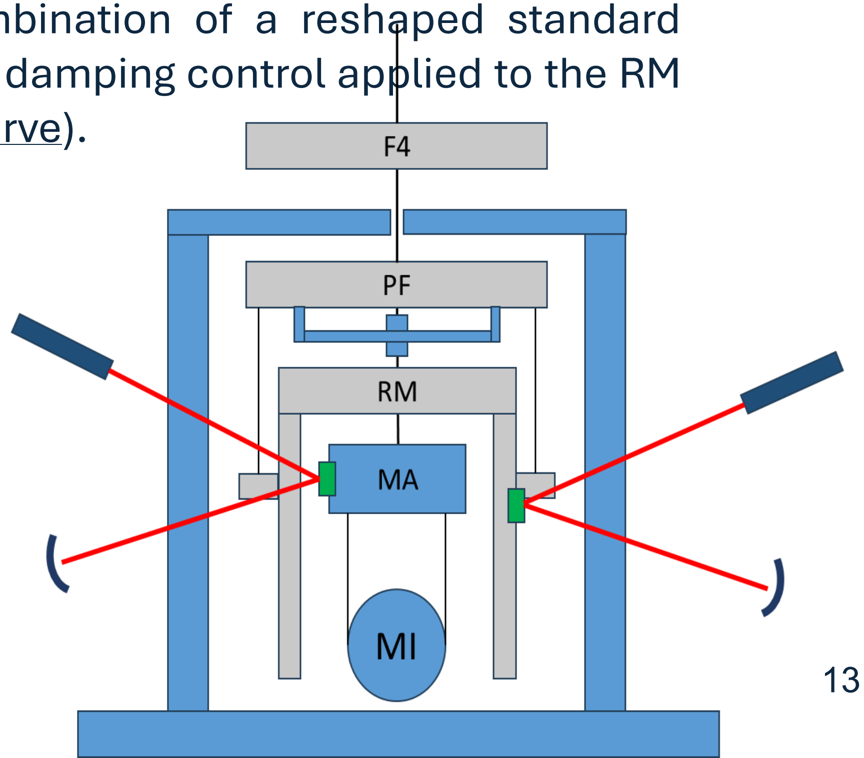
TransientTime: 2563.71
SettlingTime: 3440.158
Min: -0.173
MinTime: 69.09
Max: 0.182
MaxTime: 23.030

10 mHz residual rotation of damped PF by F4 ctrl

Consideration on the marionette sensing (OpLev case)

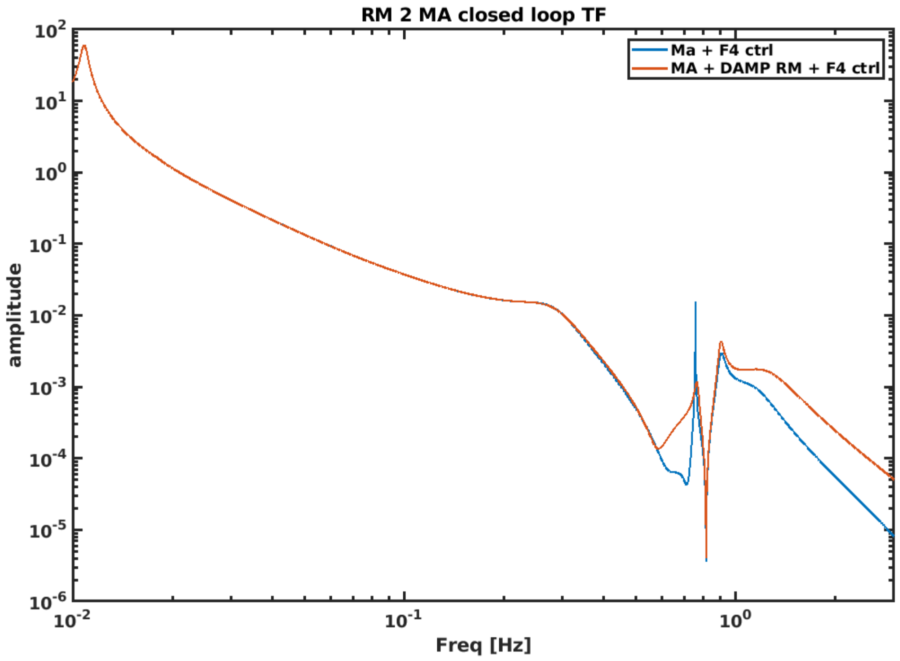


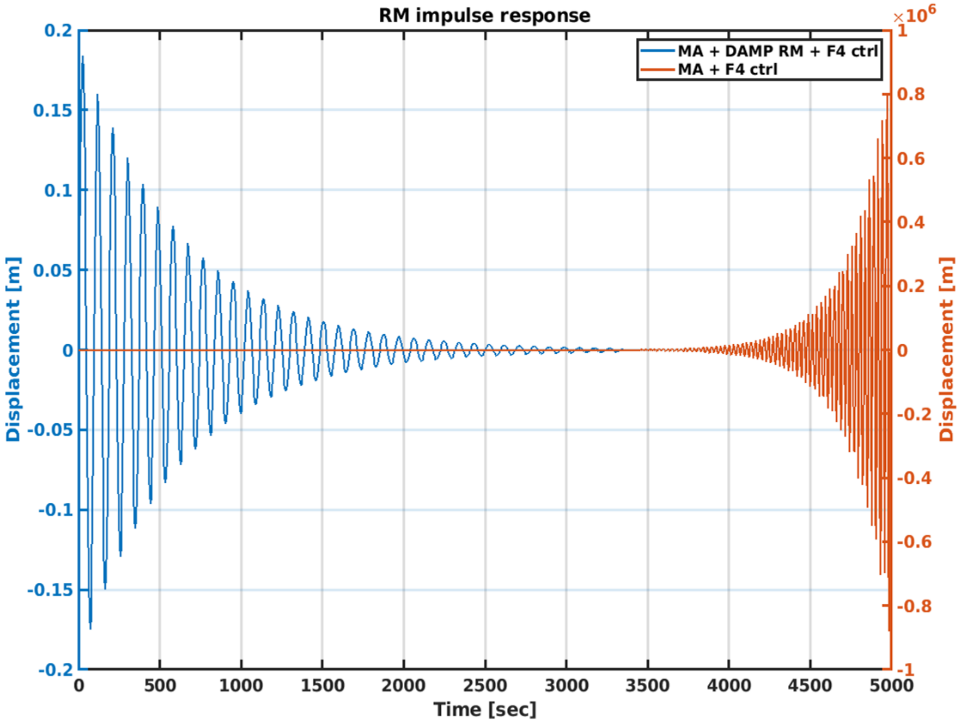
By performing such studies, some questions about the sensing strategies concerning the MAR arise.
By implementing a standard control based on the sensing of the MAR, there is a mode at 700 mHz which is left undamped (red curve). This mode has been associated to the **differential rotational mode between RM and MAR**.
A possible control based on the acquisition of the differential signal has been implemented.
This is the combination of a reshaped standard MAR control + a damping control applied to the RM mode (yellow curve).

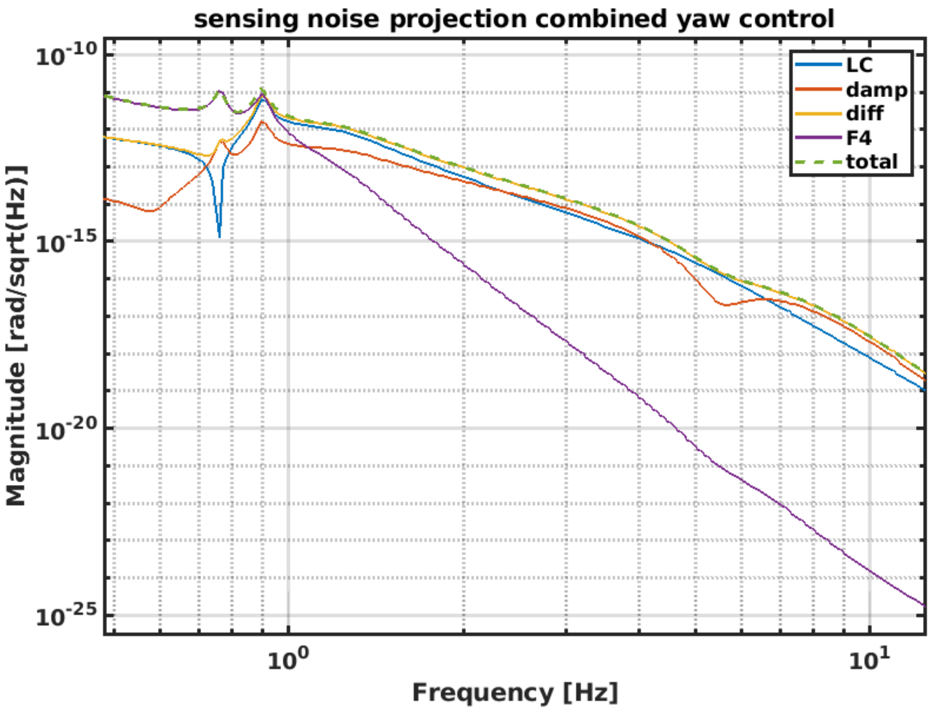


Implementation of a differential control MA-RM (damper on RM diff mode)

Overall payload control: combined control between reshaped standard control on MAR + damper on RM-MA. Resulting noise projections (**Sensing**) are taking into account the use of a double sensor to achieve the differential error signal to be damped.

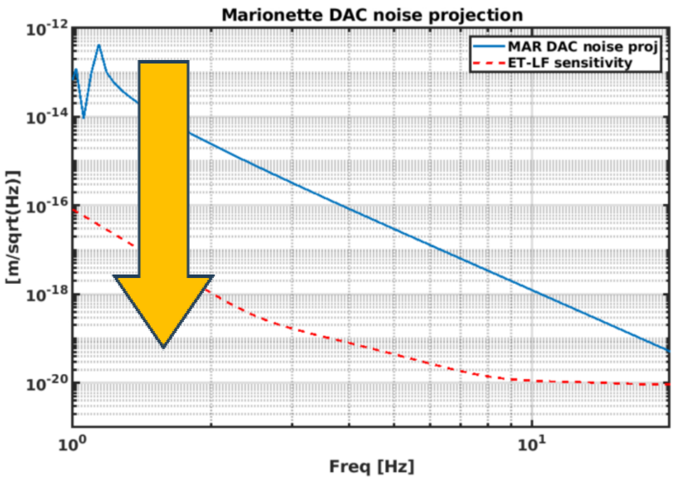




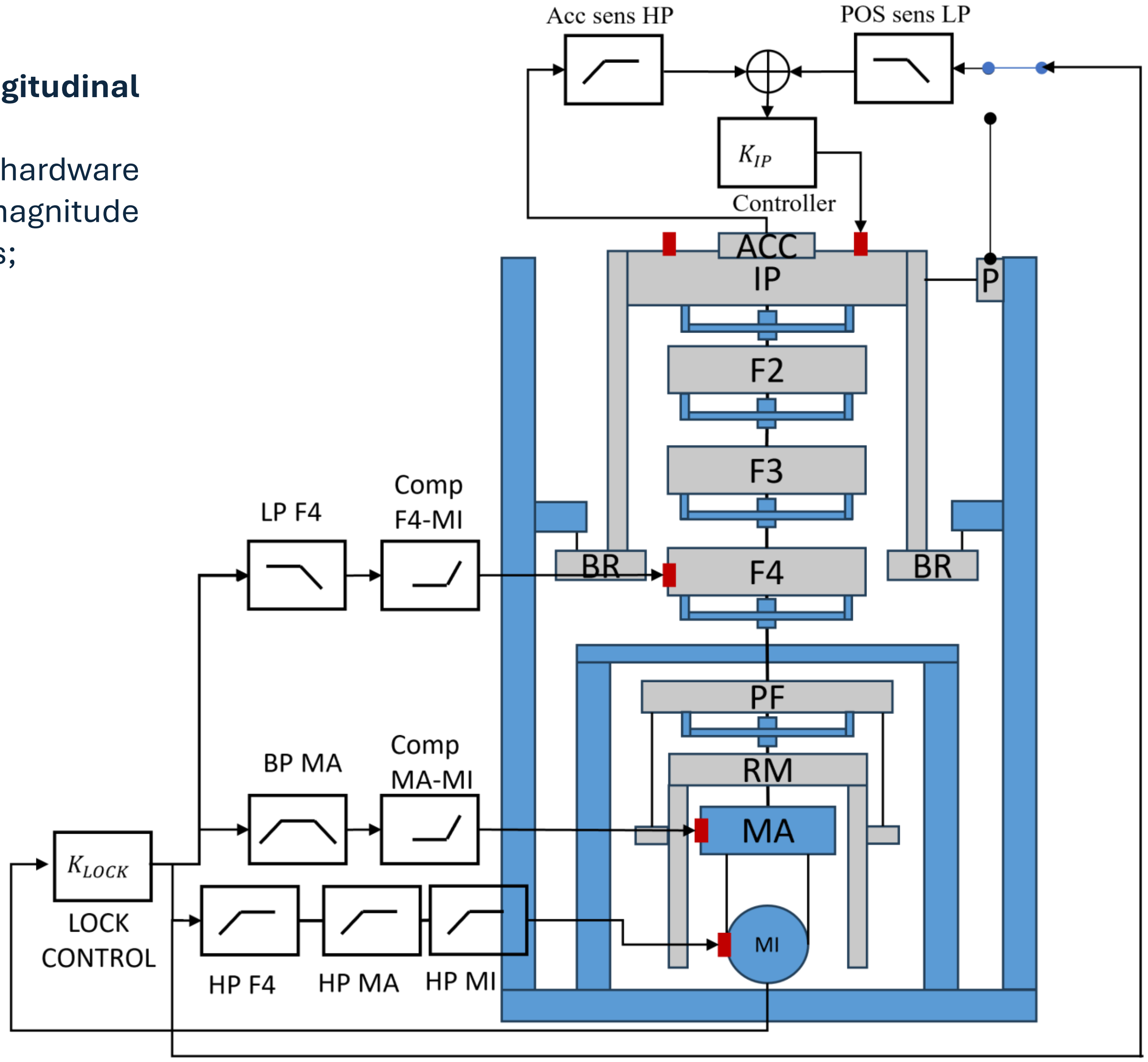


Longitudinal locking hierarchical control

Multi-stages longitudinal Hierarchical Control

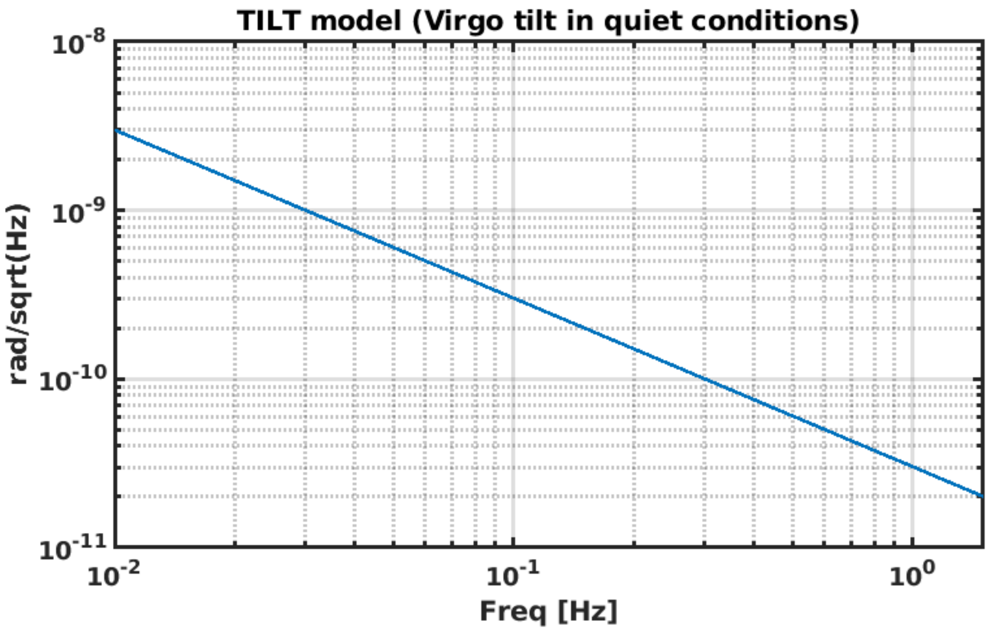


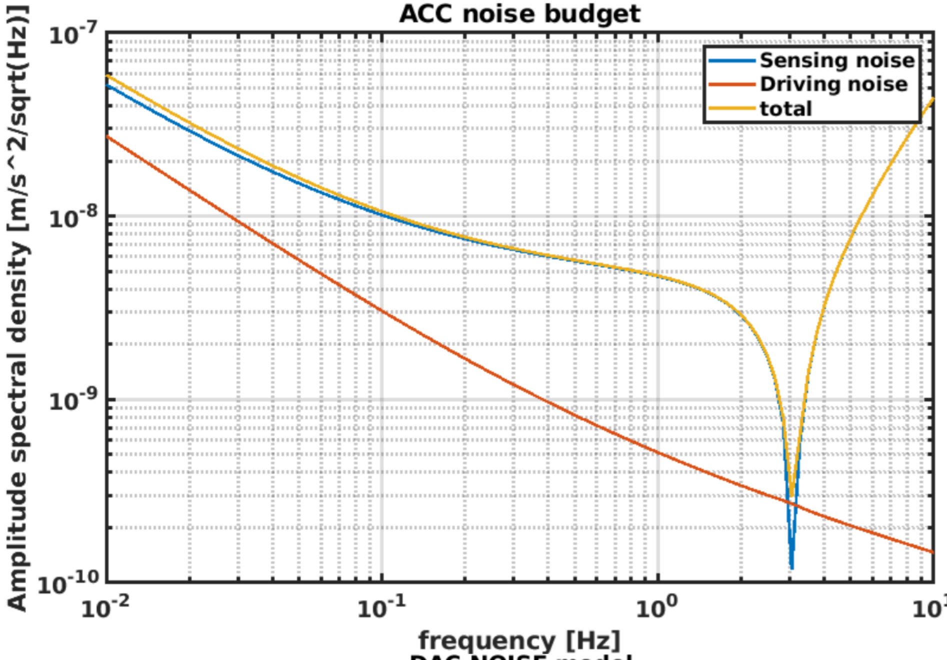
- Need to tackle the **longitudinal actuation noise budget**;
- With the current DAC hardware we are few orders of magnitude far from the requirements;

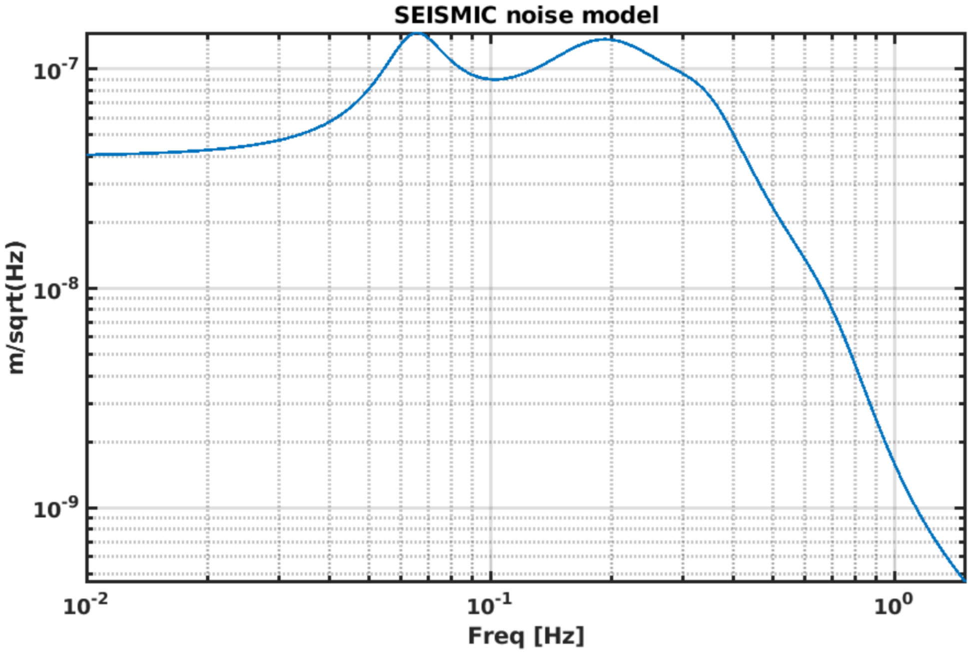


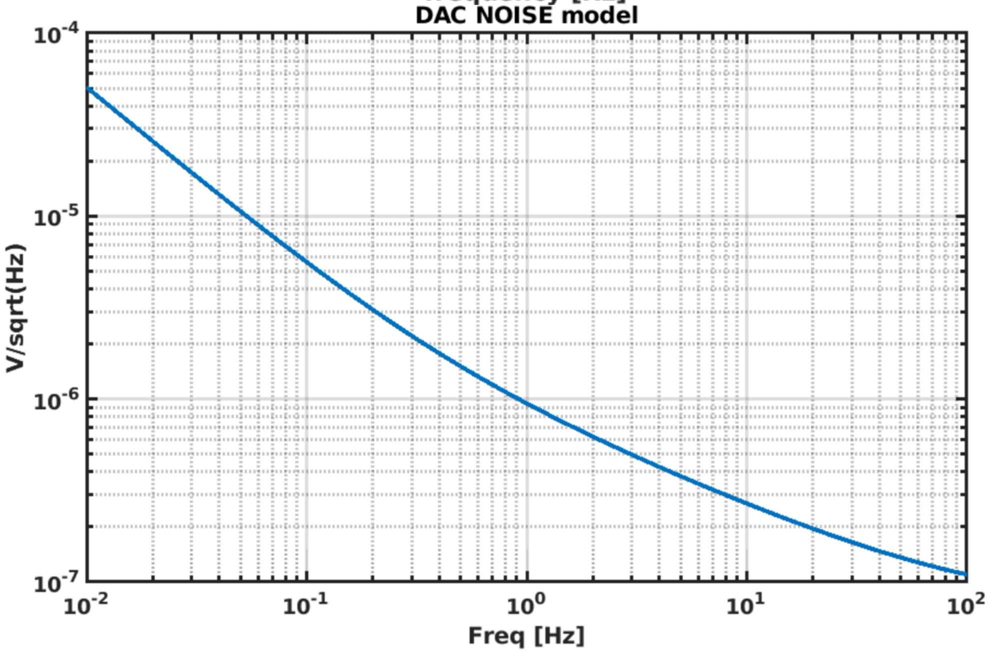
- Low-noise actuation strategy is needed: (**Hierarchical control***);
- Strategy already proven to be effective and stable on Virgo ITF**
- Exploited **actuation** points: **MIR, MAR, F4, IP** (for GIPC).

Initial assumptions for input noise models

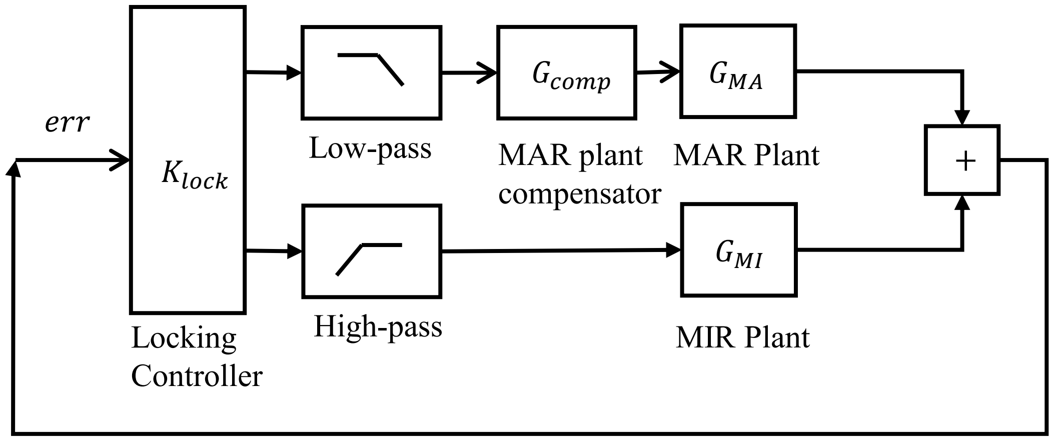


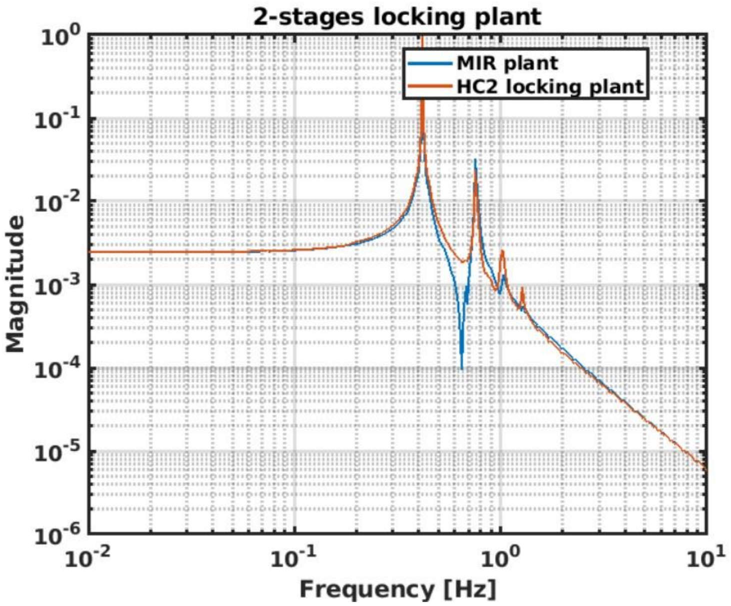


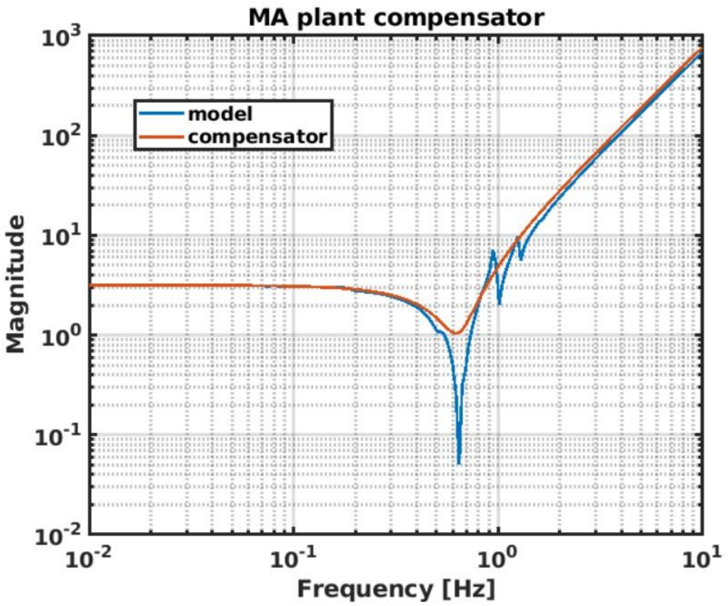




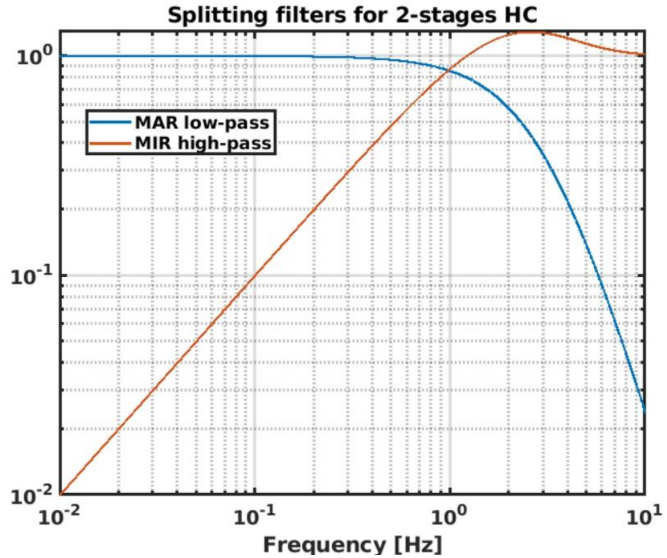
«State of the art»: Two stages lock distribution



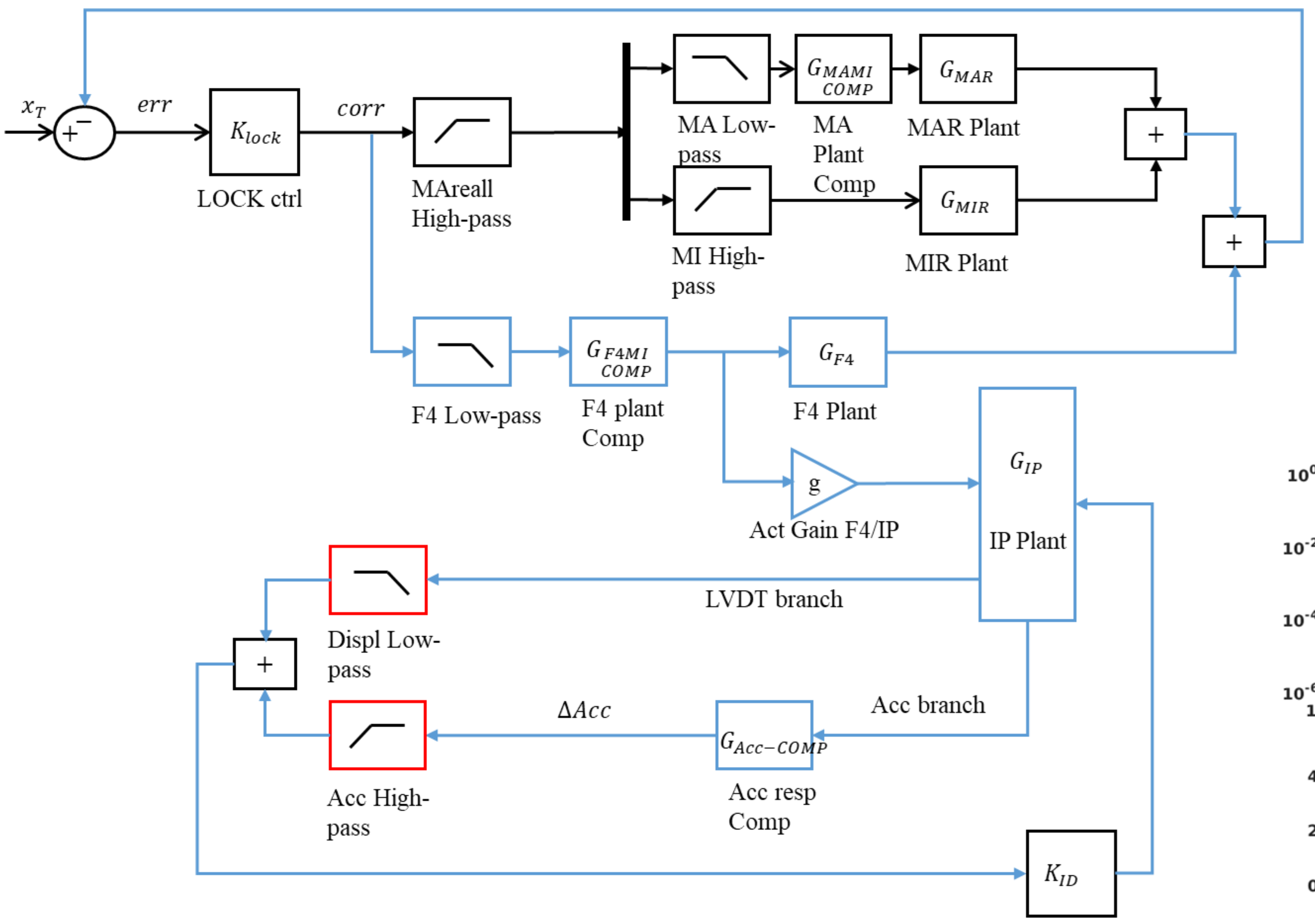


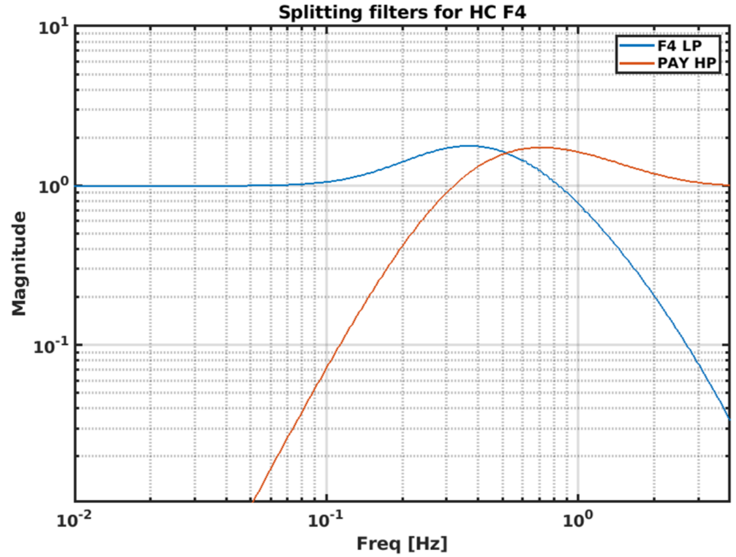


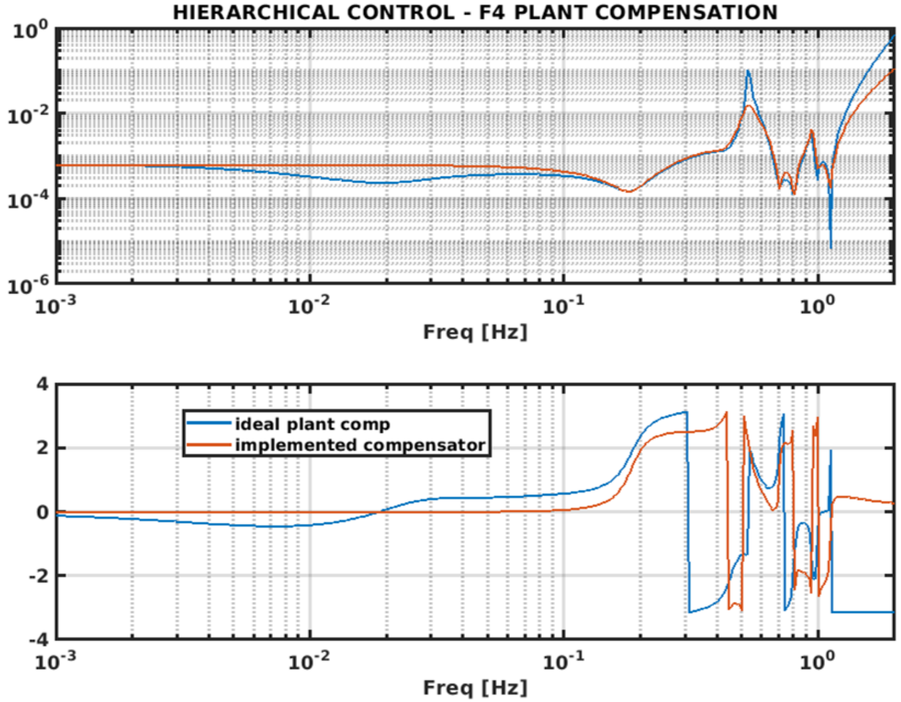
- The basic correction distribution strategy used in Virgo consists in properly reallocate the locking correction among the actuation points of the bottom stage (MAR + MIR).
- This is done by sending the low-frequency part of the actuation force to the marionette, thus reducing of several orders of mag the correction needed at the mirror level.
- To do so, a compensation of the mechanics, together with a proper splitting filters design is needed.



Multi-stages longitudinal Hierarchical Control: MI-MA-F4





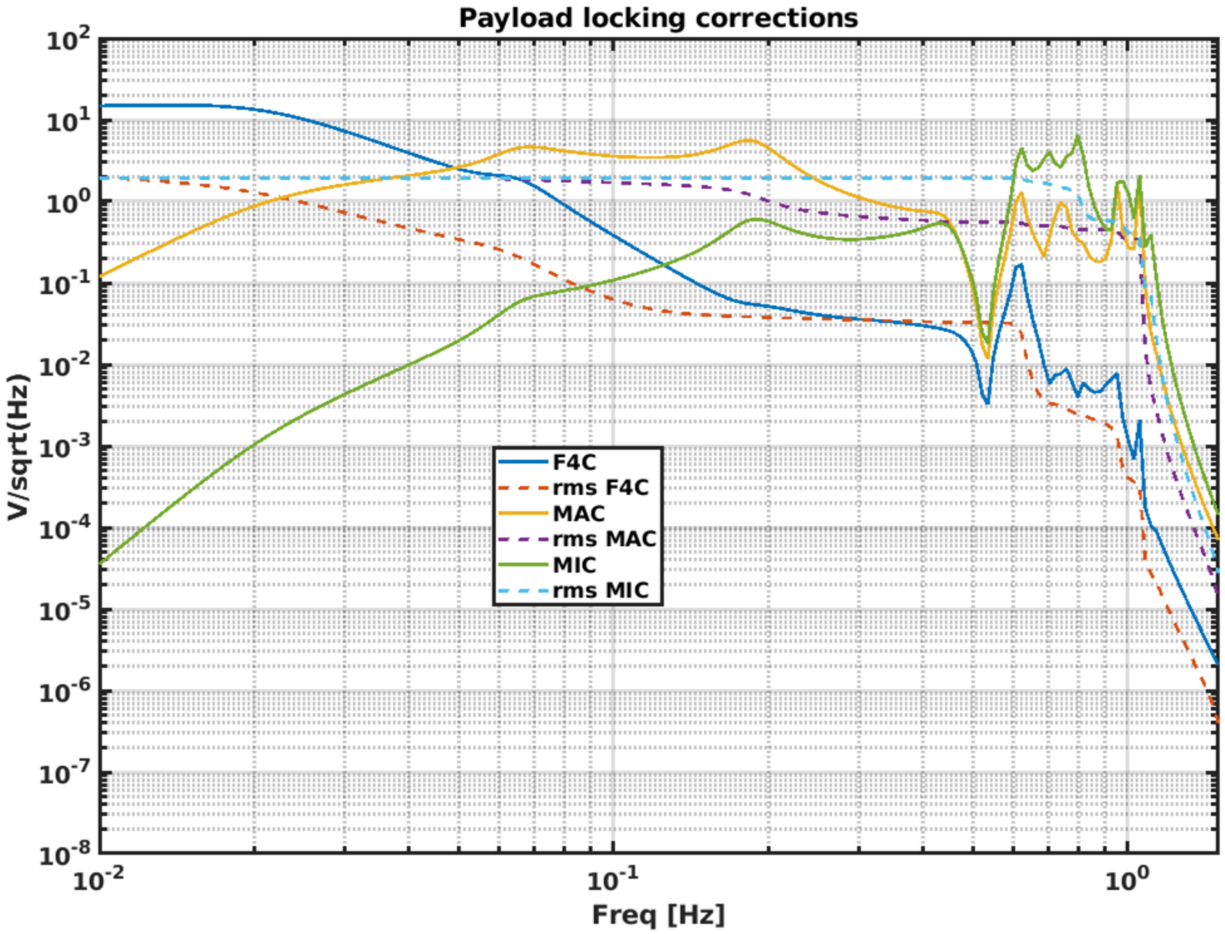


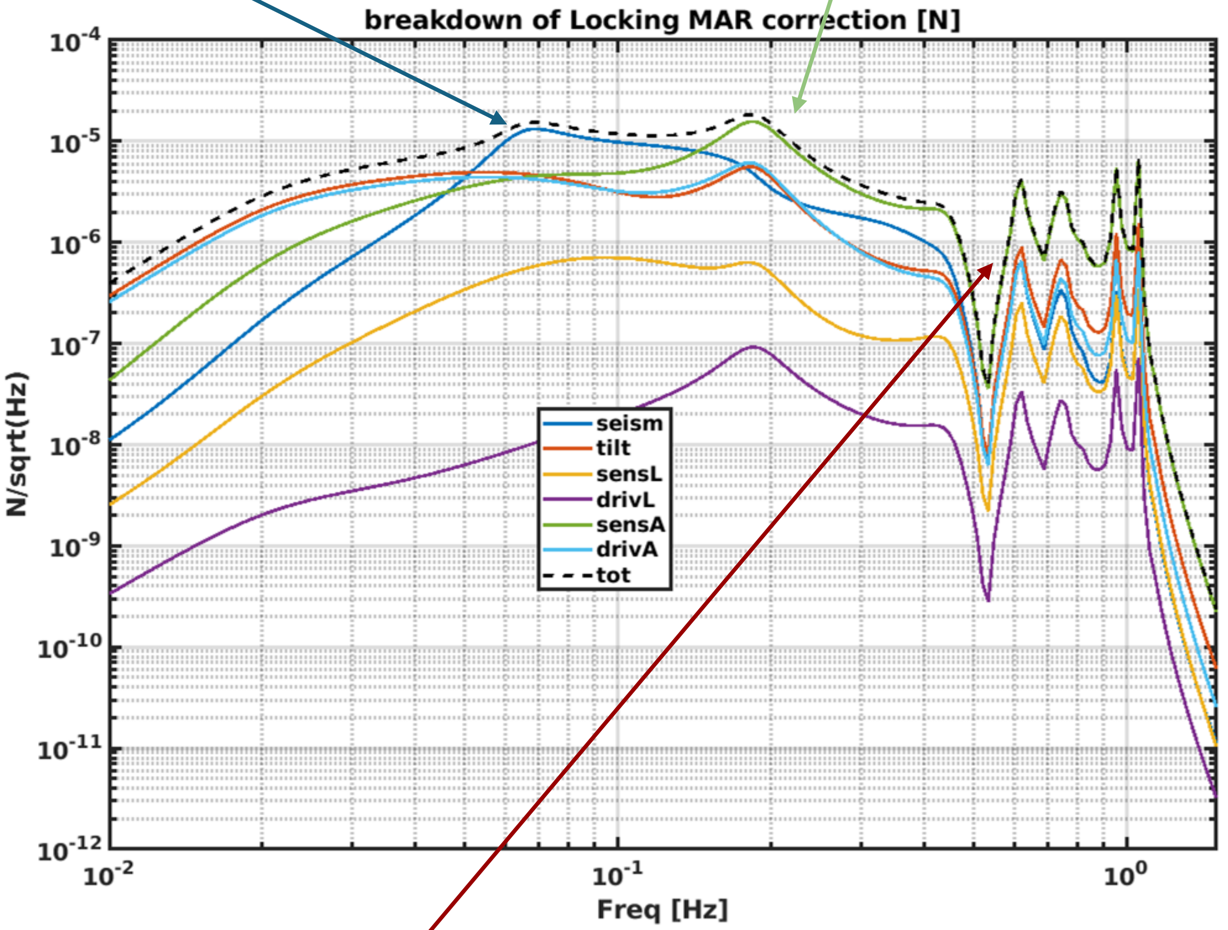
Multi-stages longitudinal Hierarchical Control: MI-MA-F4

Room for improvement:

NO GIPC implemented

NO ACC noise optimization

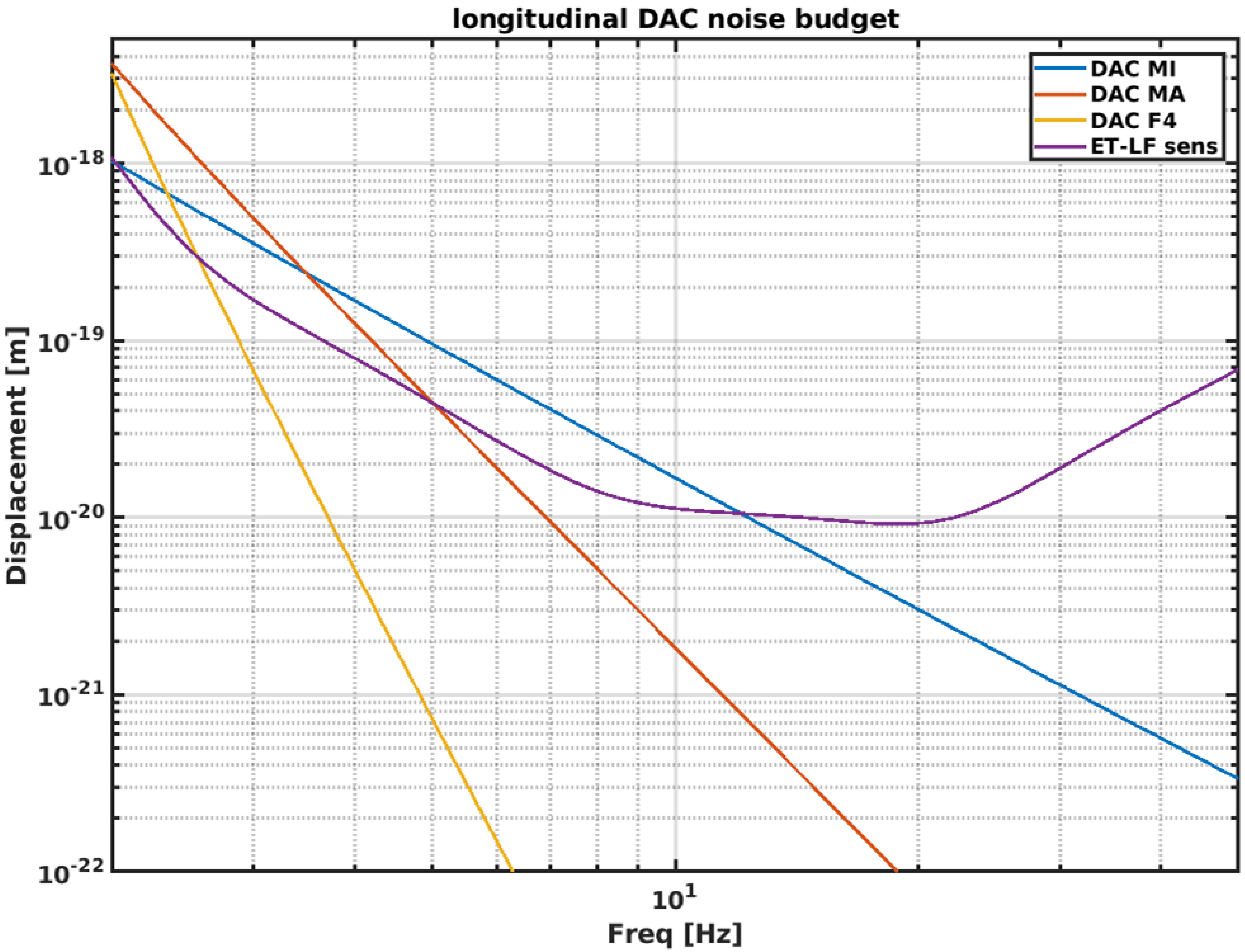




Splitting filters can be also moved ahead

- Actuators gains tuned to have a **max correction of 2 V RMS**;
- Standard inertial damping with 50 mHz blending;

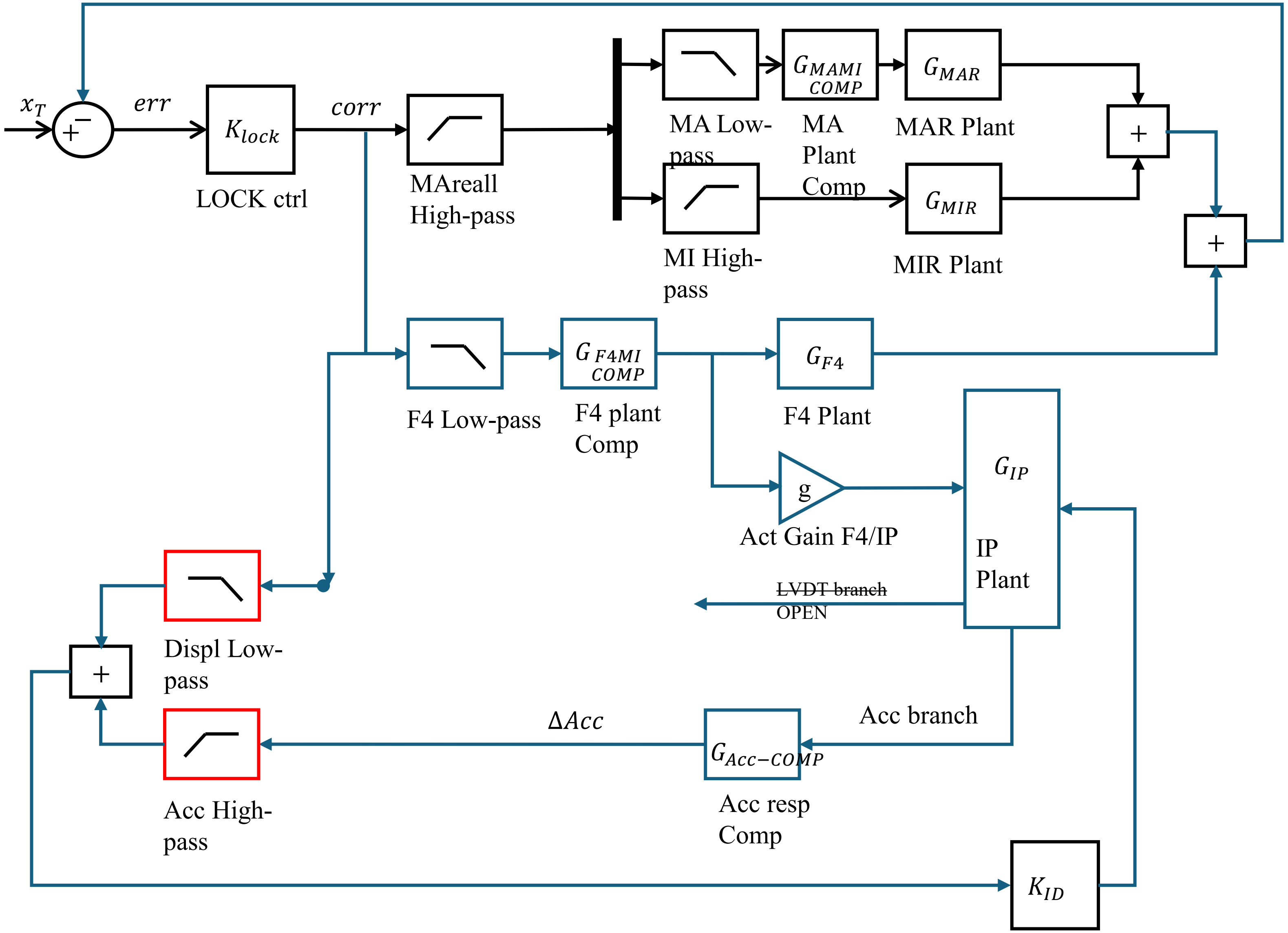
Longitudinal DAC noise budget (preliminary)



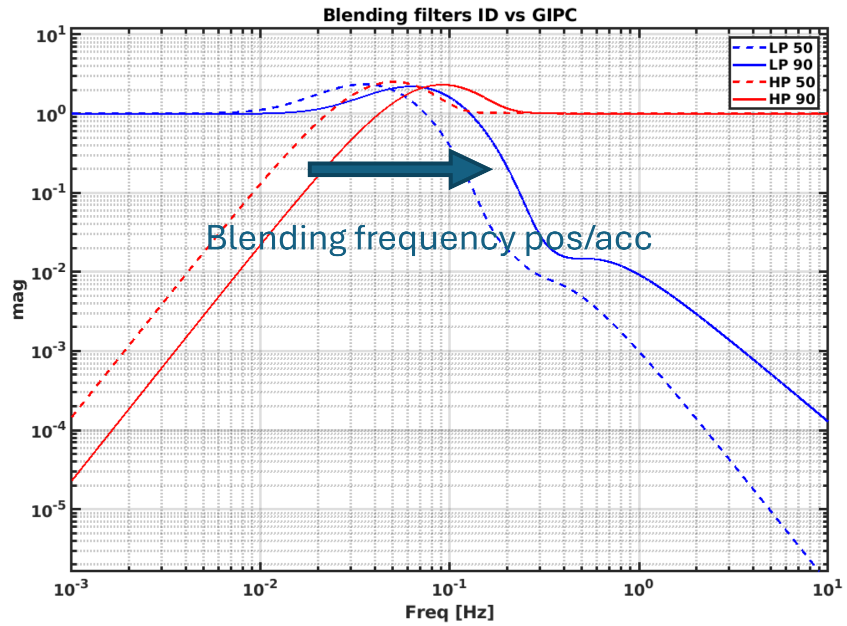
DAC noise budget with the following control configuration:

- Longitudinal correction splitted between MI, MA and F4;
- Actuators gains tuned to have a max correction of 2 V RMS;
- Standard inertial damping with 50 mHz blending;
- NO GIPC;
- NO HCIP;
- NO TILT control;
- ACC noise not optimized;
- Splitting filters not optimized;
- No DAC shaping.

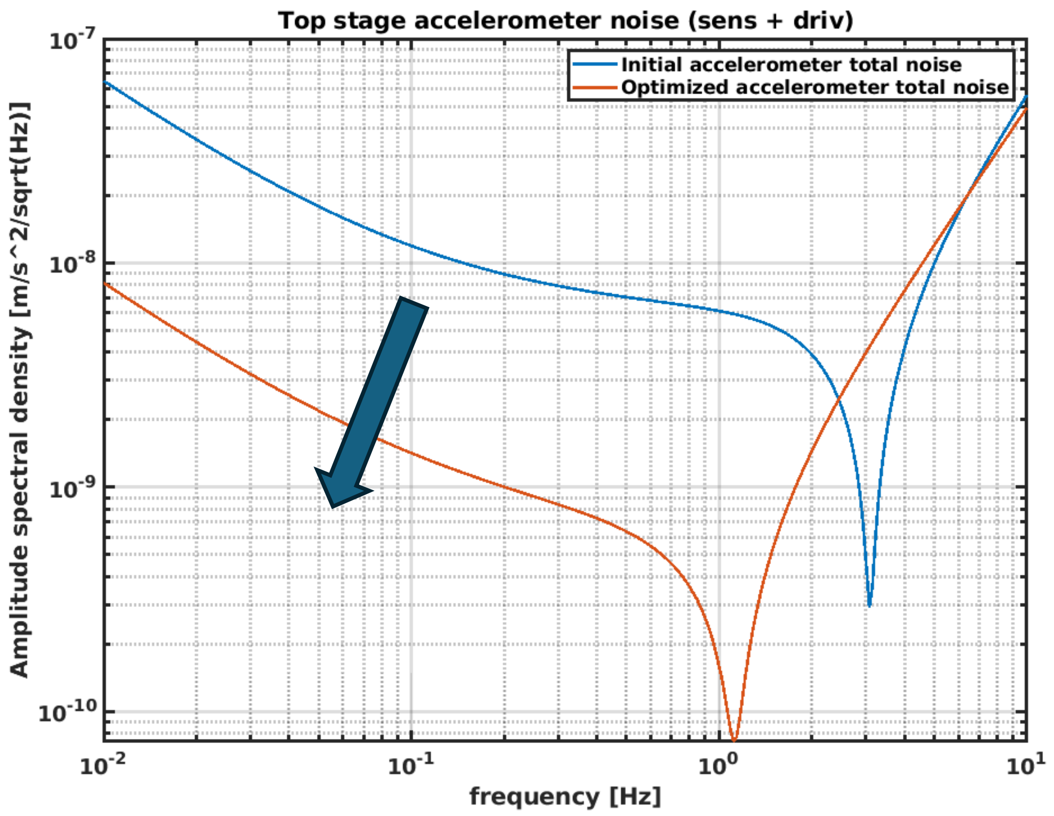
Three stages hierarchical control + GIPC



- This strategy has been tested together with the GIPC (Global Inverted Pendulum Control), in which LVDT signals are replaced by the **differential locking correction** signal;
- Blending frequency between the *Δ* accelerometer signal can be pushed up to potentially hundreds of mHz, without reinjecting the microseismic noise.



Optimization of the TOP stage Accelerometer noise level

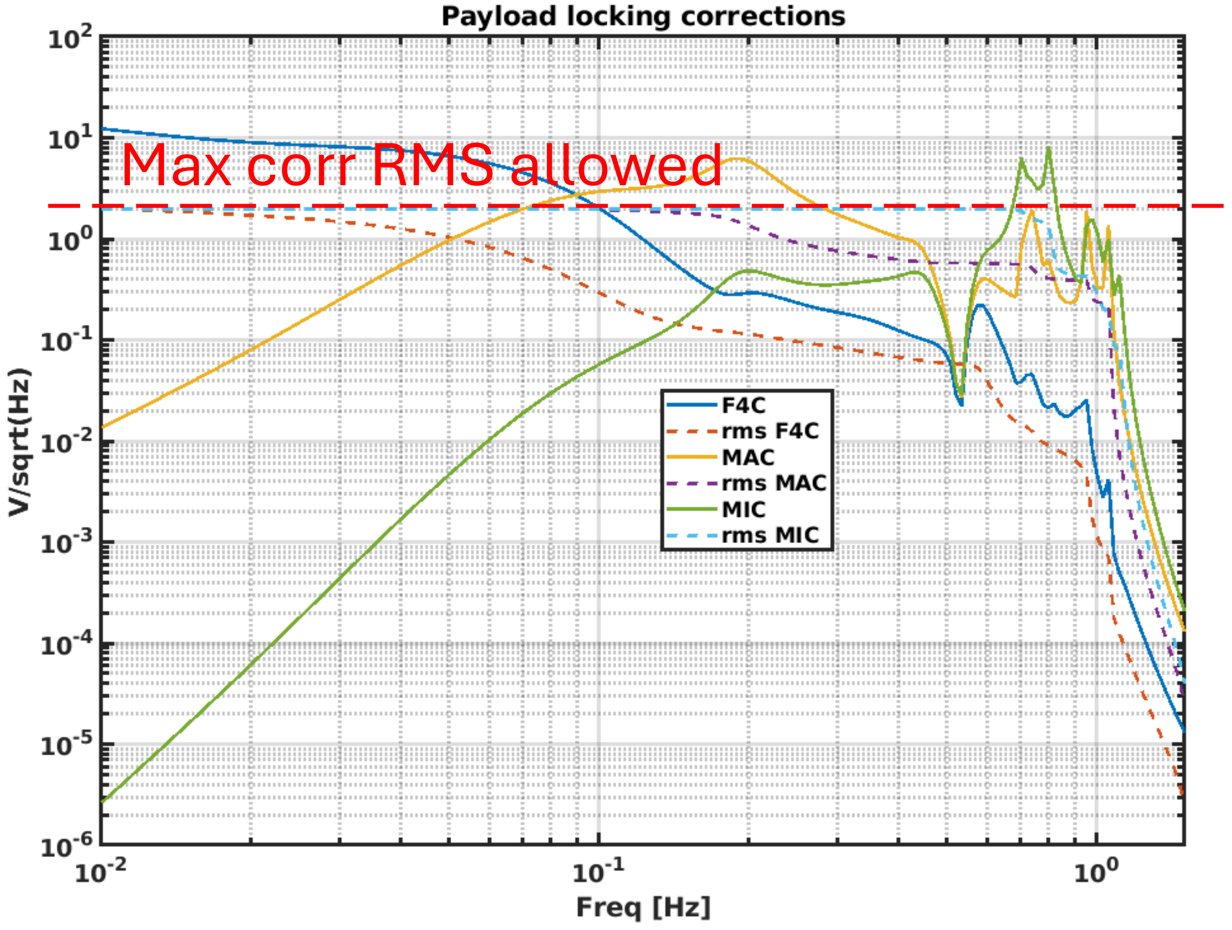


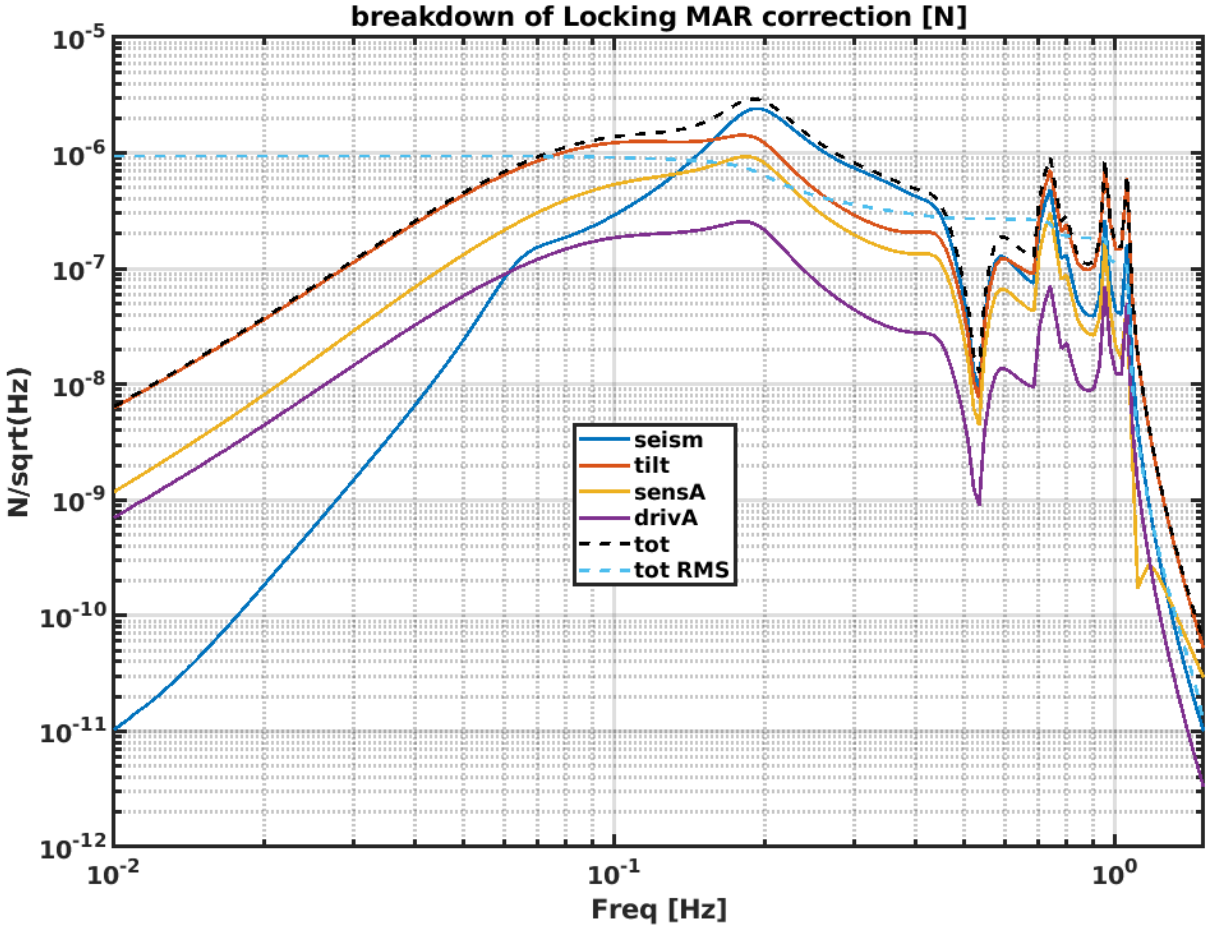
- Residual correction would be limited by the accelerometer sensing noise rentroiduced by the correction loops.
- Current noise levels achieved by the Virgo top stage accelerometer would limit the performance.
- Changing the mechanics of the accelormeter (1Hz oscillator mass) we can decrease the overall noise level of about a factor ≈10 in the region of 100 mHz.

Design requirement for the accelerometer?

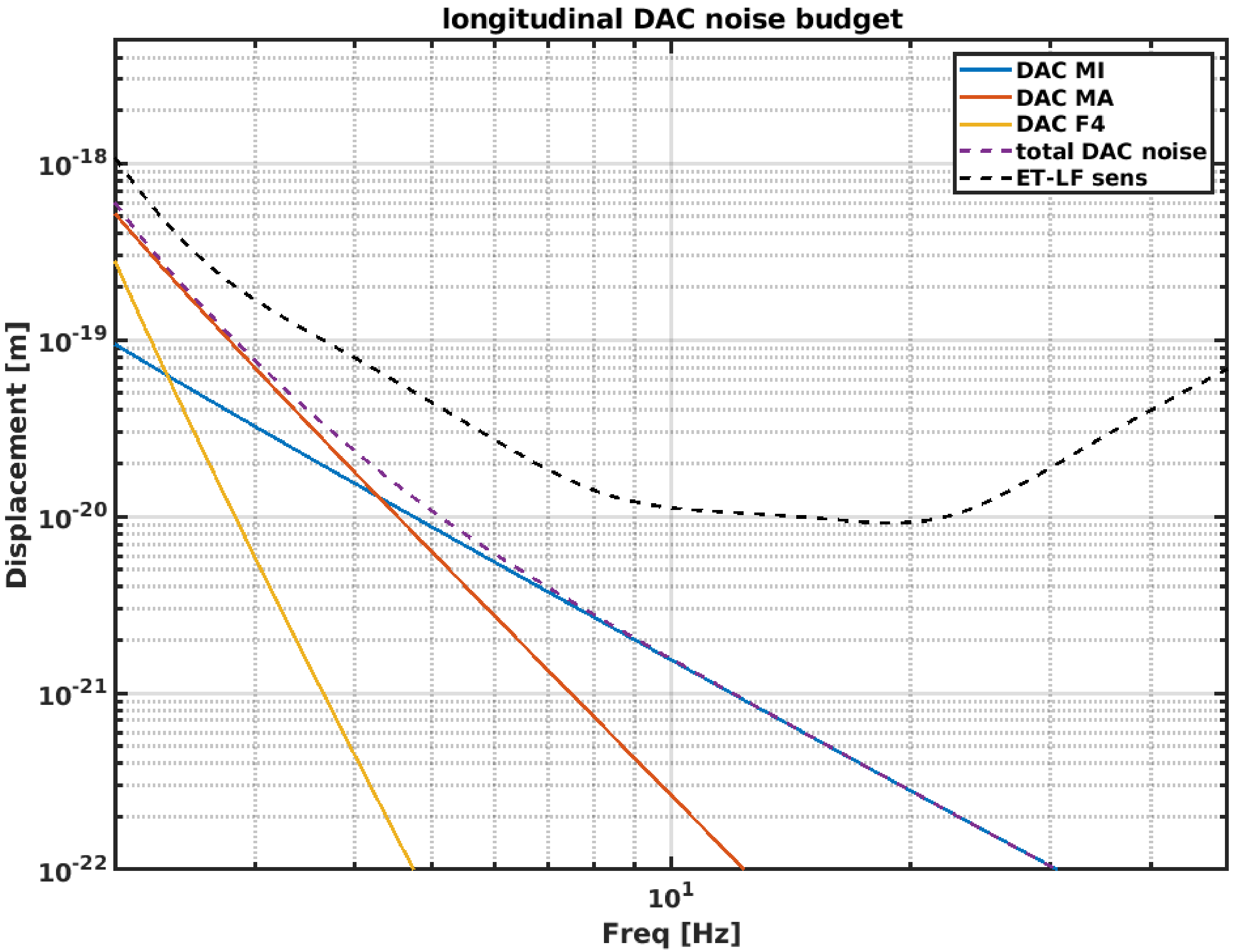
Sensitivity of 1.5 nm/s^2 ASD @ 100 mHz.

Hierarchical Control: ‘opt’ MI-MA-F4 + GIPC + Optimized TOP stage Accelerometer





Longitudinal DAC noise budget



DAC noise budget with the following control configuration:

- Longitudinal correction splitted between MI, MA and F4;
- Actuators gains tuned to have a max correction of 2 V RMS;
- Inertial damping with GIPC configuration: 90 mHz blending;
- TOP stage ACC optimized;
- Splitting filters optimized;
- NO reallocation to IP;
- NO TILT control;
- No DAC shaping.

Concluding remarks

Progress on the control strategy of the seismic isolation system and the cryogenic payload have been performed. The study is based on a iterative process based e.g. on the feedback received on last 2025 Elba meeting.

- Effect of the radiation pressure for ET-LF;
- Update on the angular control strategy: angular noise coming from yaw AA control is still limiting. Problem needs to be addressed with proper R&D.
- Single wire option suspension for cryo-PAY platform explored. Time domain analysis of the whole system and the control implementation have been addressed. Considerations on the need for relative motion sensor between MAR and cage (RM) arose.

- Longitudinal control with correction force reallocation strategy implemented: no need to modify the noise level of the DAC, thanks to a proper control strategy.

The overall strategy enhanced the 'required' levels of performance plausibly needed by tha hardware in order to reach the sensitivity goals, which are summarized below:

Device	Noise level	@ freq
Angular displacement sensor (OpLev)	10^-12 rad/sqrt(Hz)	Flat
QPD for AA	10^-14 rad/sqrt(Hz)	Flat
Top Stage Accelerometer	1.5 nm/s^2 ASD	100 mHz
DAC noise	5e-6 V ASD 75e-9 V/sqrt(Hz)	100 mHZ Flat floor @100 Hz

Open points and next steps:

- VERTICAL control and attenuation
- Heat link implementation.