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Lightsaber: A simulator of the angular sensing and control system for GW detectors

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ISB workshop

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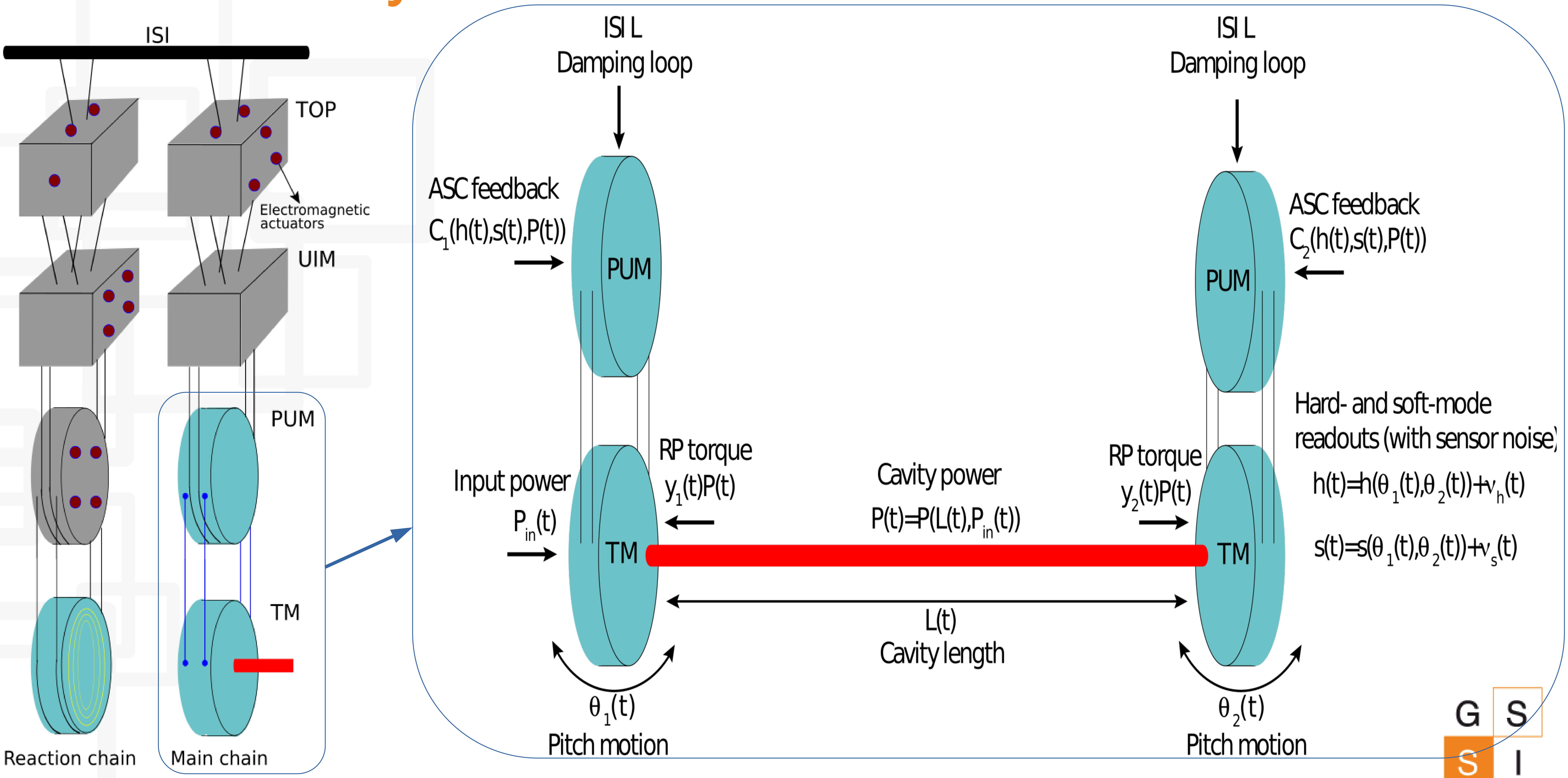
Program

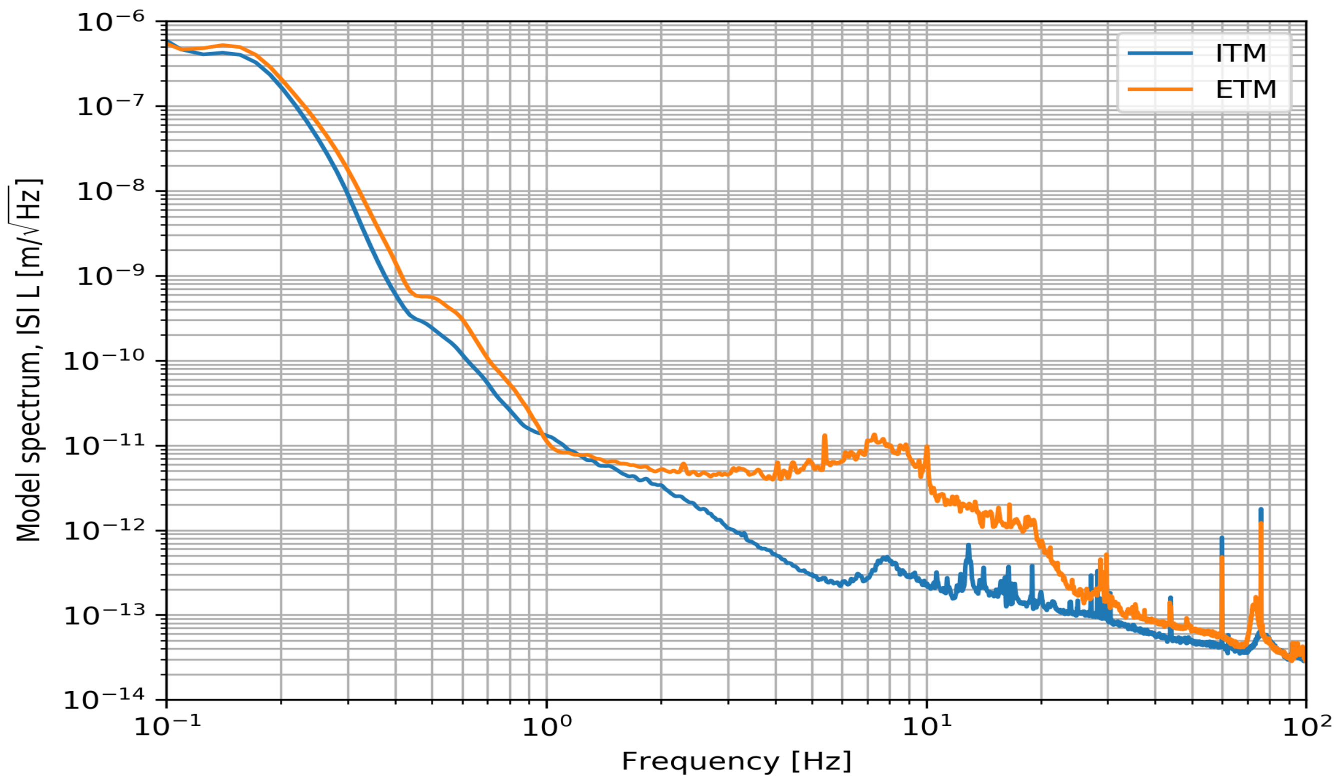
G S
S I

Simulated system

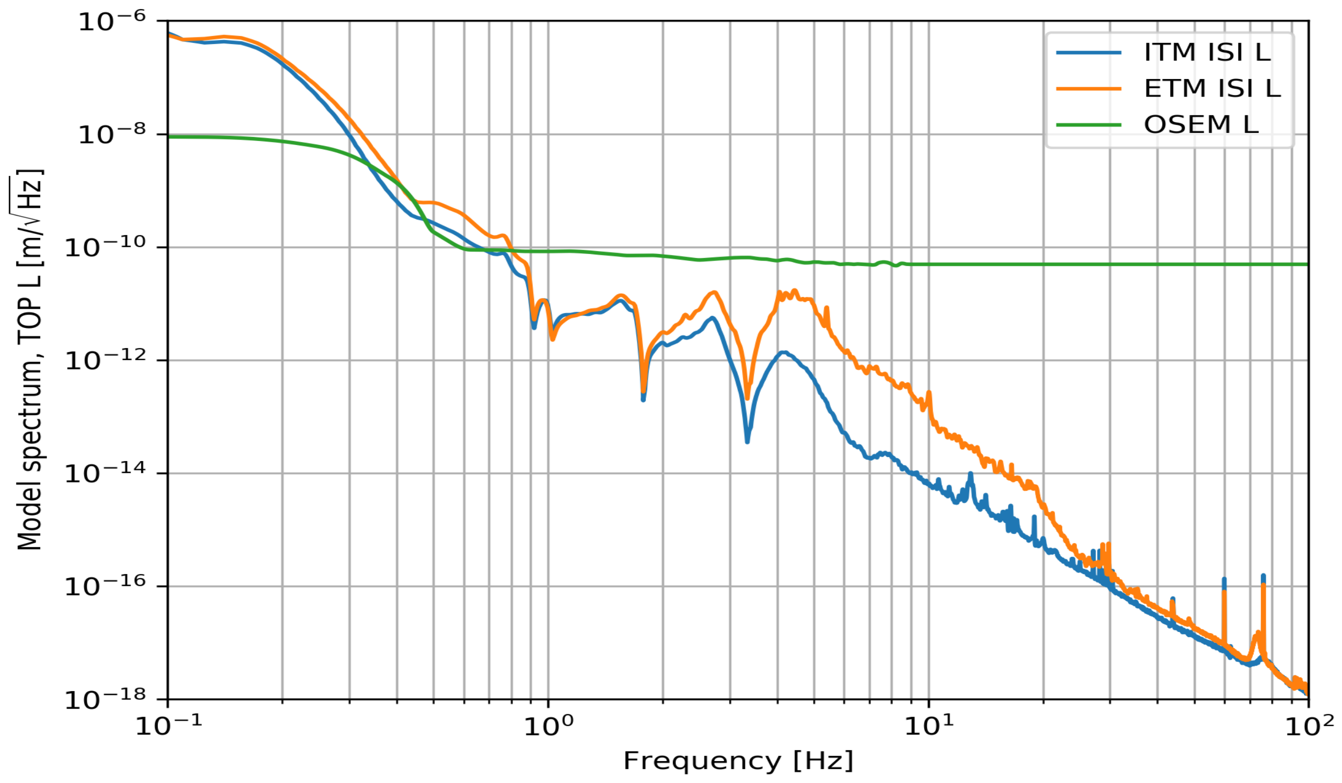


GSSI

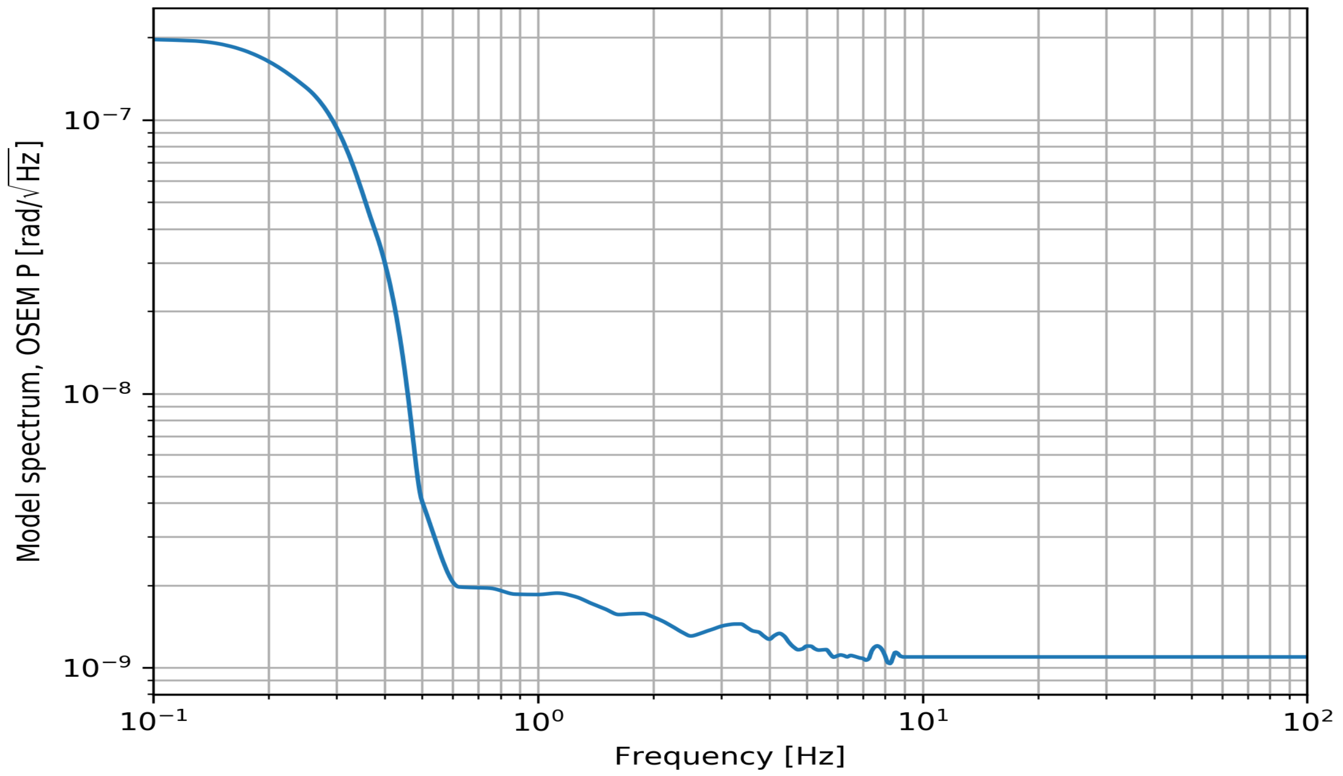
Input noises



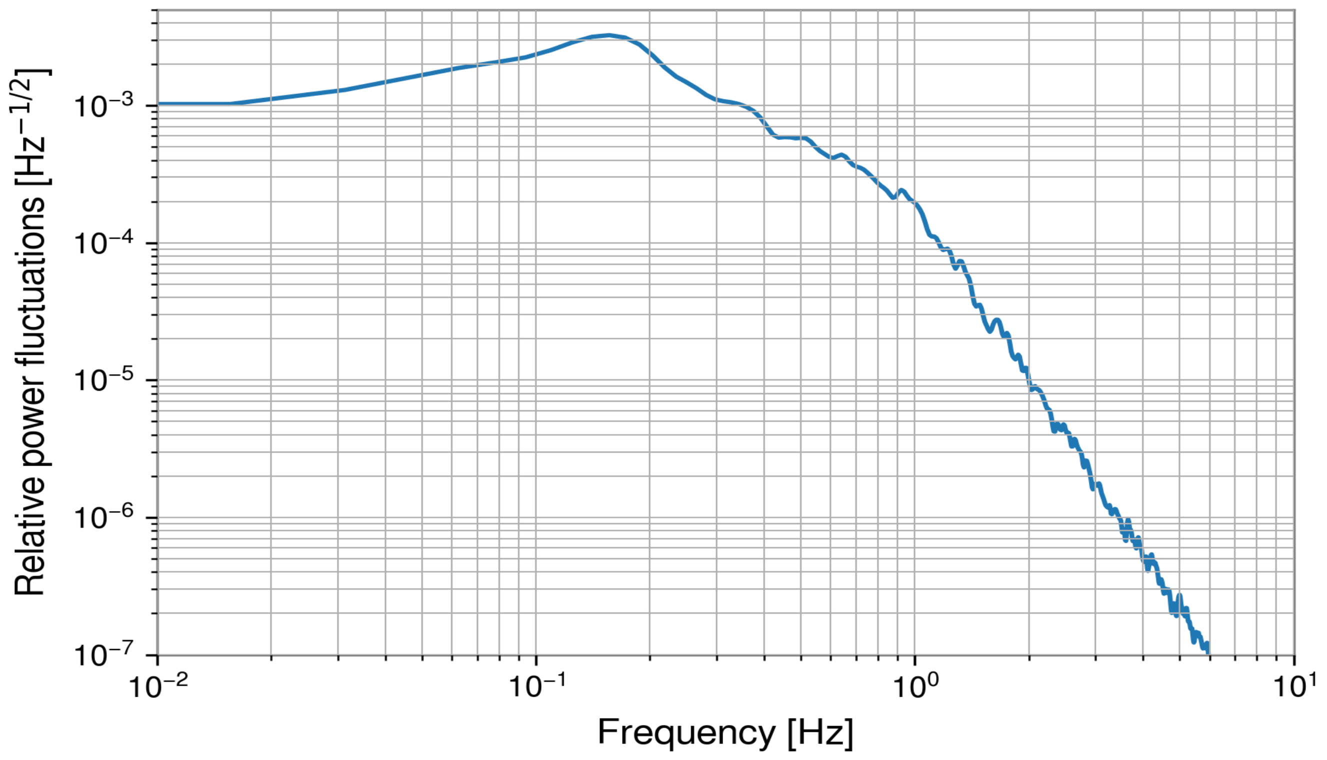
a) ISI L



b) TOP L

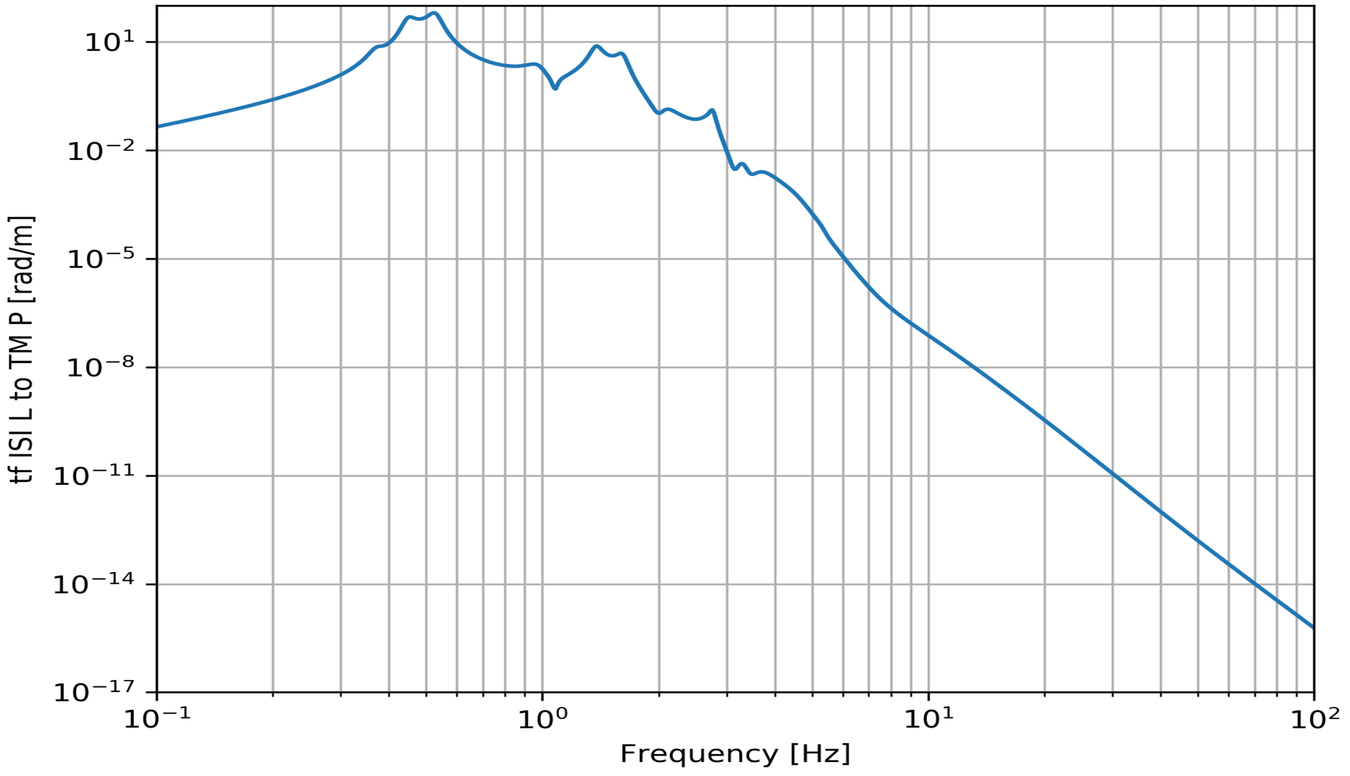


c) OSEM P

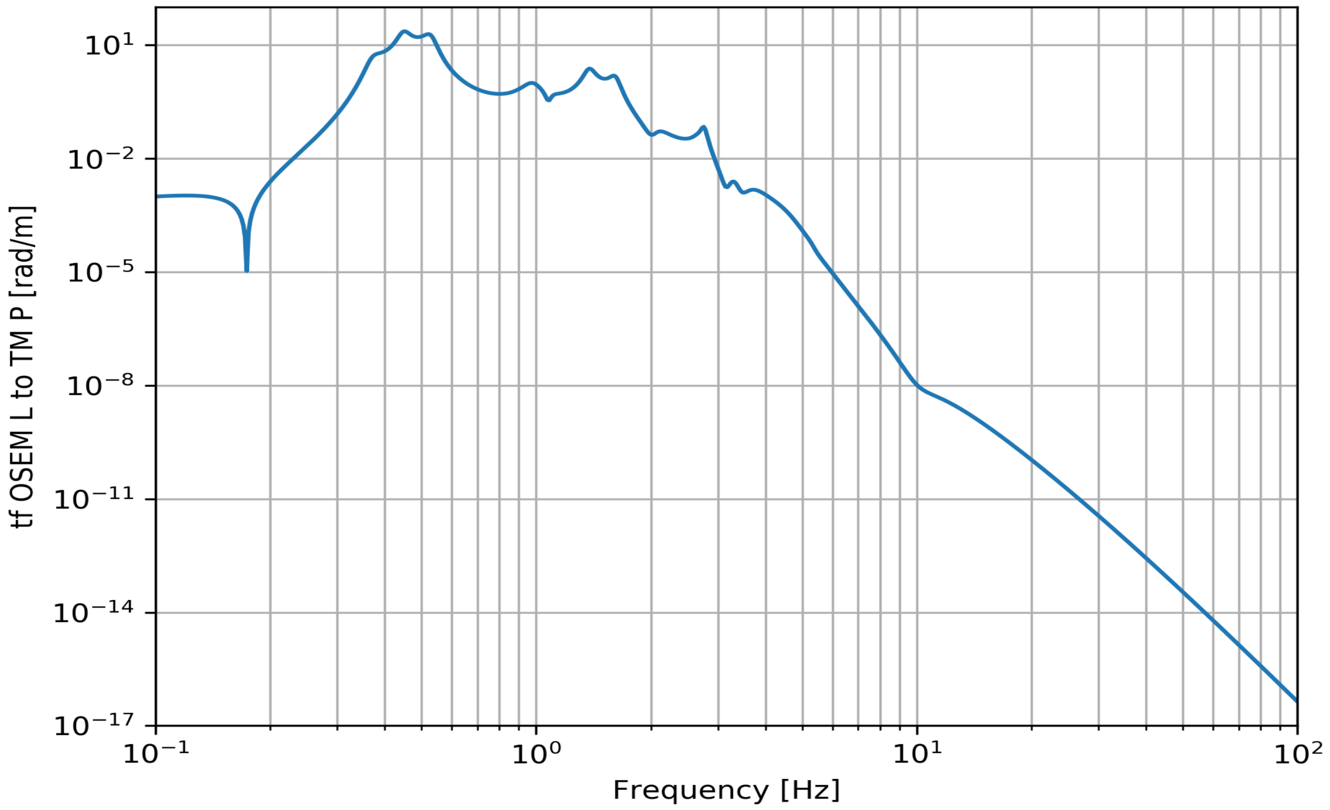


d) RIN

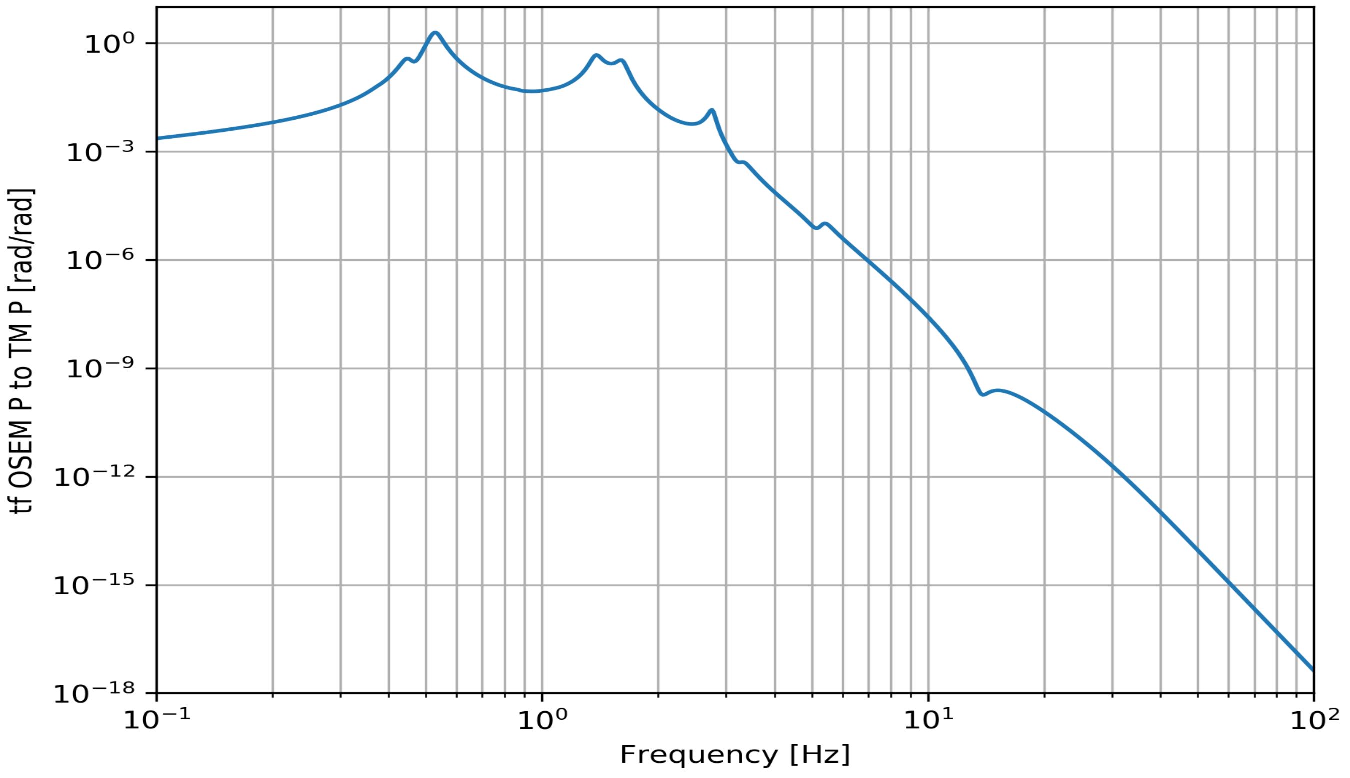
Transfer functions



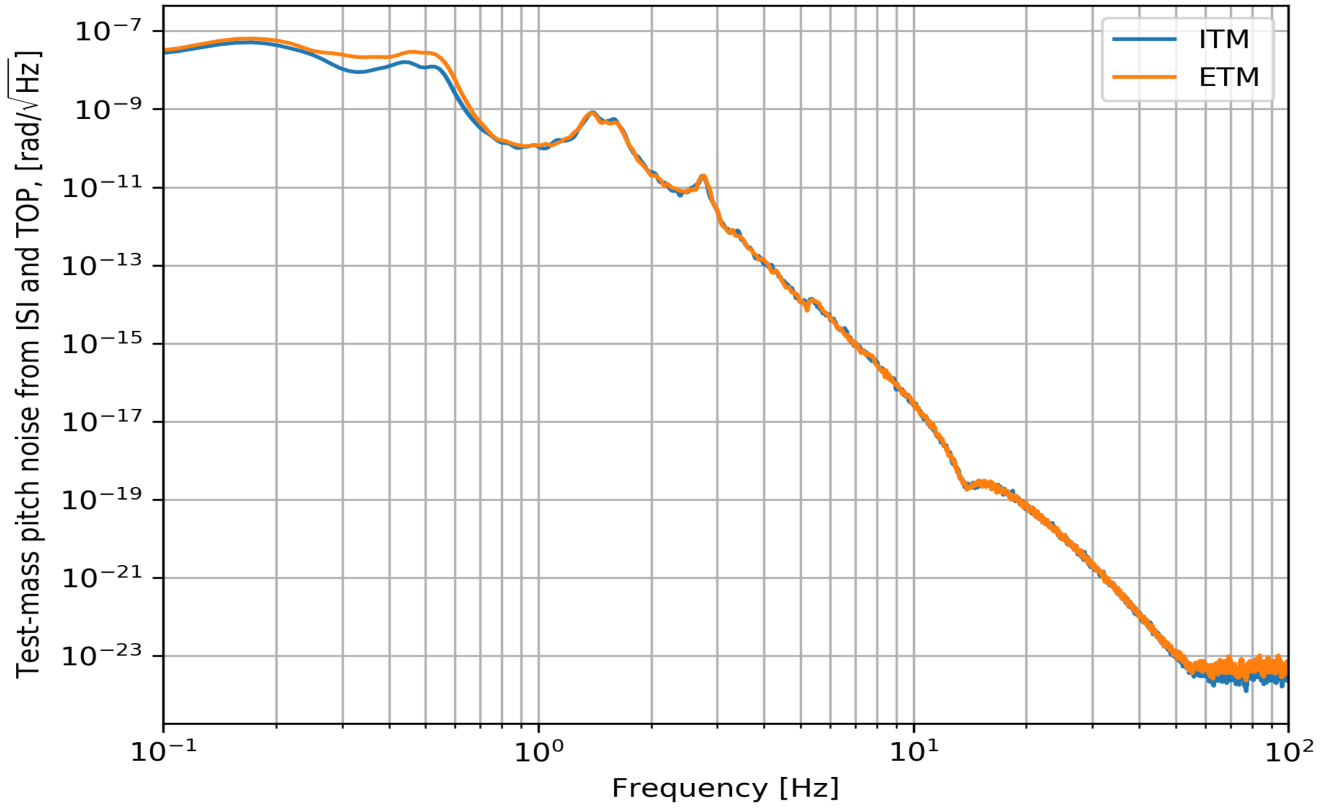
a) tf ISI L to TM P



b) tf OSEM L to TM P



c) tf OSEM P to TM P



d) Overall external noise

Nonlinearities

- Most input noises are simulated by spectral methods
- SOS – covers the last two stages of the suspension system and the angular controls
- Nonlinear optomechanical couplings are included explicitly through equations of motion, i.e., not as effective time-variant SOS models
- Nonlinear optomechanical couplings:
  1) Fluctuations of arm-cavity power depend nonlinearly on cavity length changes
  2) Radiation-pressure torque is a bilinear term that contains the beam-spot motion as well as power fluctuations
  3) Strain noise is produced as a bilinear coupling between angular motion of test masses and beam-spot motion

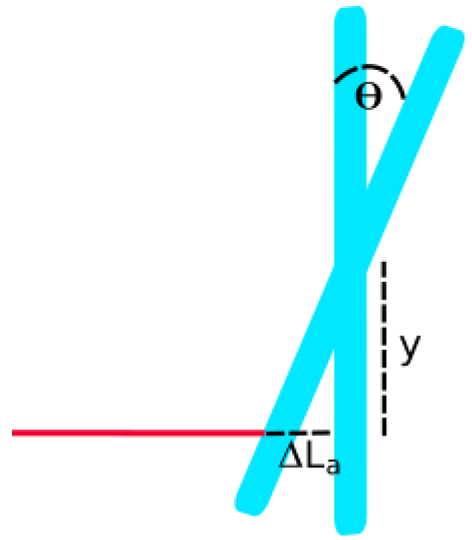
$$P(t) = \frac{\tau^2 P_i(t)}{\left|1 - \rho \exp\left(2\pi j \frac{\Delta L(t)}{\lambda}\right)\right|^2}$$

$$\tau_{\mathrm{RP}}(t) = \frac{2P(t)}{c} y(t)$$

$$\Delta L(t) = y(t) \times \theta(t)$$

- Light propagation times inside the arm cavities are neglected, which means that the noise estimates are only accurate below 45 Hz corresponding to the arm-cavity pole

$$g_{1,2} = 1 - \frac{L}{R_{\mathrm{ITM,ETM}}} \qquad \vec{y} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \frac{L}{1 - g_1 g_2} \begin{bmatrix} g_2 & 1 \\ 1 & g_1 \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}$$



More on Lightsaber

- While the plant simulation uses local degrees of freedom of individual suspension systems, the control is applied on a global angular basis, which requires a conversion between the local and global bases for sensing and actuation

$$\begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} 1 & -r \\ r & 1 \end{bmatrix} \begin{bmatrix} \theta_S \\ \theta_H \end{bmatrix}$$

- The filter outputs are transformed back to the local basis for the actuator output at the two PUMs

- The feed-forward Sidles-Sigg compensation path is implemented as it was during the O3 run at the Hanford detector

$$r = \frac{(g_1 - g_2) + \sqrt{(g_1 - g_2)^2 + 4}}{2}$$

- Superposition of noises

- fs = 256 Hz, t = 1024 s

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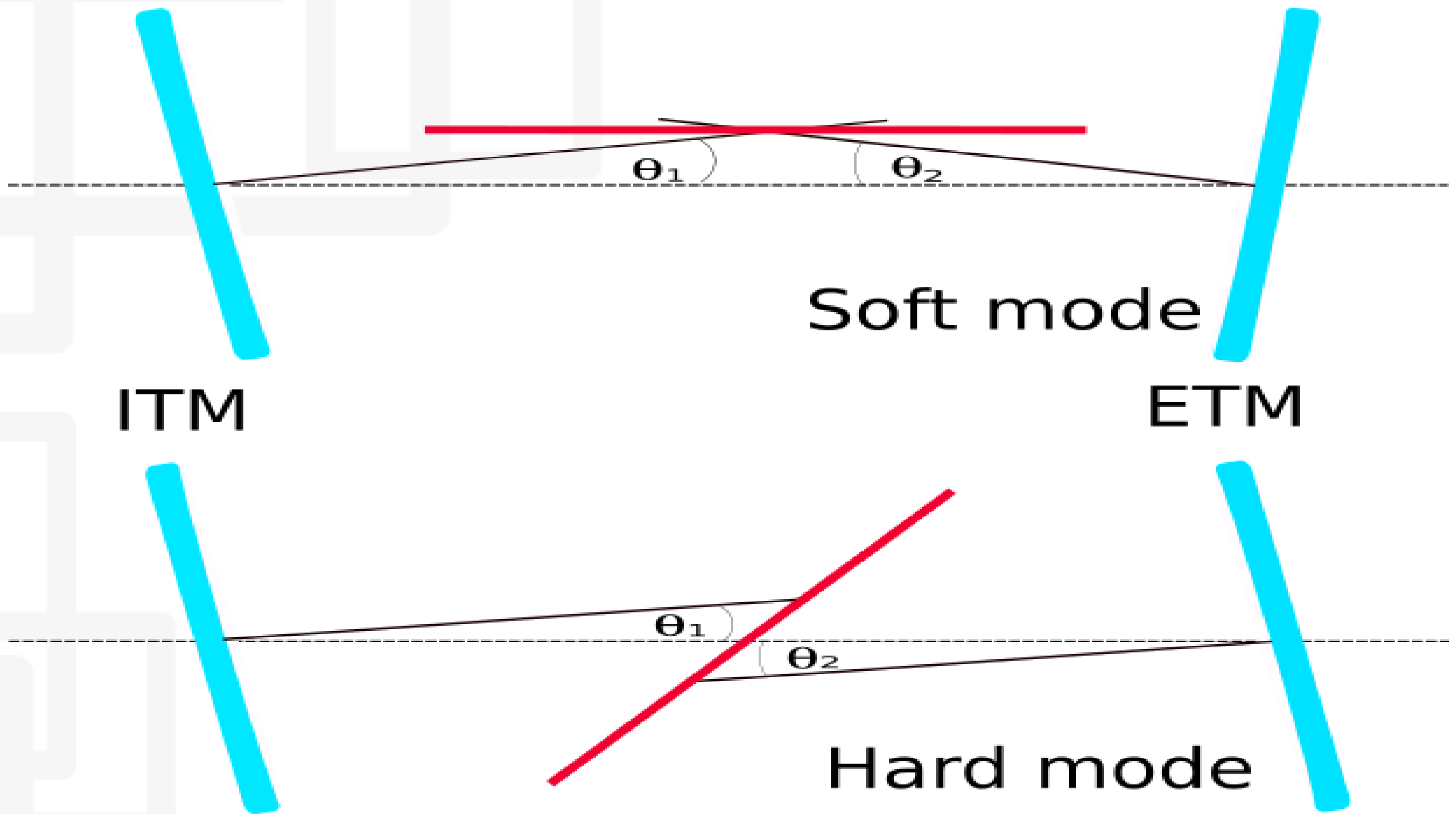
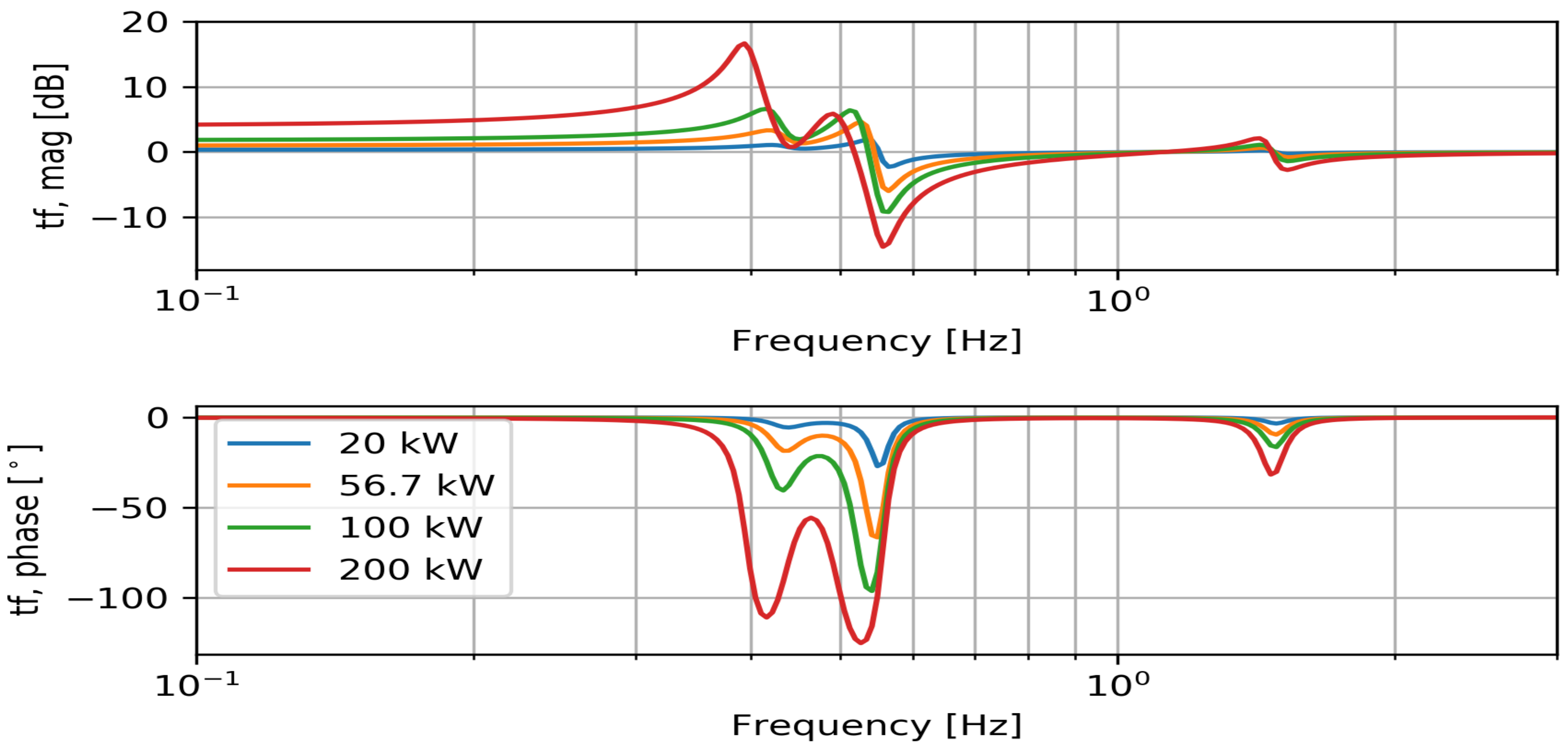
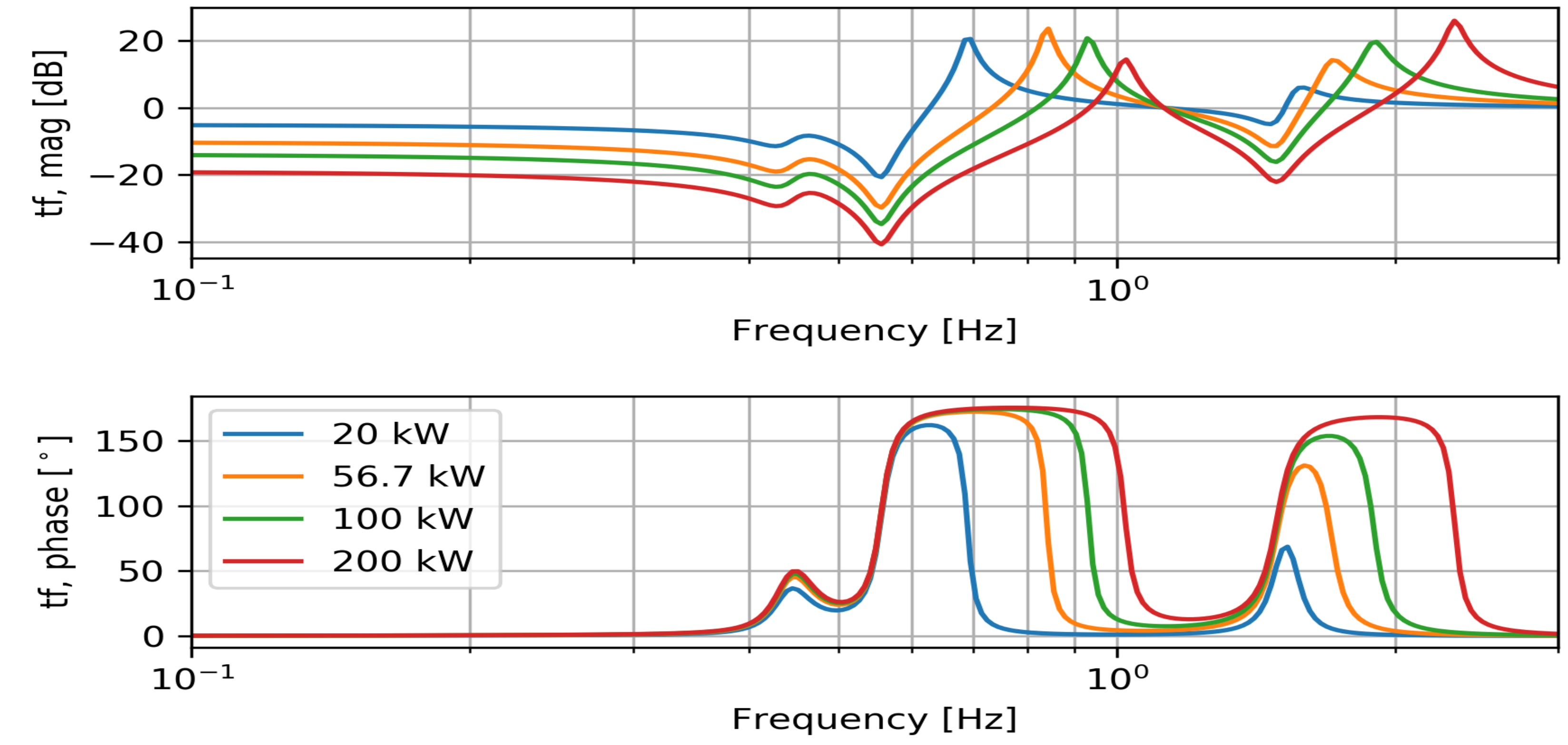
Optomechanical system

- Radiation pressure exerts a torque on the suspended mirrors, adding to the fixed restoring torque of the suspension
- ASC allows us to operate IFO with angular mechanics dominated by RP
- Normal mode basis which decouples the effects of RP in 2 independent modes
- Bode plots of Sidles-Sigg feedback transfer function changing the arm cavity power





a) Soft mode



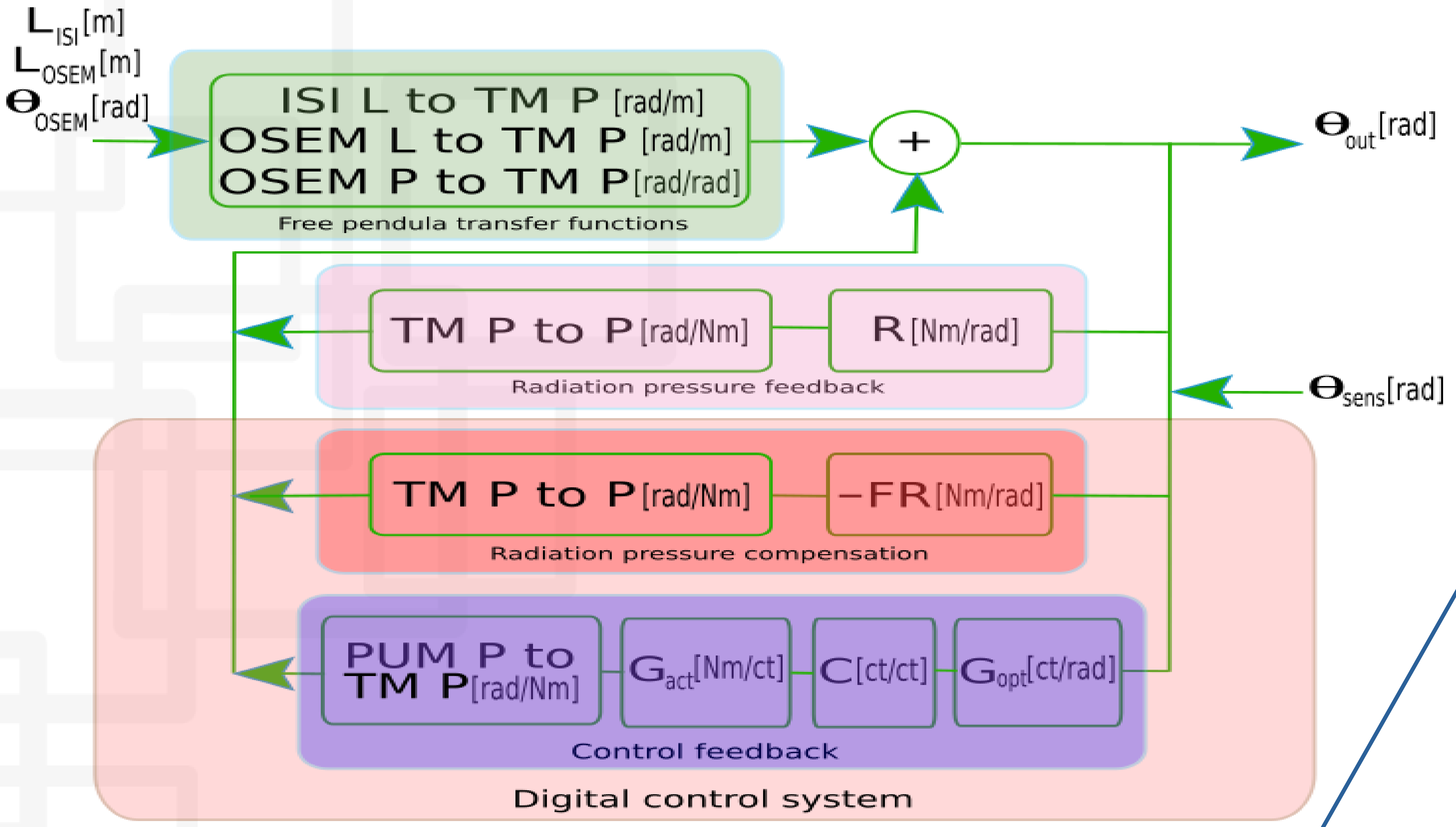
b) Hard mode

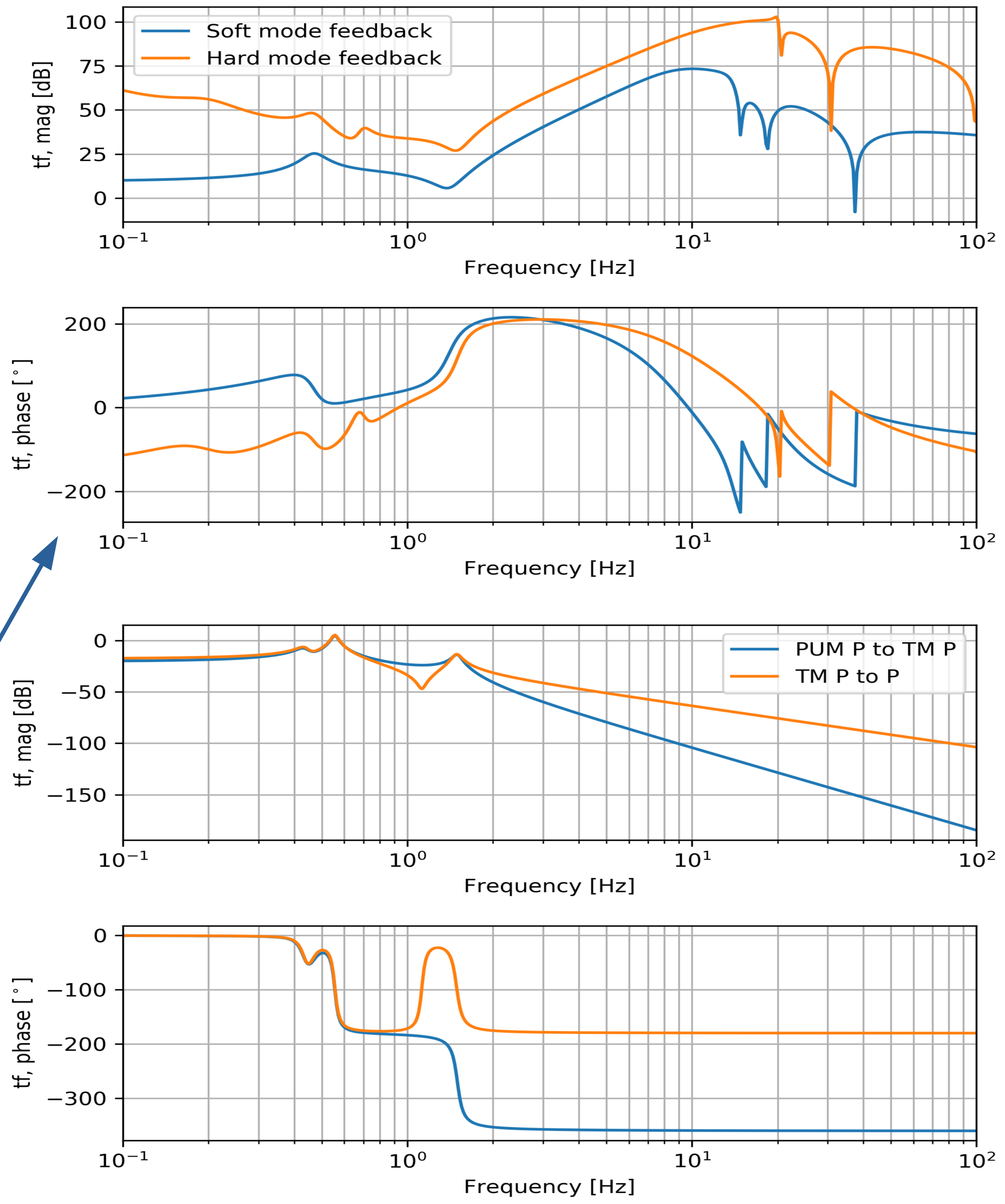
$$f_{S,H} = \frac{1}{2\pi}\sqrt{\frac{L_p + \lambda_{S,H}}{I}},$$

$$\lambda_{S,H} = \kappa_{\mathrm{RP}}\frac{g_1 + g_2 \pm \sqrt{(g_1 - g_2)^2 + 4}}{2},$$

$$\kappa_{\mathrm{RP}} = \frac{2PL}{c(g_1 g_2 - 1)}$$

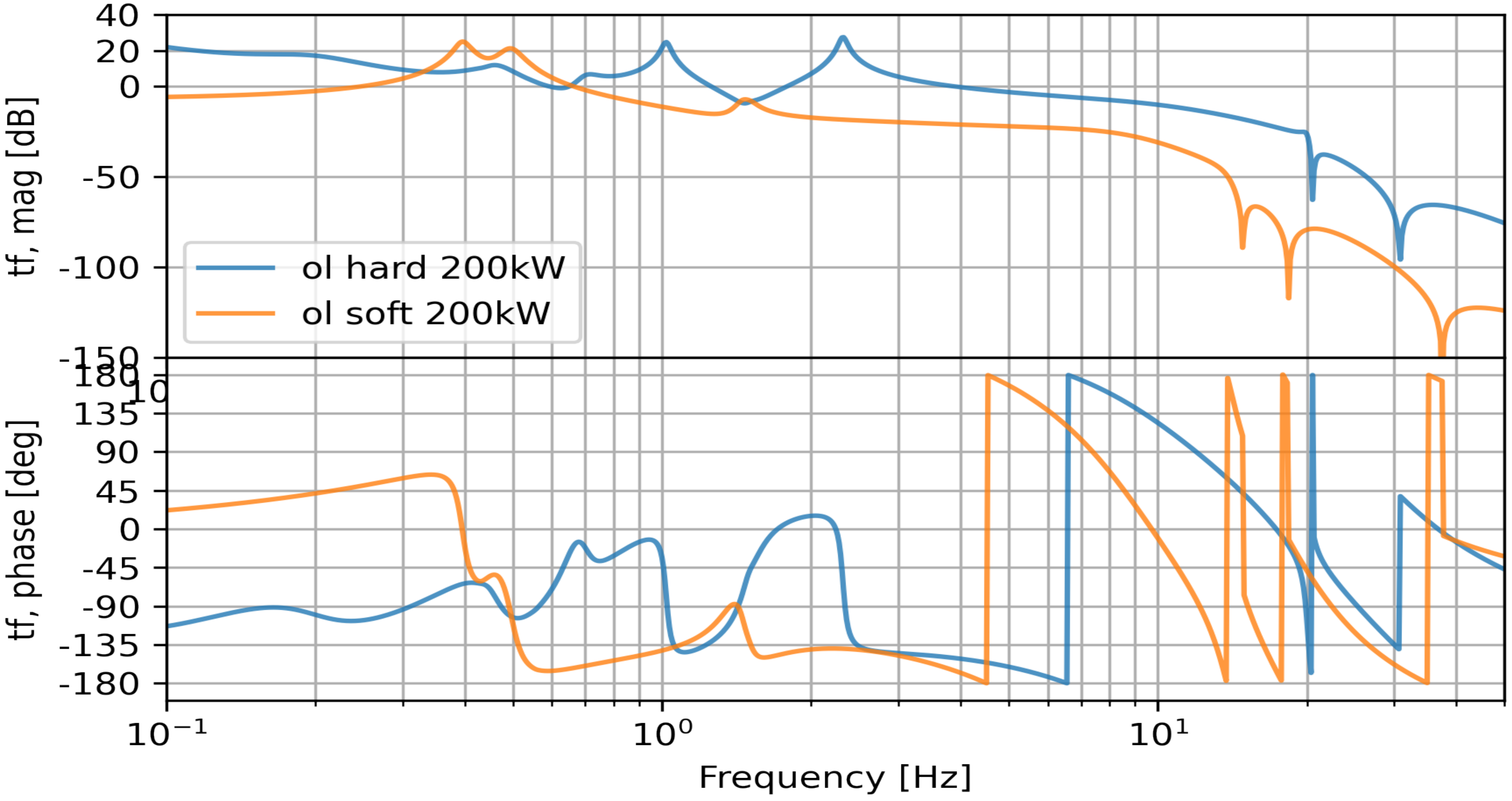
Diagram and Bode plots





- The linear couplings of the simulation are based on SOS models, which means that also the ZPK specifications of control filters are internally converted into SOS models
- This part of the suspension system needs to be included in the dynamics of the time-domain simulation, it is represented as a SOS model

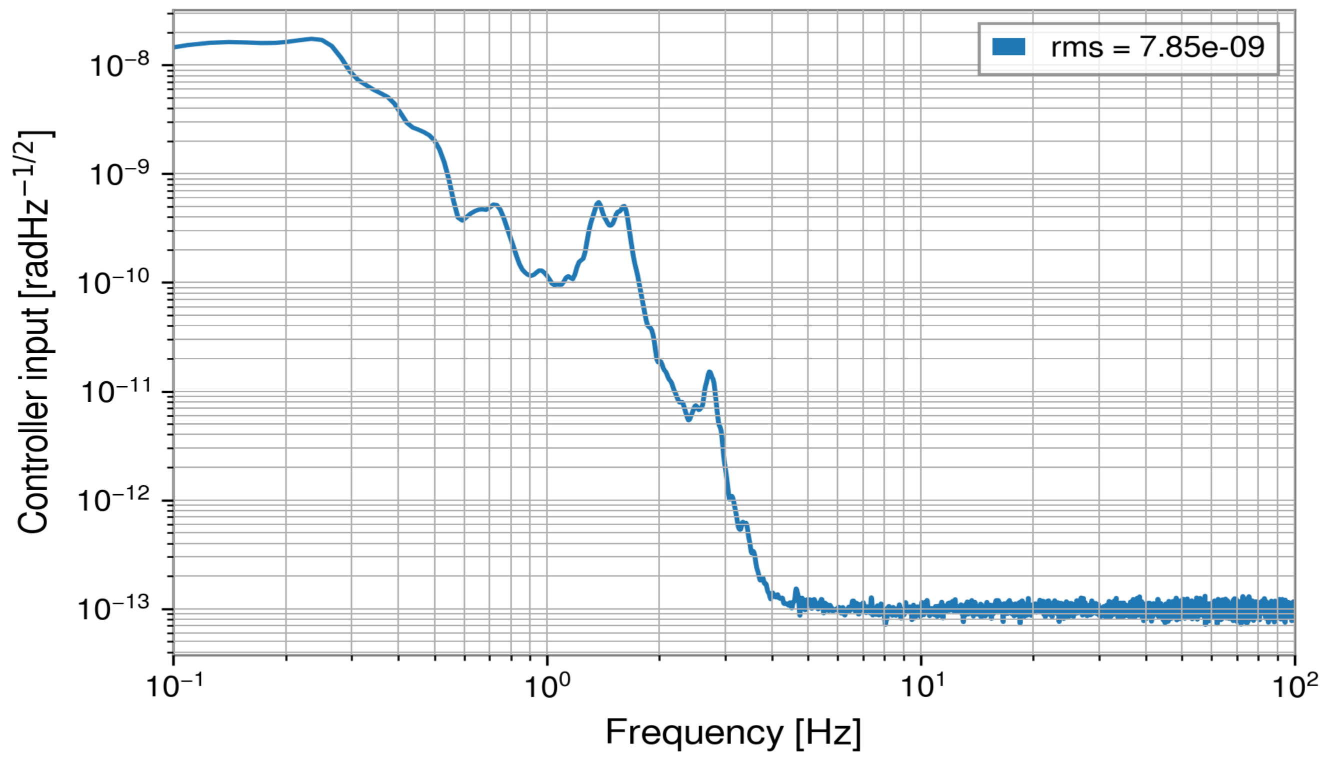
$$R_{S,H} = \frac{2P}{c}\left.\frac{dy}{d\theta}\right|_{S,H} \qquad \left.\frac{dy}{d\theta}\right|_{S,H} = \frac{L}{2}\frac{(g_2+g_1)\pm\sqrt{(g_2-g_1)^2+4}}{(g_2 g_1 - 1)}$$

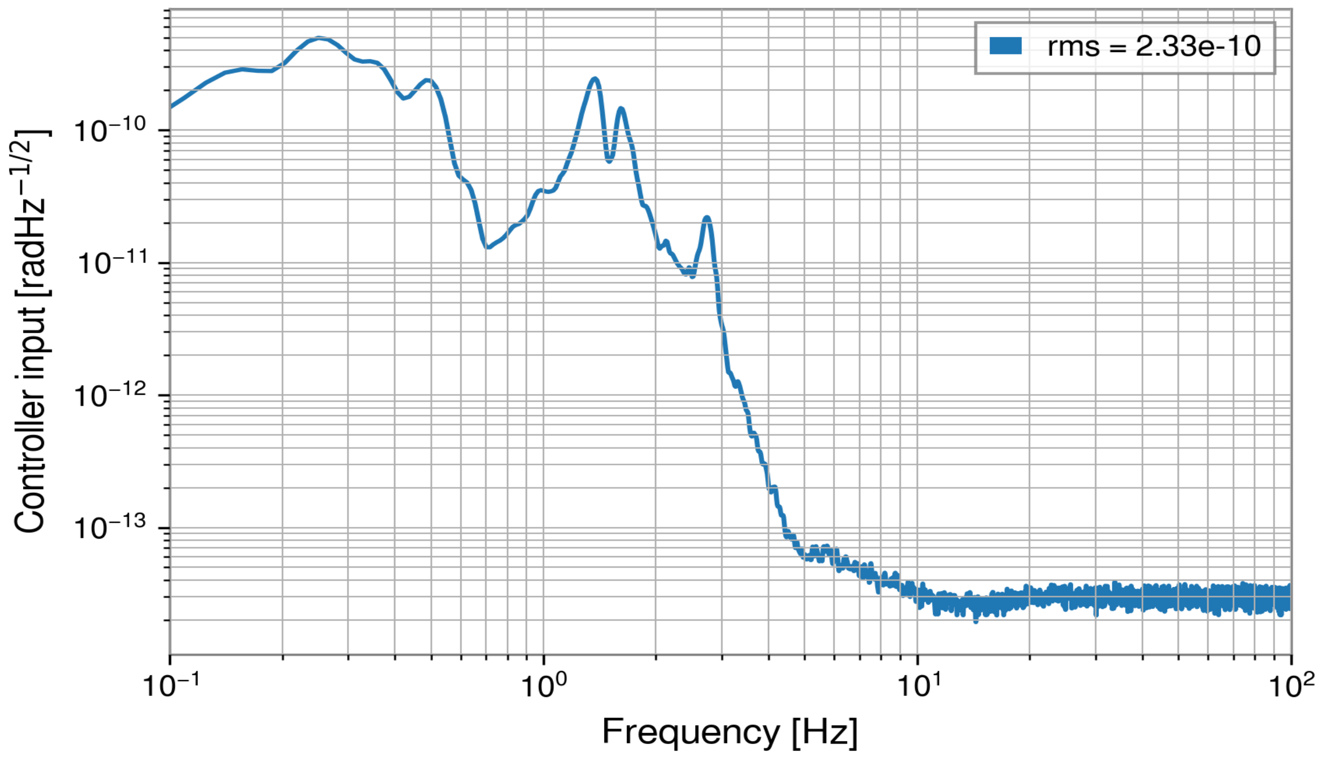


Bode plots of OLTFs for soft and hard modes.

Controller input and output

Controller input

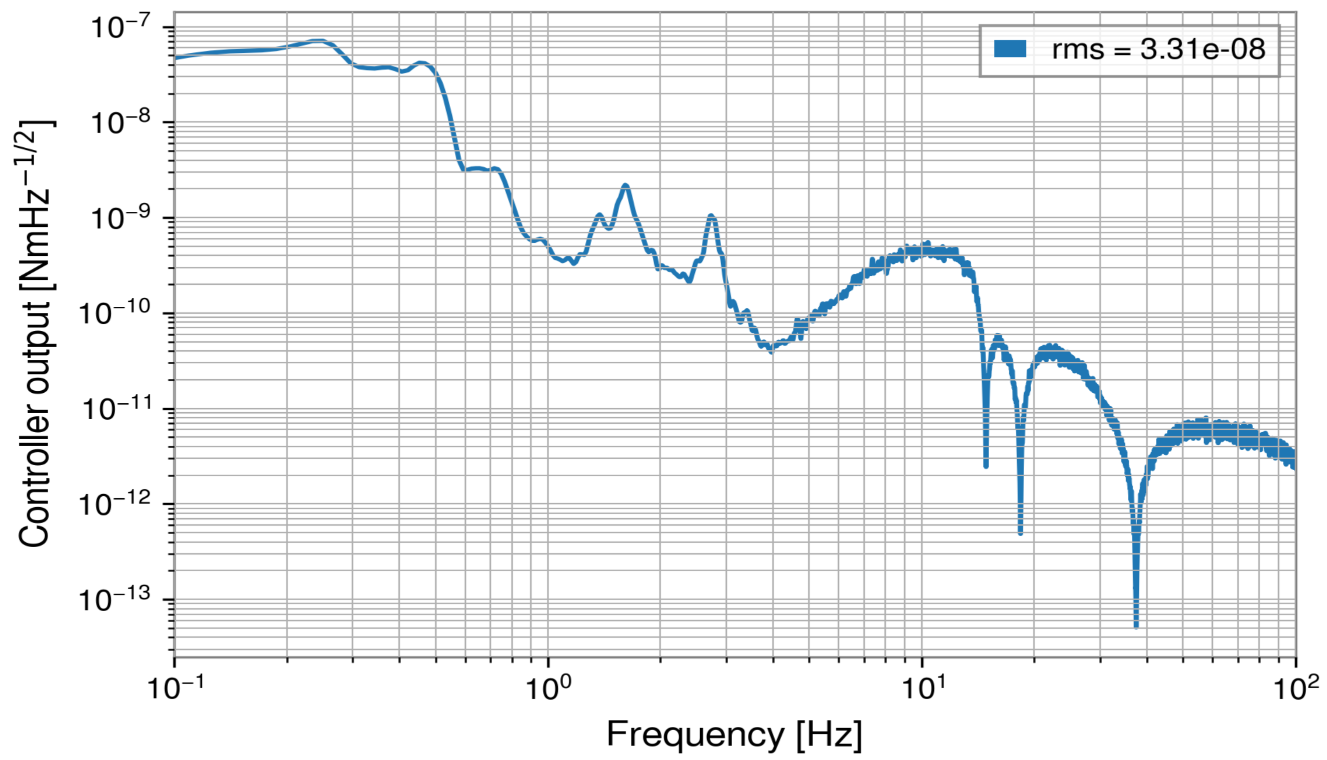


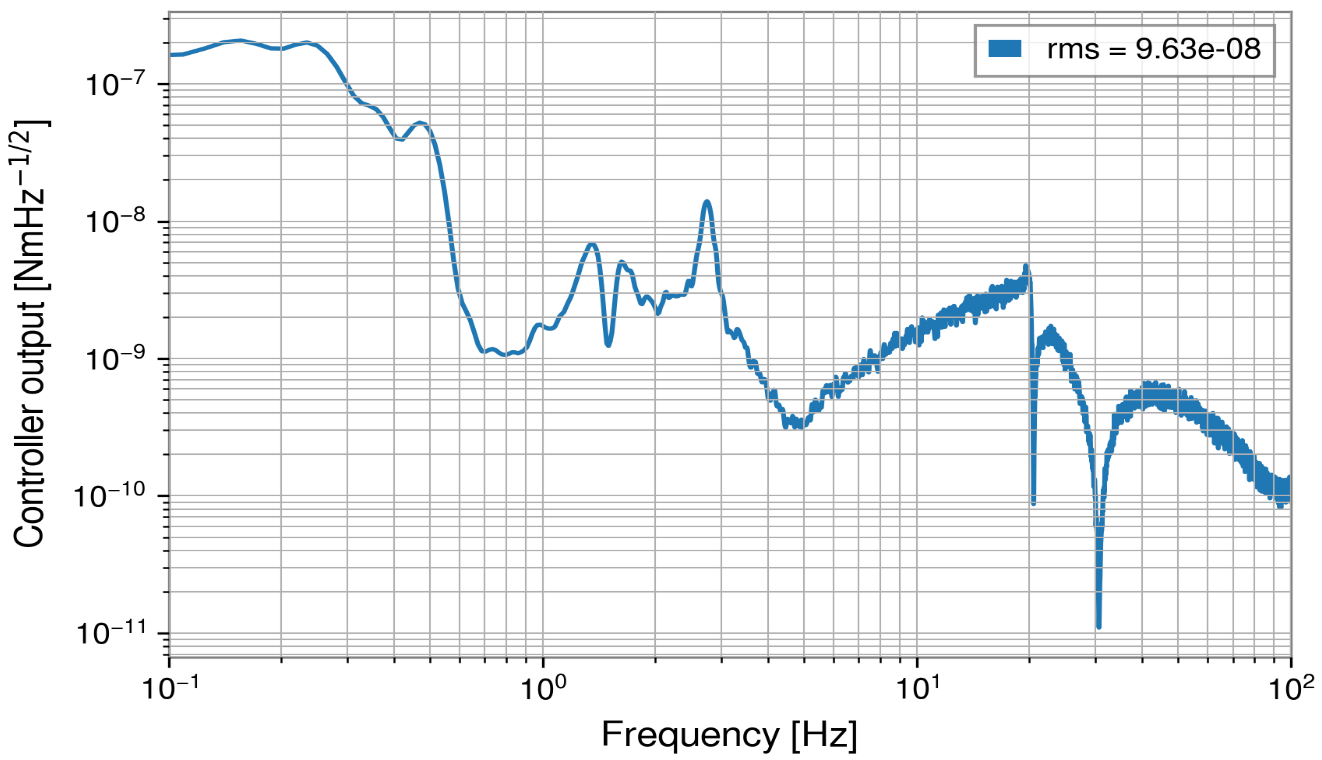


a) soft mode

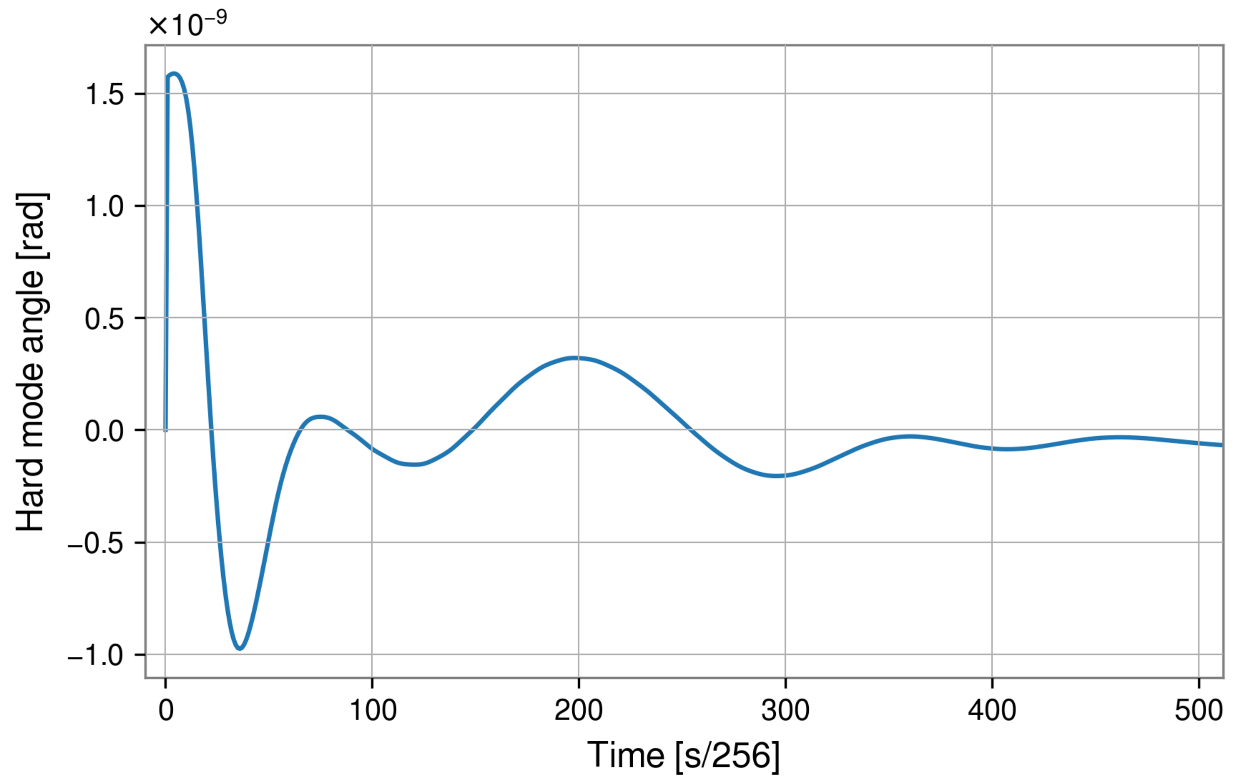
b) hard mode

Controller output

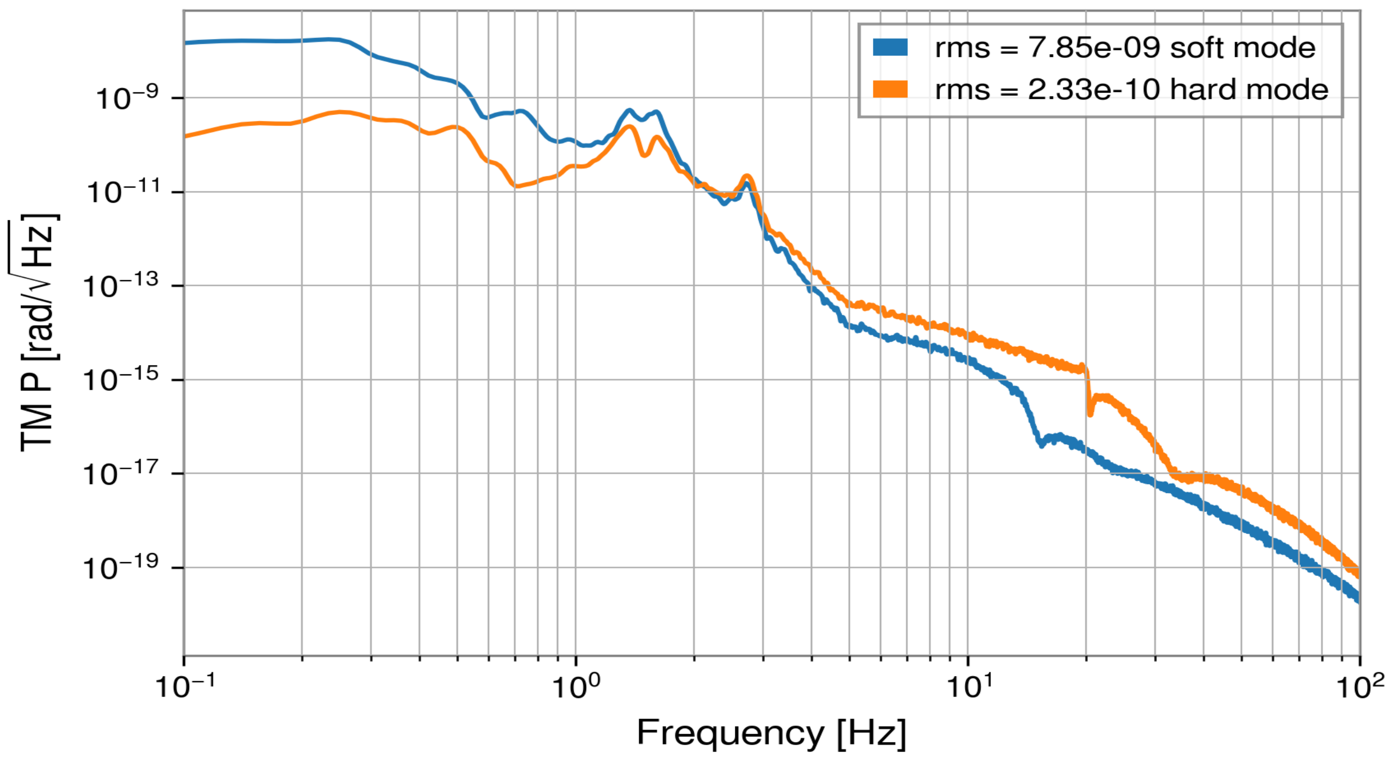




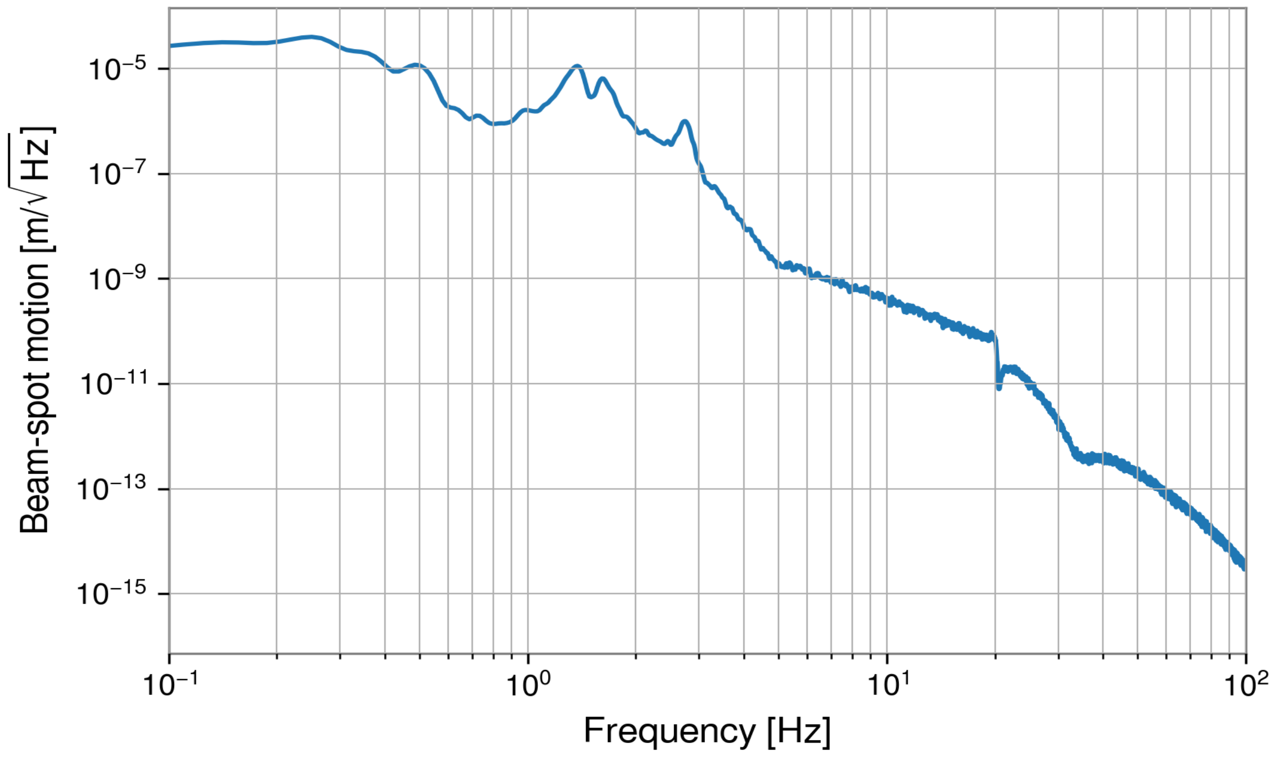
Results



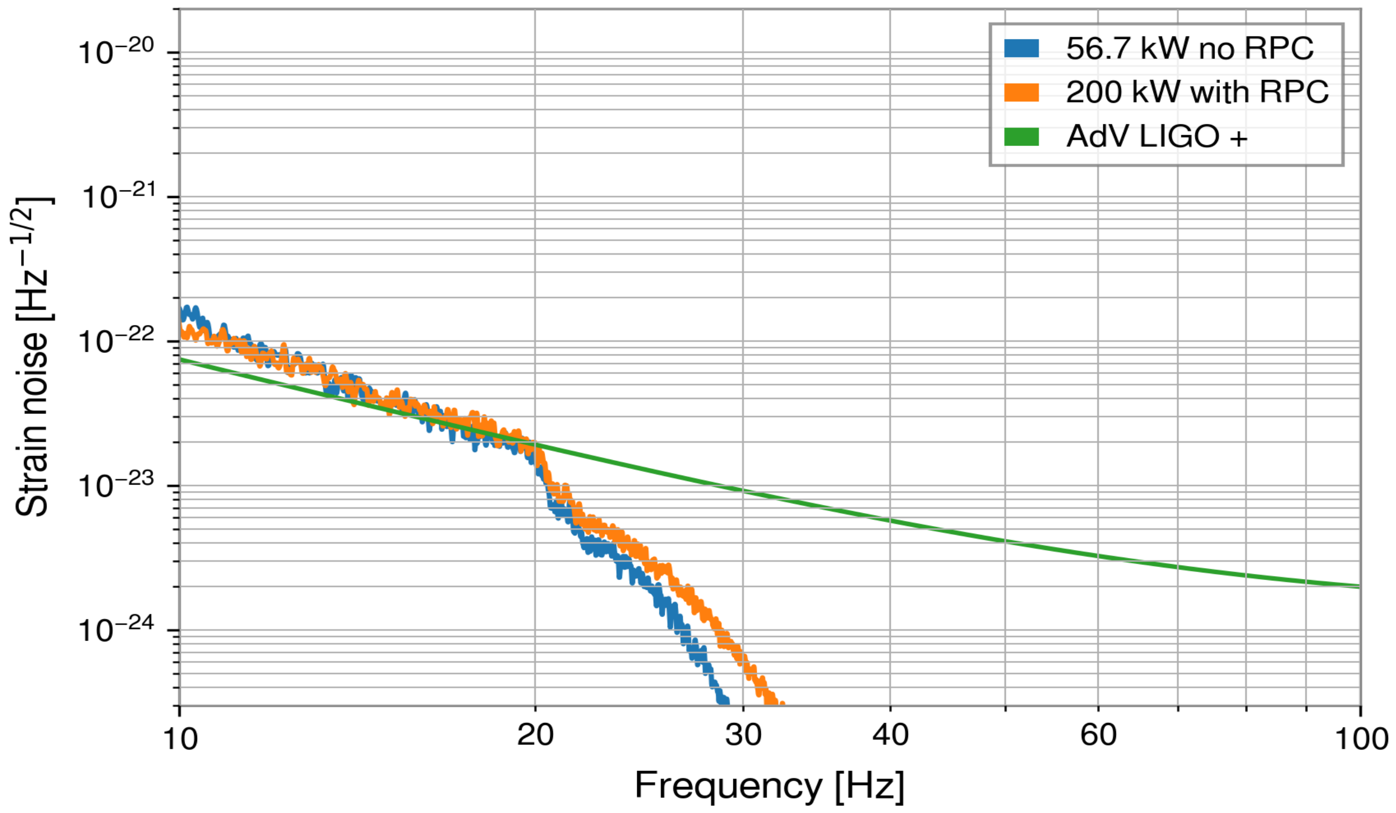
a) Controls engagement demonstration



b) Test mass pitch motion



c) Simulated BS motion



d) Strain noise

Conclusion

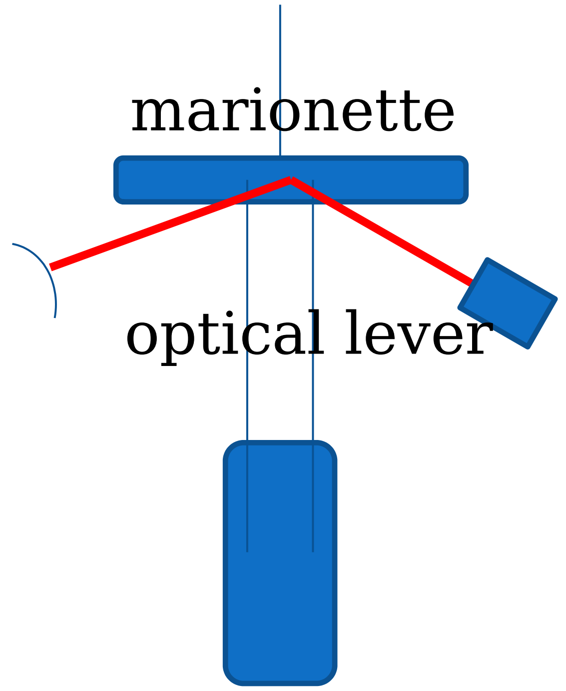
- LIGO – limited by ASC noise
- Requirements:
  1. 1 nrad RMS
  2. Lowest possible noise above 10 Hz

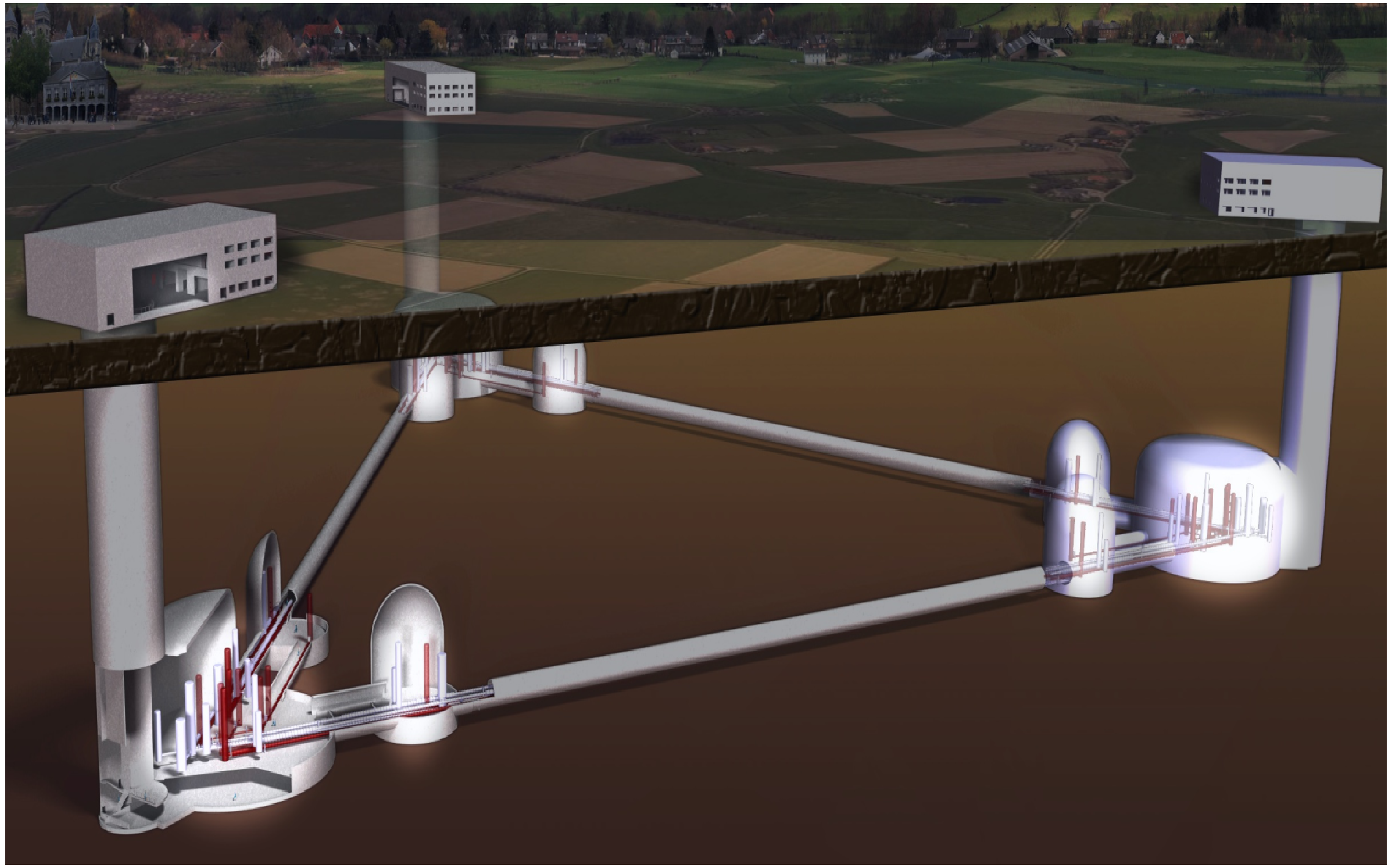
- Time-domain simulation of the ASC system in LIGO
- The complexity comes from the nonlinear optomechanical couplings between the suspended test masses and the high-power laser beam inside the arm cavities
- Angular motion of test masses couples nonlinearly to differential arm length.
- The Lightsaber is accurate to serve as a useful modeling tool
- The plant model is for the LIGO detectors, but it is straightforward to modify the mechanical system, angular readouts, etc to represent other detectors
- Another application – allows to test ASC controllers before implementing them in a detector – this can be especially valuable for certain non-stationary modern control schemes
- A detailed understanding of noise produced by the ASC is crucial to plan future generations of GW detectors

GS
SI

ET-LF

- ET – issue needs to be addressed already with its design
- Low light power, increased mass of TM (reduce the angular optomechanical instabilities)
- Natural resonant frequency ~0.05 Hz in pitch and ~0.2 Hz in yaw
- R = 5580 m, r = 22.5 cm, h = 57 cm
- Resonant frequencies for ET-LF are:
  - soft mode pitch: 0.0218 Hz
  - hard mode pitch: 0.1413 Hz
  - soft mode yaw: 0.1949 Hz
  - hard mode yaw: 0.2397 Hz
- Obtained shifted frequencies are comfortably low, ET-LF was conceived with the hope to have low angular frequencies





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