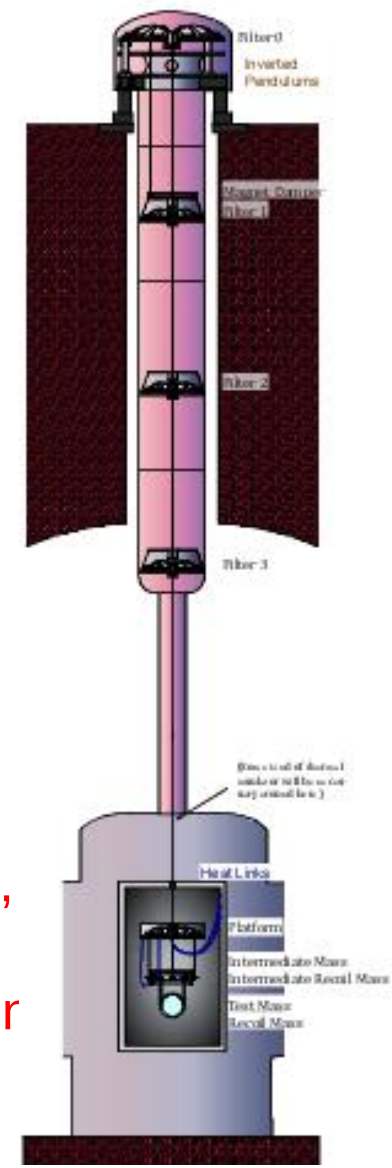
JGW-G1100606

2011/09/18 Annual Meeting of JPS

Three-dimensional Rigid-Body Models of the Vibration Isolation Systems for LCGT



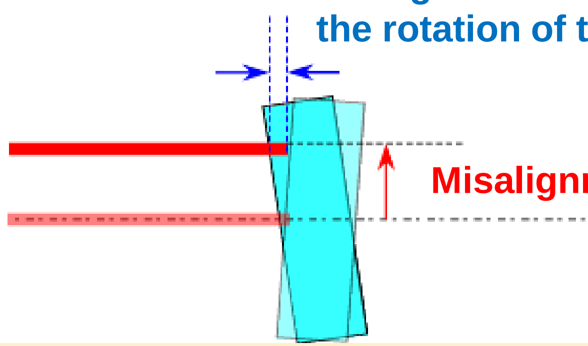
ICRR, M2, Takanori Sekiguchi

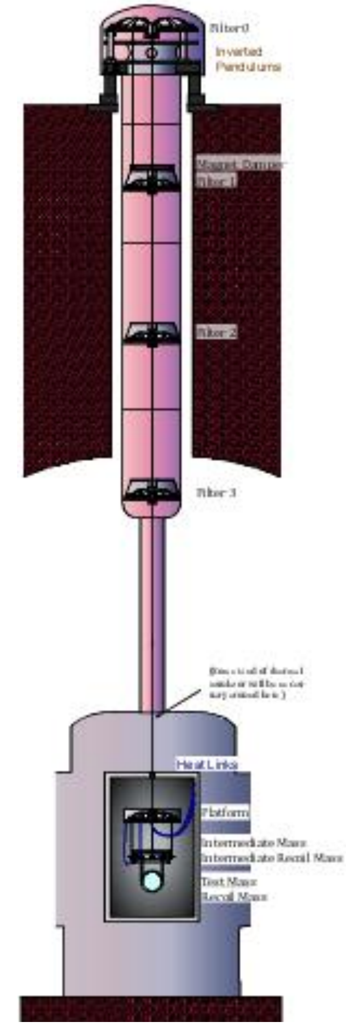
ICRR, NAOJ[A], ERI[B], Sanio Univ[C], INFN[D], U. Tokyo[E]

R. Takahashi, K. Yamamoto, T. Uchiyama, H. Ishizaki[A], A. Takamori[B], R. DeSalvo[C], E. Majorana[D], Y. Michimura[E], M. Ohashi, K. Kuroda, LCGT Collaboratior

Introduction

- Mechanical models are necessary to estimate seismic noise and control noise in the interferometer
- Conventional 1-D models：No couplings between different DoFs
- Rotation occurs by couplings with translational motions
  → Rotation amplitudes of the mirror must be estimated by 2-D or 3-D models
- When the beam-spot is off-centered, rotation of the mirror changes the light-pass.

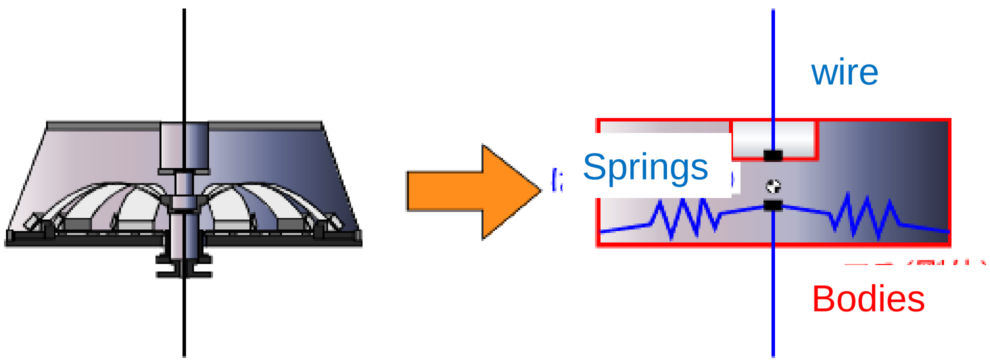




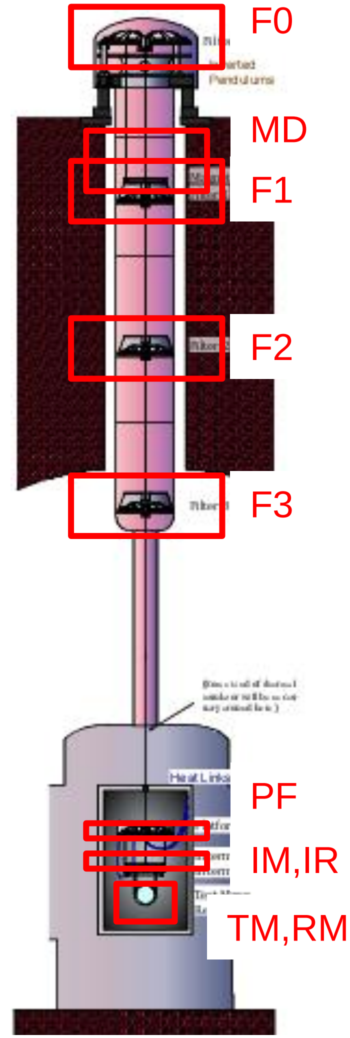
We construct 3-D models, and estimate the amplitude of the mirror rotation due to the seismic motion.

Construction of the Models

- Vibration Isolation Systems=
  Rigid Bodies＋Elastic Elements（wires, springs）



- Each body has 6 DoFs (X,Y,Z,θx,θy,θz).
- Wire potential is divided into stretches and torsions.
- A GAS filter works as a uni-dimensional ideal spring.
- Elasticity of the heat links is taken into account.
- No deformation of the bodies, no violin motions of the wires



LCGT Type-A System： 10 bodies (57 DoFs)

Calculation Sequence

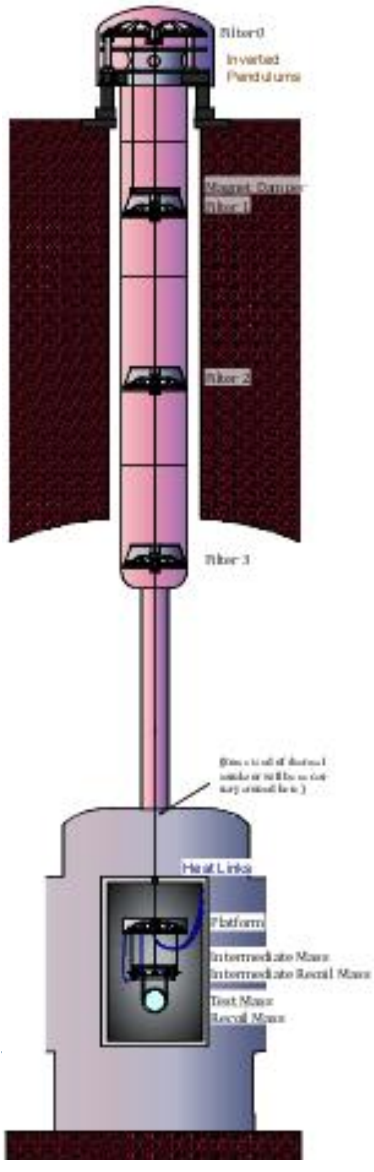
- Set the parameters (geometry, mass, moment of inertia, etc.)
- Calculate the potential (U), dissipation (F) and kinetic (T) energies.
- Find the local minimum (equilibrium point) of the potential (U).
- Linearize the equations of motion around the given equilibrium point.

$$\frac{d}{dt}\frac{\partial T(\mathbf{x},\dot{\mathbf{x}})}{\partial \dot{x}_i}+\frac{\partial F(\dot{\mathbf{x}})}{\partial \dot{x}_i}+\frac{\partial U(\mathbf{x})}{\partial x_i}=f_i \quad \xrightarrow{\text{Linearize}} \quad \mathbf{M}\ddot{\mathbf{x}}+\mathbf{C}\dot{\mathbf{x}}+\mathbf{K}(\mathbf{x}-\mathbf{x}_{eq})=\mathbf{f}$$

- Calculate the eigen-frequencies and frequency response of the system.

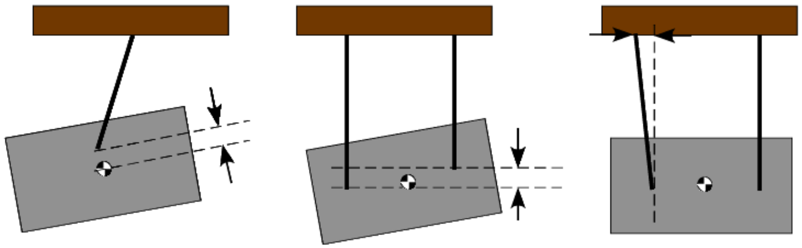
Mathematica is used for the calculation.

Estimation of the spectrum densities of the angular fluctuation of the test-mass mirrors, due to seismic motions



Angular Motions of the Bodies

- Angular motions are excited by couplings with translational motions.
- The couplings come from asymmetry of the systems: vertical separations between suspension points and CoMs, asymmetry in the wire lengths or diameters, asymmetry in the spring constants, etc.

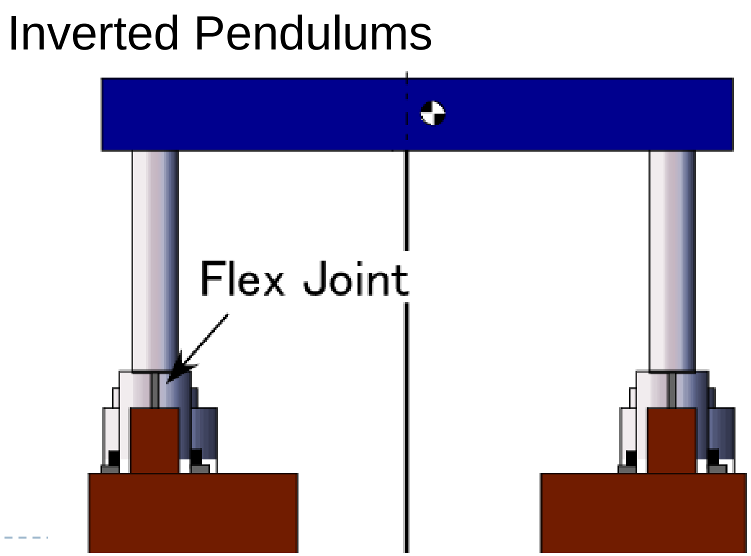


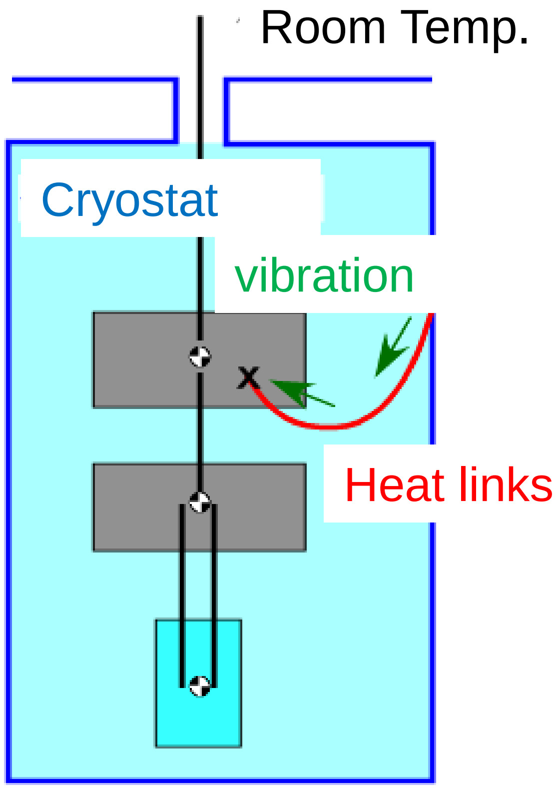
- It is impossible to expect the asymmetry of the real systems.

→ Asymmetries are randomly given, and the computation is iterated for many times (Monte Carlo simulation)

Asymmetry

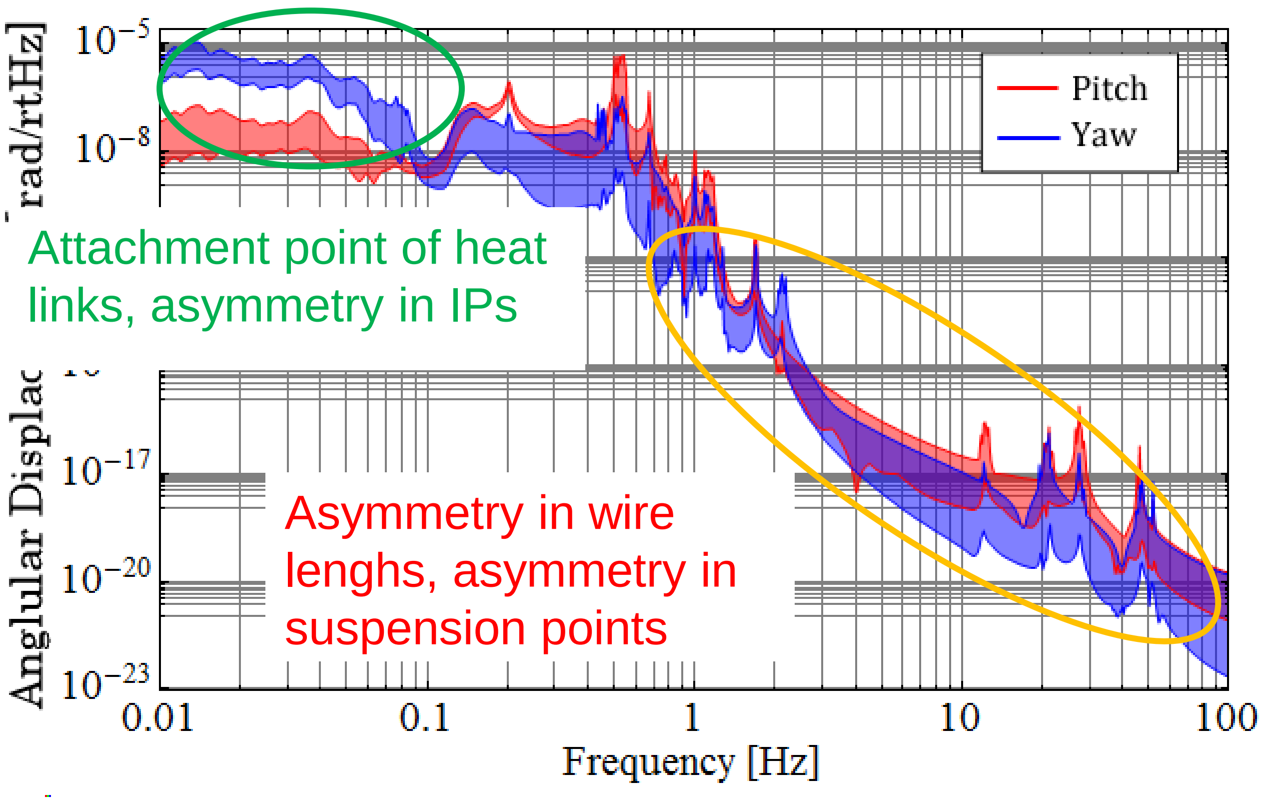
- Wire lengtsh：±0.5 mm
- Wire diameters：±5 %
- Suspension points：±0.5 mm for x, y, z
- Effective stiffness of the inverted pendulums：±50 %
- Attachment point of the heat link：±5 cm from CoM

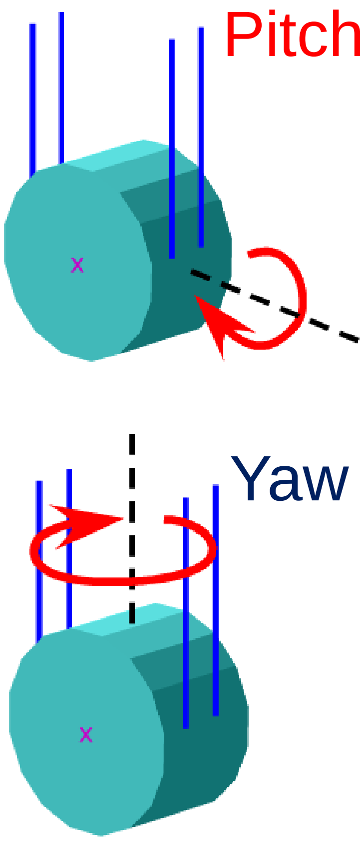




Spectrum Density of the Mirror Angular Fluctuation

- Iteration：20
- Seismic motion spectrum：Measured data in February, 2007

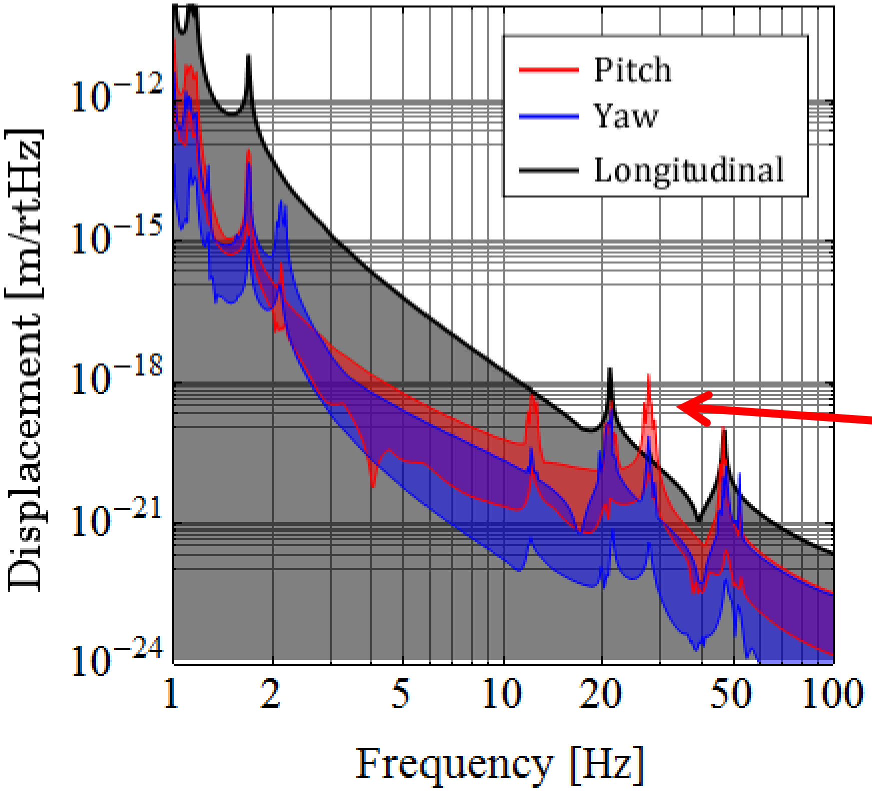


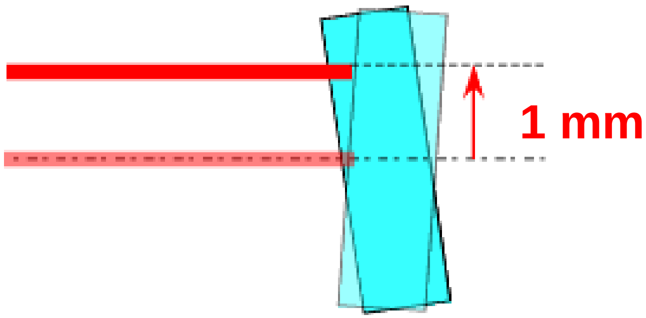


Rough Estimation

Impact on the Sensitivity

- Assume 1 mm misalignment of the beam spots.

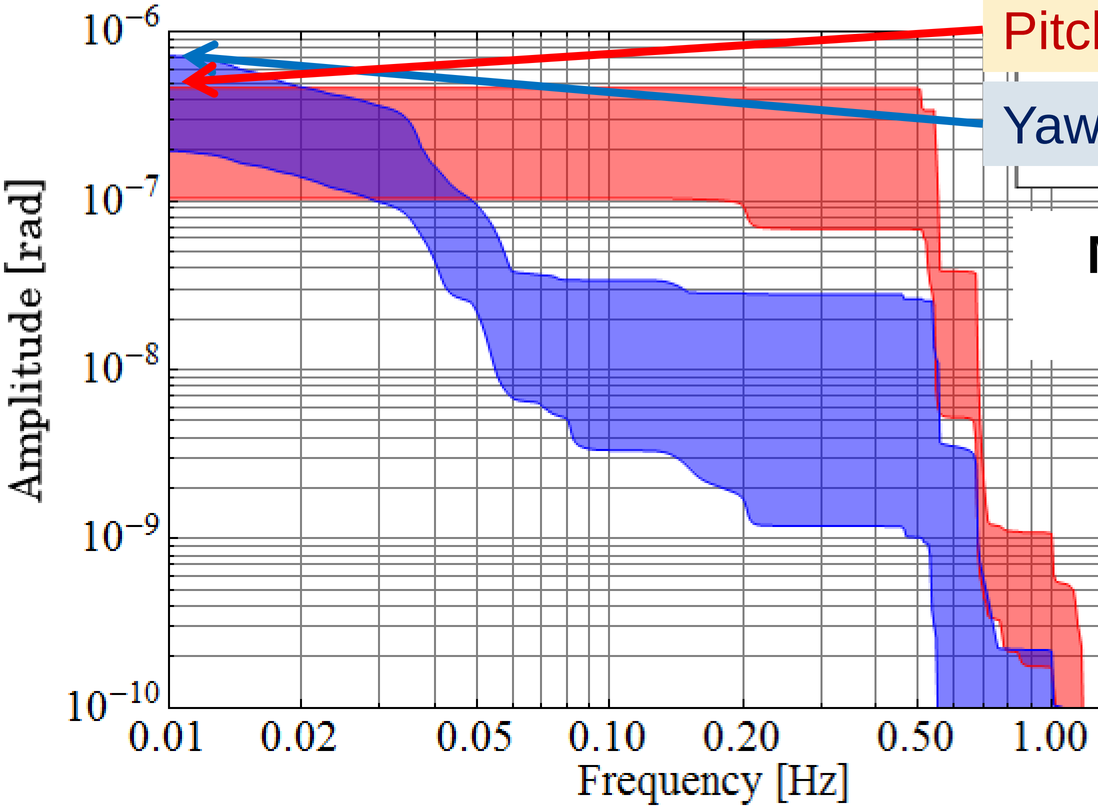




Pitch resonance of mirrors

The impact on the sensitivity by the angular motion is relatively small, compared with the impact by the translational motion.

RMS Amplitude



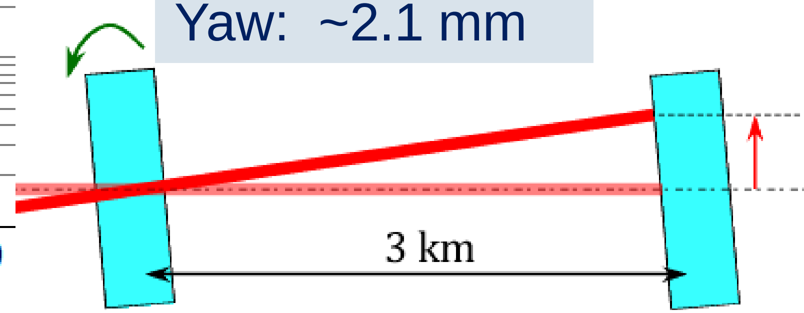
Pitch: 0.5 µrad (0.01 Hz) Maximum

Yaw: 0.7 µrad (0.01 Hz) Maximum

Misalignment of the beam spot due to the rotation

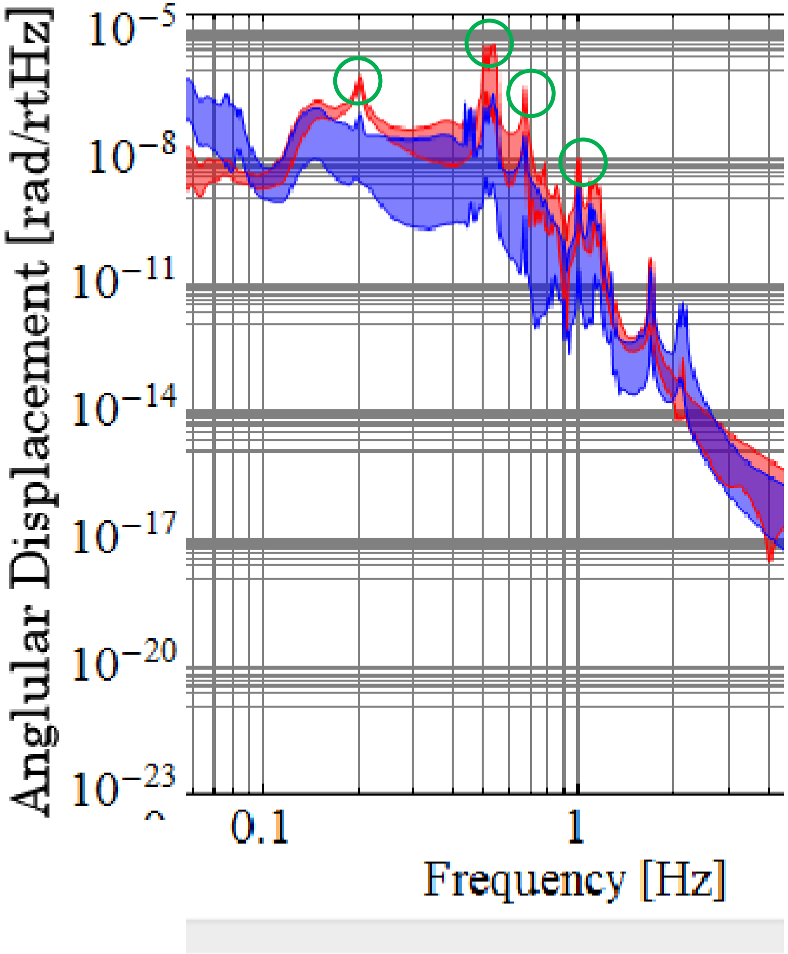
Pitch: ~1.5 mm

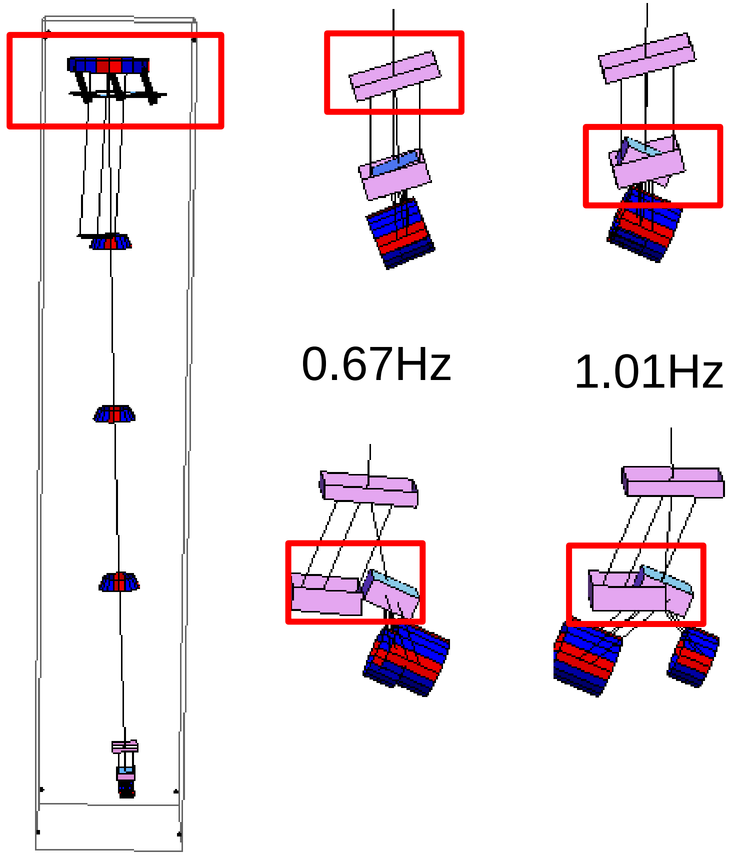
Yaw: ~2.1 mm



We need to consider the curvature of the mirrors, and the radiation pressure effects. → **Another talk from Y. Michimura**

To suppress the RMS





Summery

- We construct 3-D rigid-body models of the vibration isolation systems.
- We estimate the angular fluctuation of the test-mass mirrors due to the seismic motions.
- We find that the impact on the sensitivity by the mirror angular motion is smaller than the impact by the translational motion (under the given asymmetry for this time).

Future Works

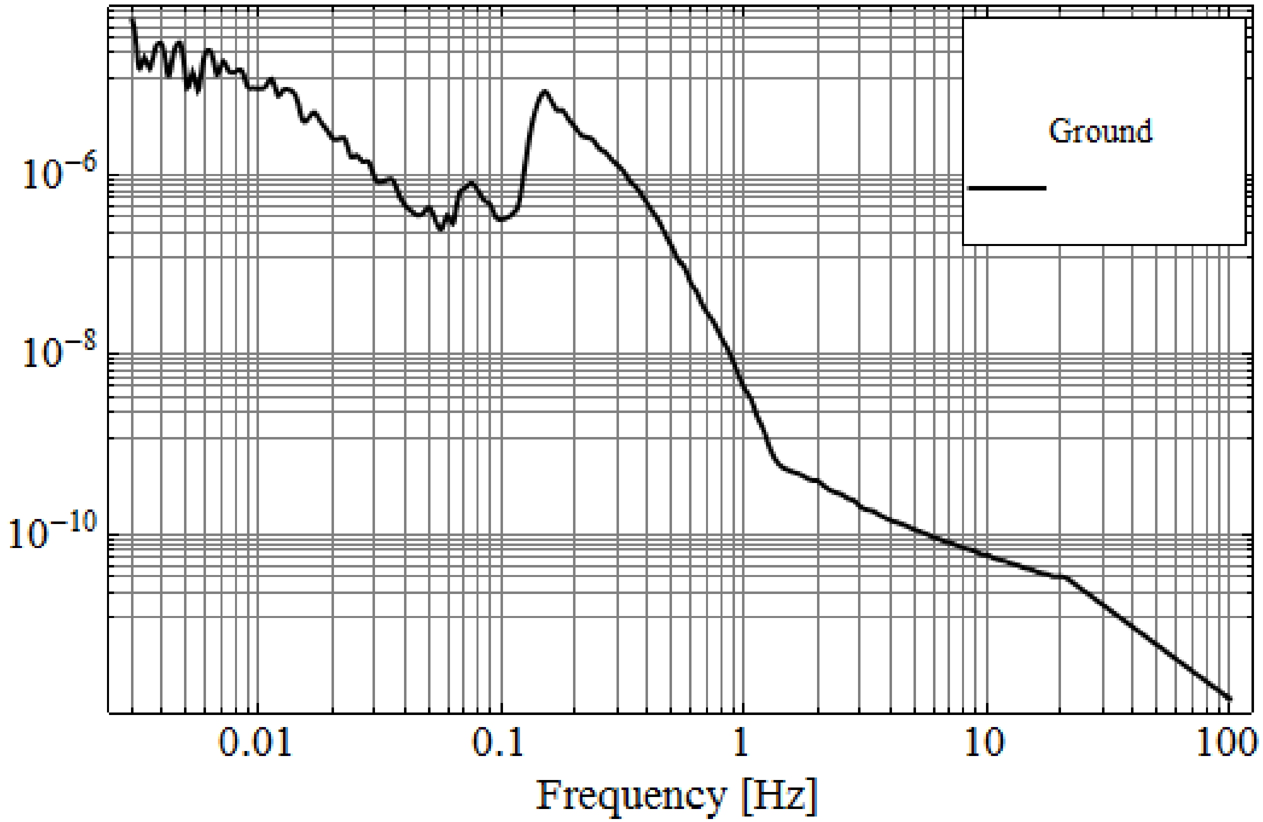
- Validation of the calculation by prototype experiments
- Development of the local control systems of mirrors
- Estimation of the suspension thermal noise of the multi-pendulums

The End

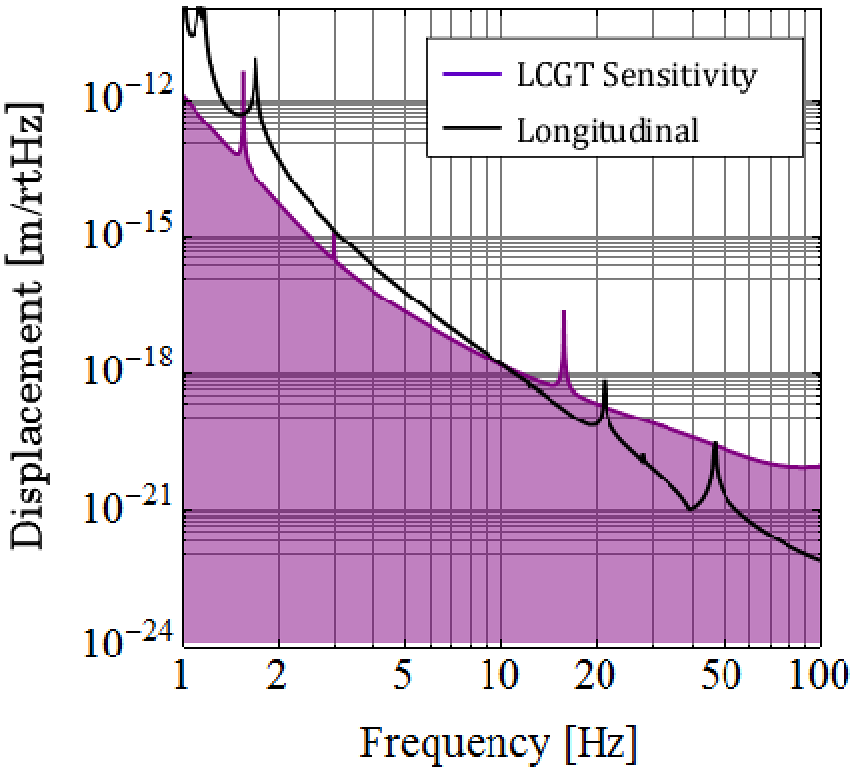
Appendix

Seismic Motion in Kamioka Mine

- Measured data on Feb. 13th, 2007
（>20Hz is interpolation by f^(-2) function）
- Bad seismic weather. (Normally, the seismic motion is much smaller around 0.1~1 Hz)

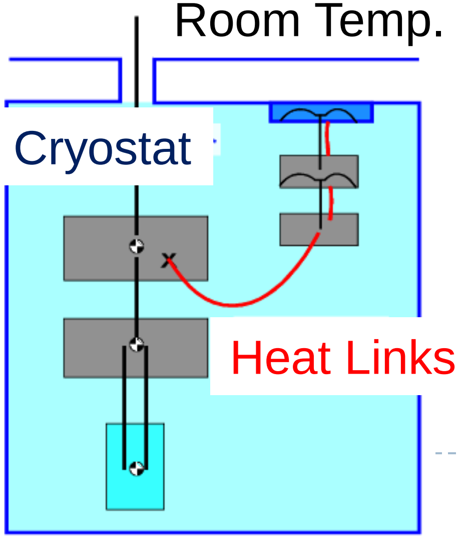


Need More Attenuation!



Sensitivity curve (Jan. 2011) V.S.
Seismic noise (H+V/300)

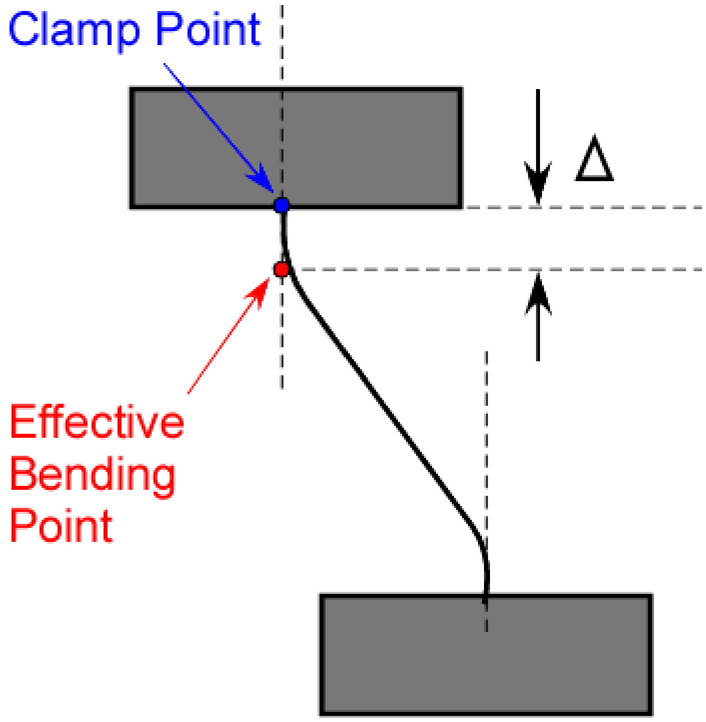
- Seismic noise is barely under the nominal sensitivity in > 10 Hz.
- > 2 Hz is affected by the heat links.
- The vibration on the inner shield of the cryostat might be larger than the ground vibration.
- We will need vibration isolation for the heat links



Compensation of Effective Bending Points

- Due to the elasticity of the wire, the effective bending point and the clamp point is separated by:

$$\Delta = \sqrt{\frac{EI}{T}}$$



E: Young's modulus

I: Moment of area

T: Tension

Dissipation

- Dissipation considered in the calculation：
  Viscous damping and Structure damping
- Viscous damping: Damping force is proportional to the relative velocity (Eddy current damping in our case)

$$E_{\mathrm{Damp}} = \frac{1}{2} C(\dot{x}_1 - \dot{x}_2)^2$$

- Structure damping: Caused by the internal friction of the elastic elements. The spring constants are extended to the complex numbers.

$$k \rightarrow k(1 + i\phi)$$

Dissipation Dilution

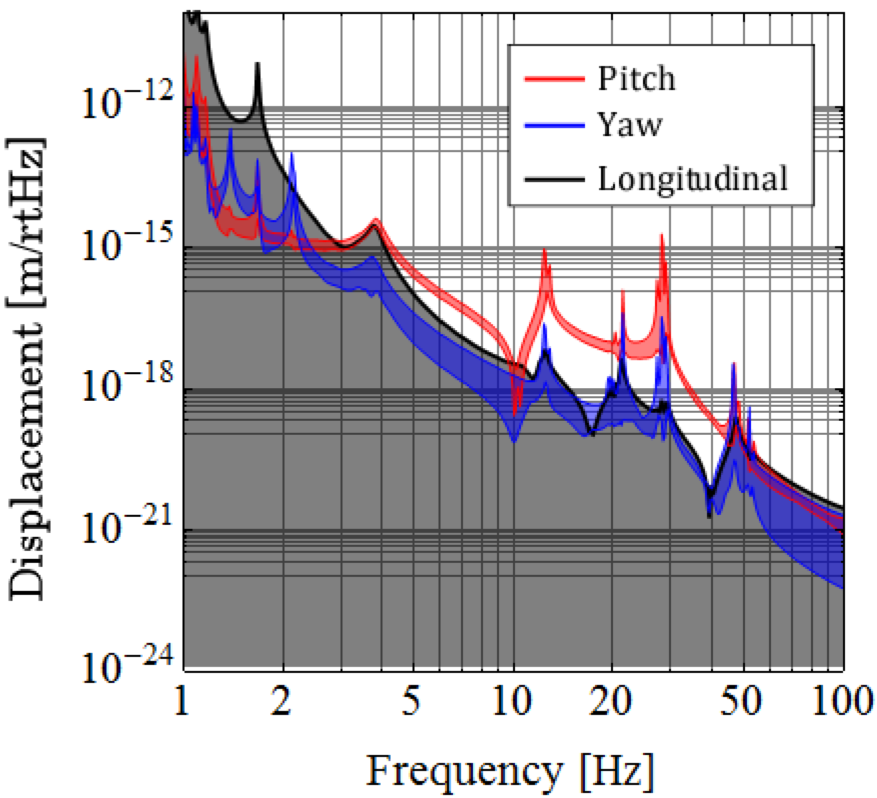
- In our models, the restoring force of pendulum is caused by the elasticity of the wires.
- In actual cases, the restoring force is caused mainly by the gravitational energy, so that the loss of the pendulum is smaller than the loss angle of the wire material.

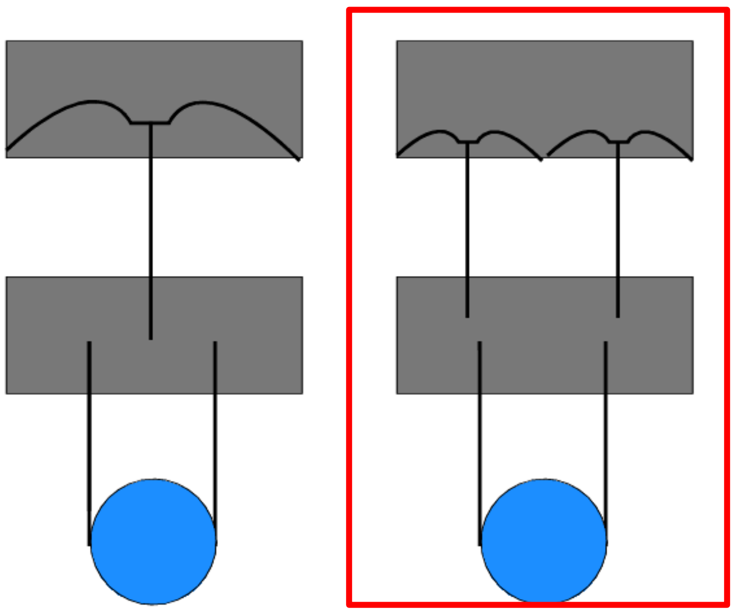
$$\phi_{\text{Pendulum}} = \frac{1}{2L}\sqrt{\frac{EI}{T}}\phi_{\text{Wire}}$$

- To take this into account, the dissipation of the vertical bonce of the wire and the horizontal motion of the suspended body is separately calculated.

What If the IM is Suspended by 4 Wires?

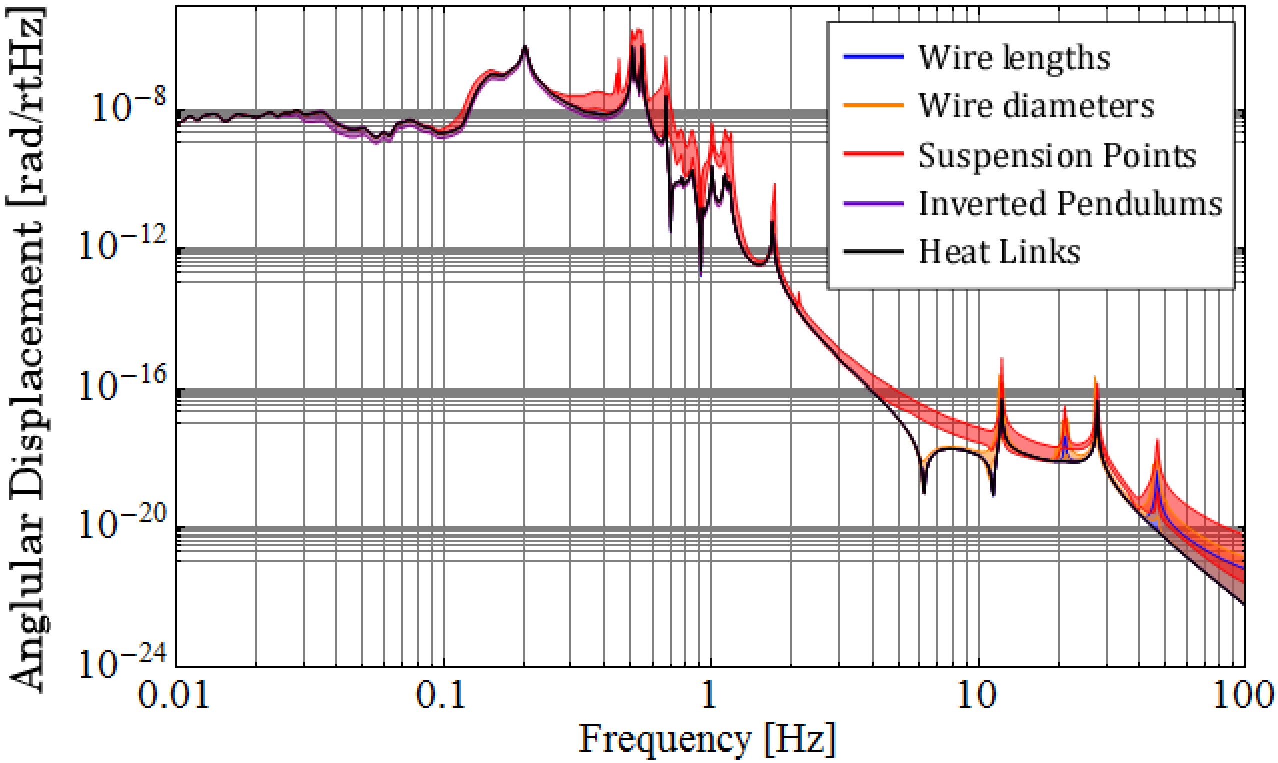
- Pitch-longitudinal couplings are relatively large.
- Additionally, we expect vertical-pitch couplings due to the asymmetry of the spring constants of mini-GAS filters.





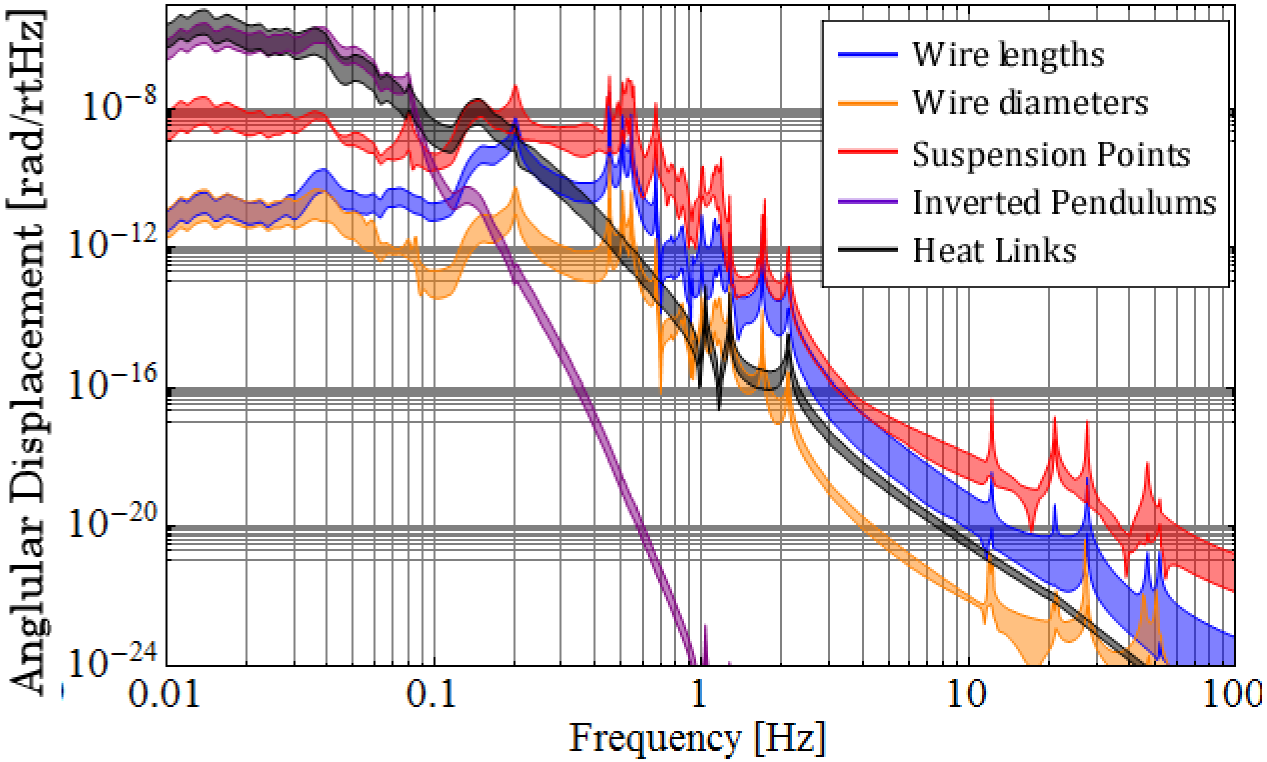
Impact of Each Kind of Asymmetry

- Pitch



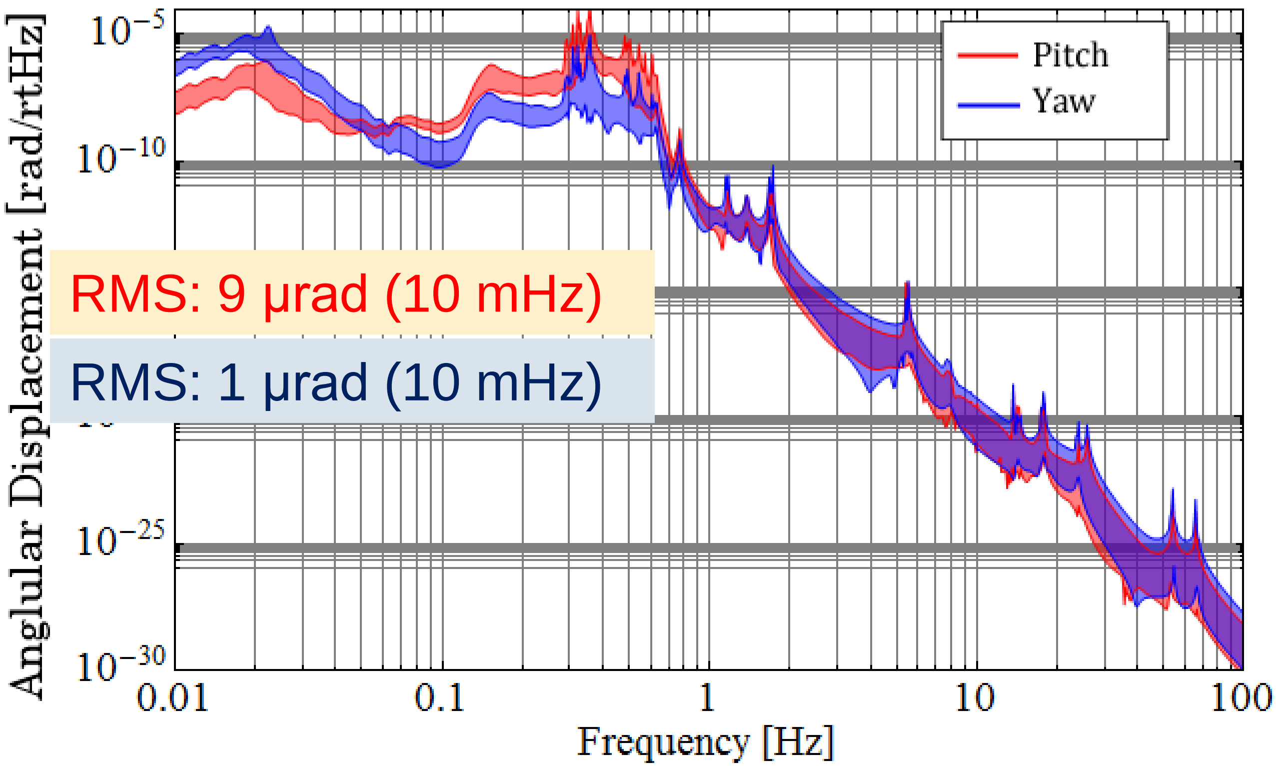
Impact of Each Kind of Asymmetry

- Yaw



Angular Fluctuation of the Mirrors

- Recycling Mirrors



Angular Fluctuation of the Mirrors

- Beam Splitter