

**A part of Status of Type B
suspensions in KAGRA
and
Implementing the State Space Approach
for Controlling a Suspension System in KAGRA**

@ The University of Perugia, Italy

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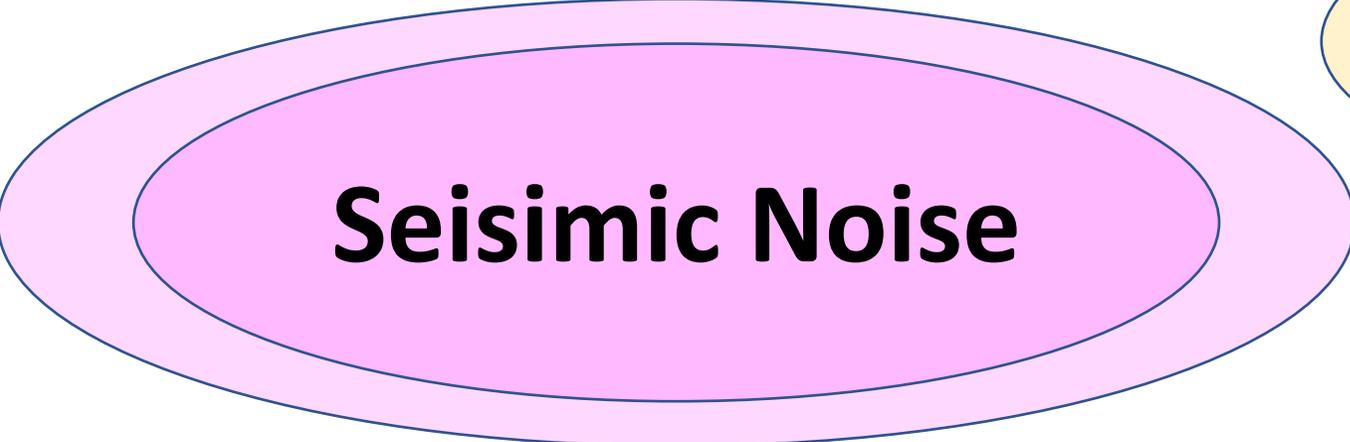
on behalf of KAGRA collaboration

Overview

- Introduction
- GAS filter tuning
- Cross coupling cancellation
- State space represent

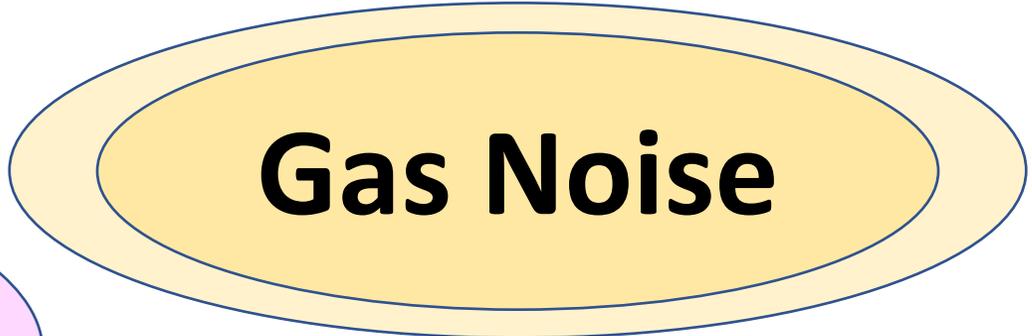
Introduction

Noise Sources



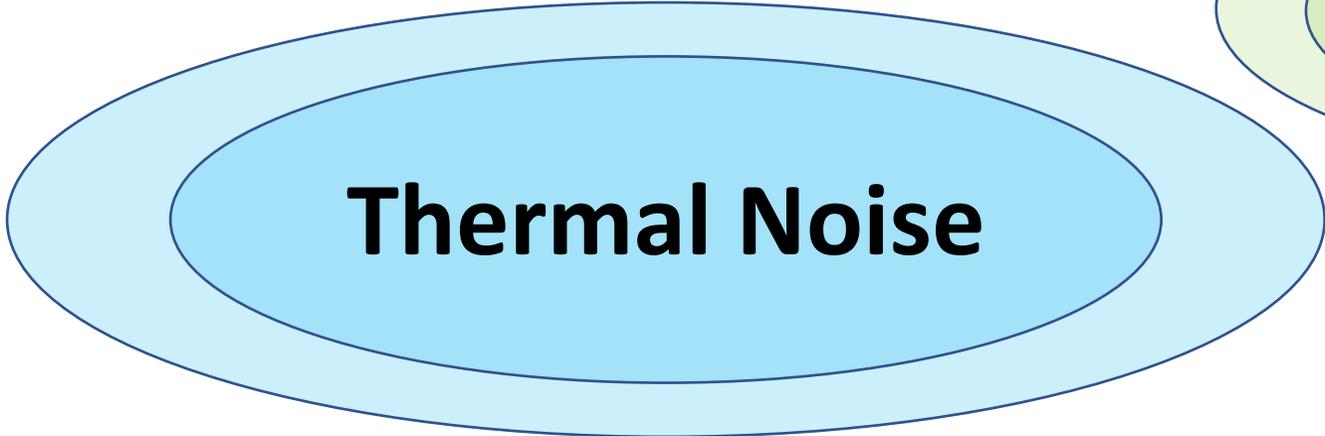
Seismic Noise

A diagram consisting of two concentric ovals. The inner oval is a solid magenta color, and the outer oval is a lighter, semi-transparent magenta color. The text "Seismic Noise" is centered in the inner oval.



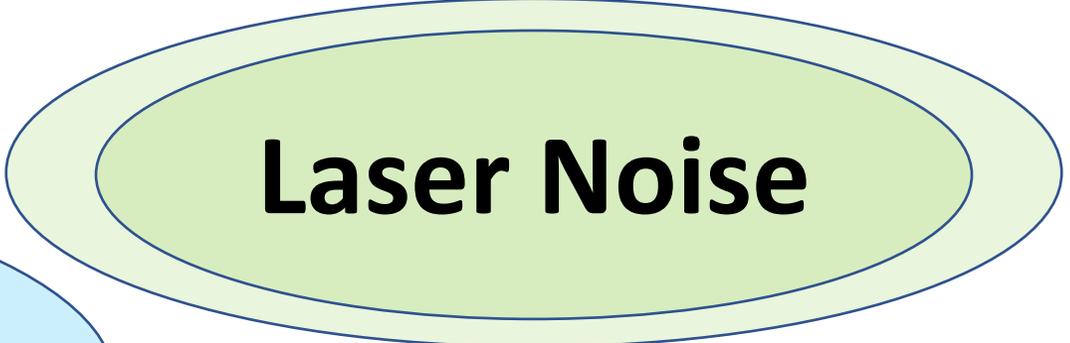
Gas Noise

A diagram consisting of two concentric ovals. The inner oval is a solid yellow color, and the outer oval is a lighter, semi-transparent yellow color. The text "Gas Noise" is centered in the inner oval.



Thermal Noise

A diagram consisting of two concentric ovals. The inner oval is a solid light blue color, and the outer oval is a lighter, semi-transparent light blue color. The text "Thermal Noise" is centered in the inner oval.



Laser Noise

A diagram consisting of two concentric ovals. The inner oval is a solid light green color, and the outer oval is a lighter, semi-transparent light green color. The text "Laser Noise" is centered in the inner oval.

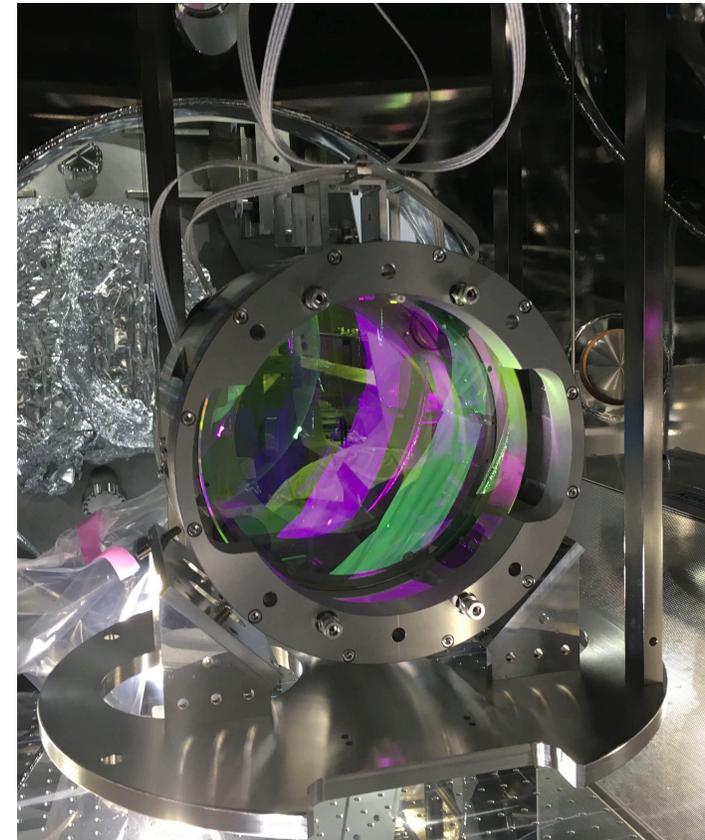
And so on...

How can we reduce Seismic noise?

1. Choosing a tranquil area

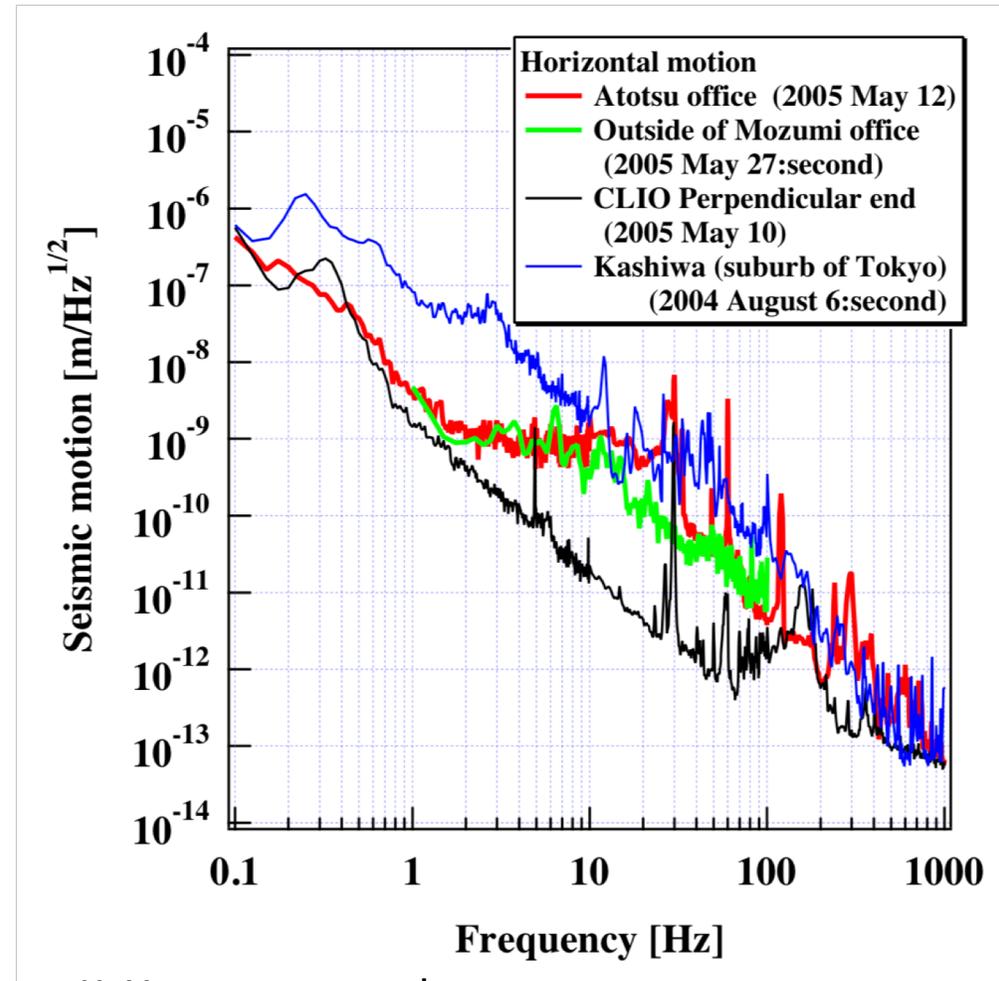


2. Hanging a mirror



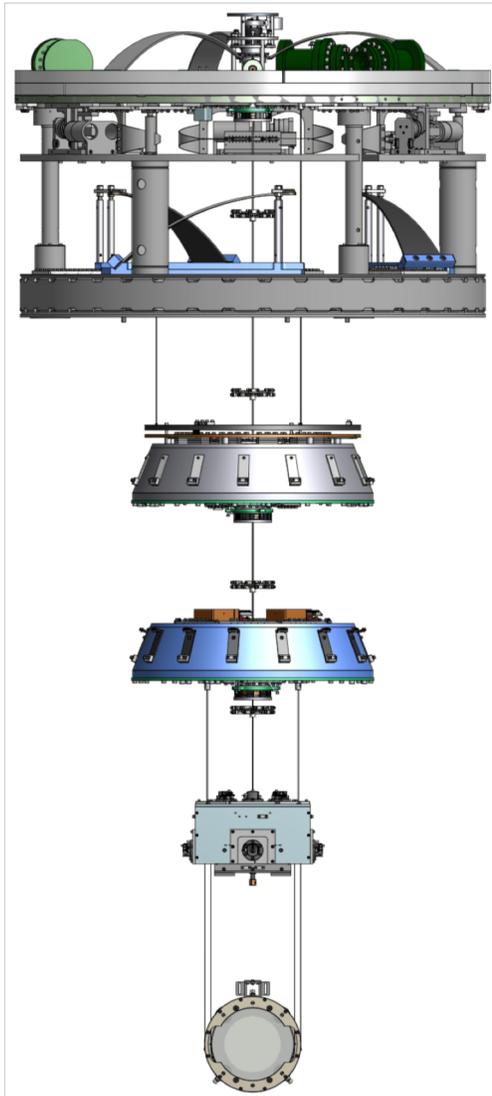
Seismic feature

- Underground reduces the motion of ground 1/100 times smaller in 1 – 100 Hz than that of ground.

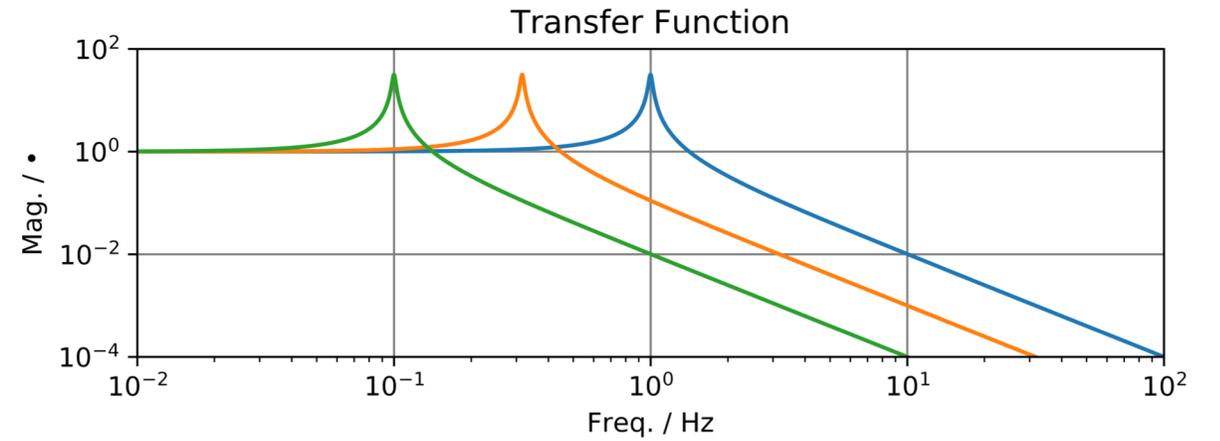


K. Yamamoto et al.,
“Measurement of seismic motion at Large-scale Cryogenic
Gravitational wave Telescope project site”

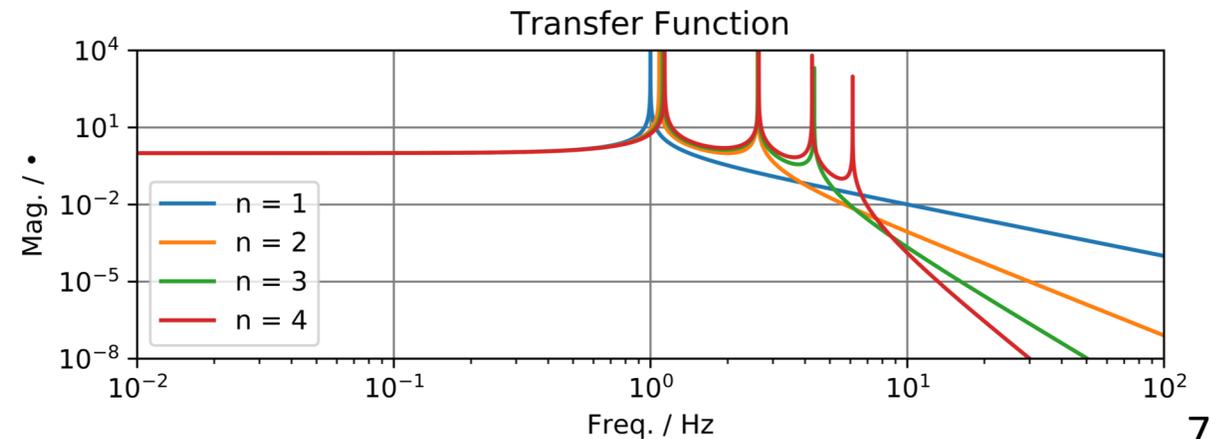
Pendulum Features

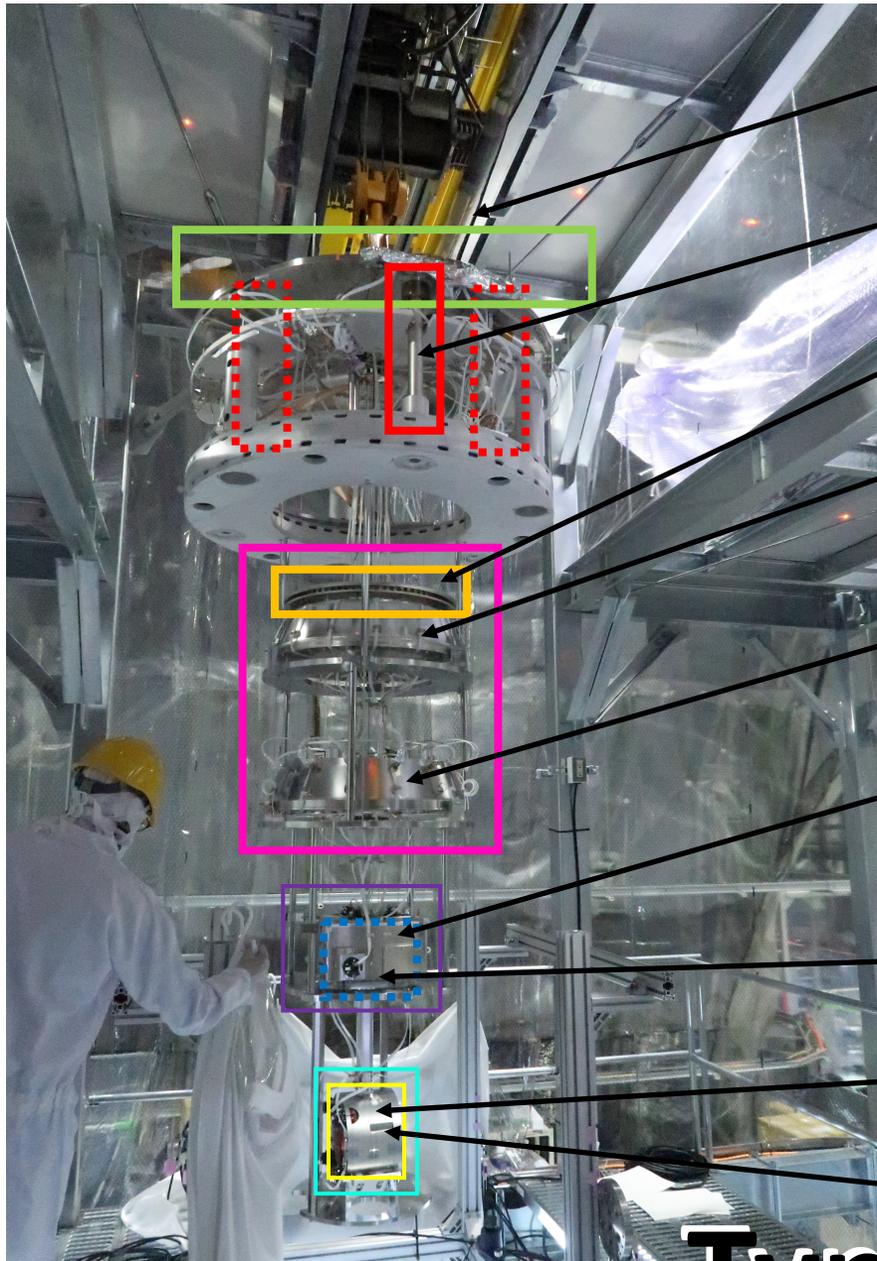


Low resonant frequency



Multiple Pendulums





Top Filter (F0)

Inverted Pendulum

magnet damper

Standard Filter (F1)

Bottom Filter (F2)

Intermediate

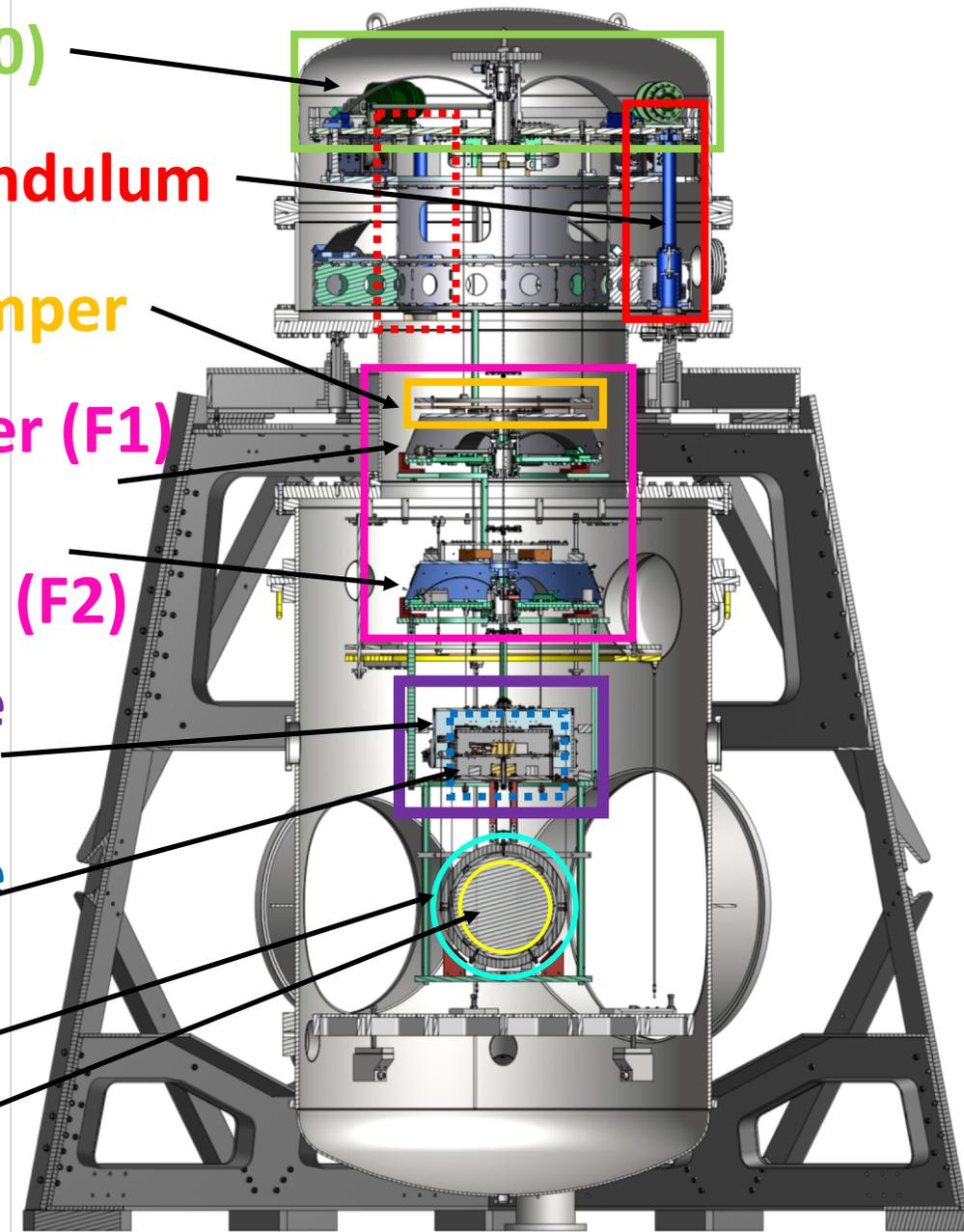
Recoil Mass

Intermediate

Mass

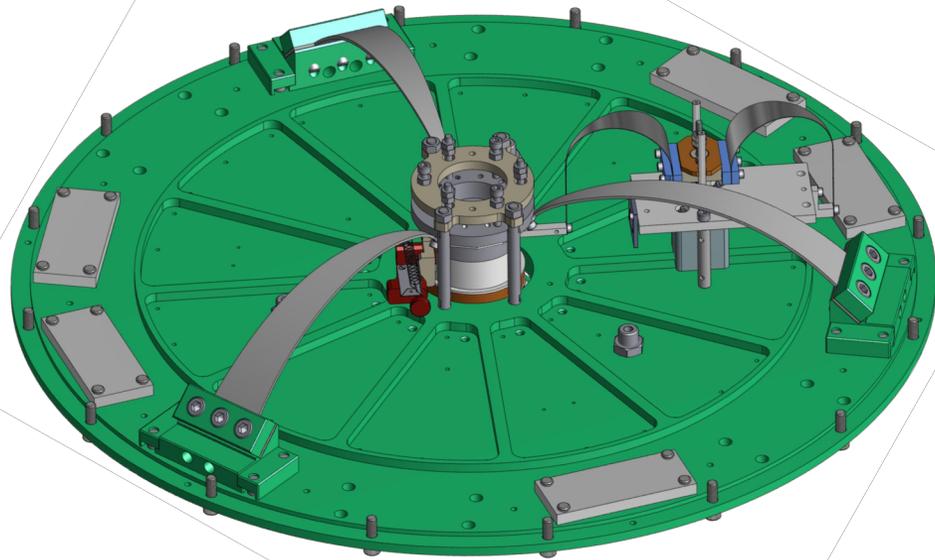
Recoil Mass

Test Mass

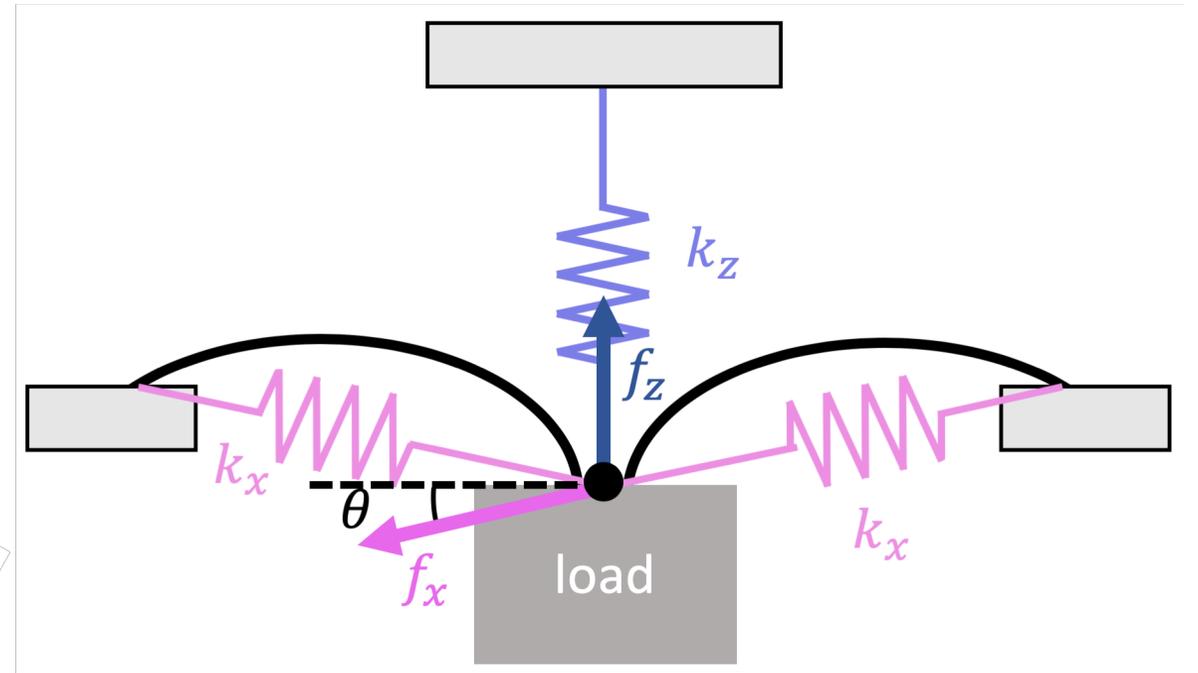


GAS filter tuning

What is GAS?



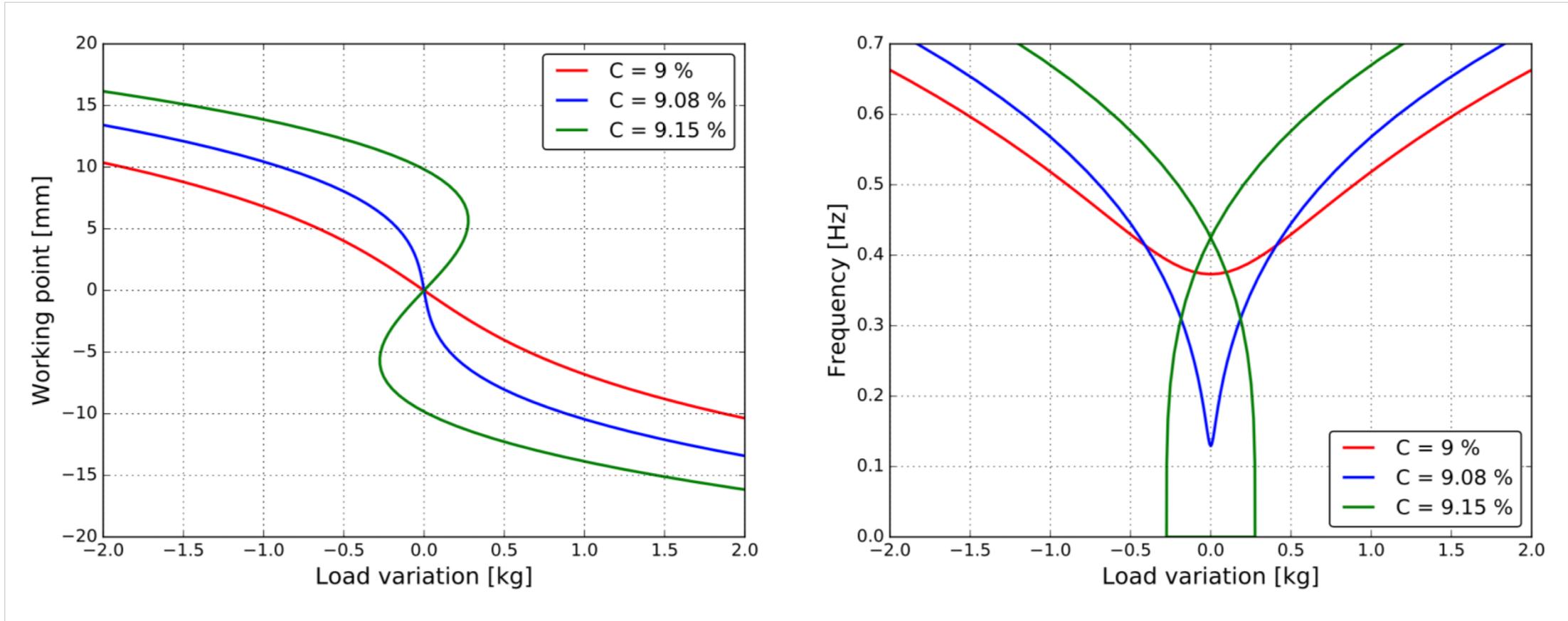
~ 0.3 Hz



$$k_{\text{eff}} = k_z - \left(\frac{l_{0x}}{x_0} - 1 \right) k_x$$

$$\omega_0 = \sqrt{\frac{k_{\text{eff}}}{M}}$$

GAS blade behavior

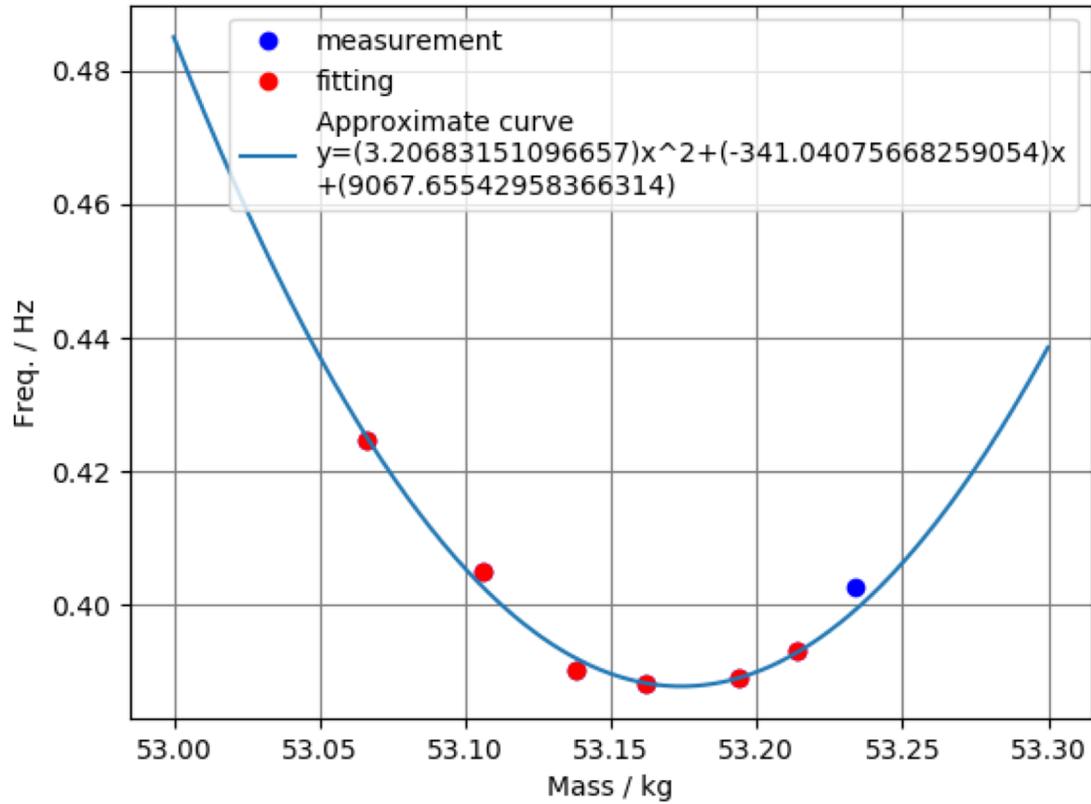


$$C = (l_{0x} - x_0) / l_{0x} \quad m = 200 \text{ kg}$$

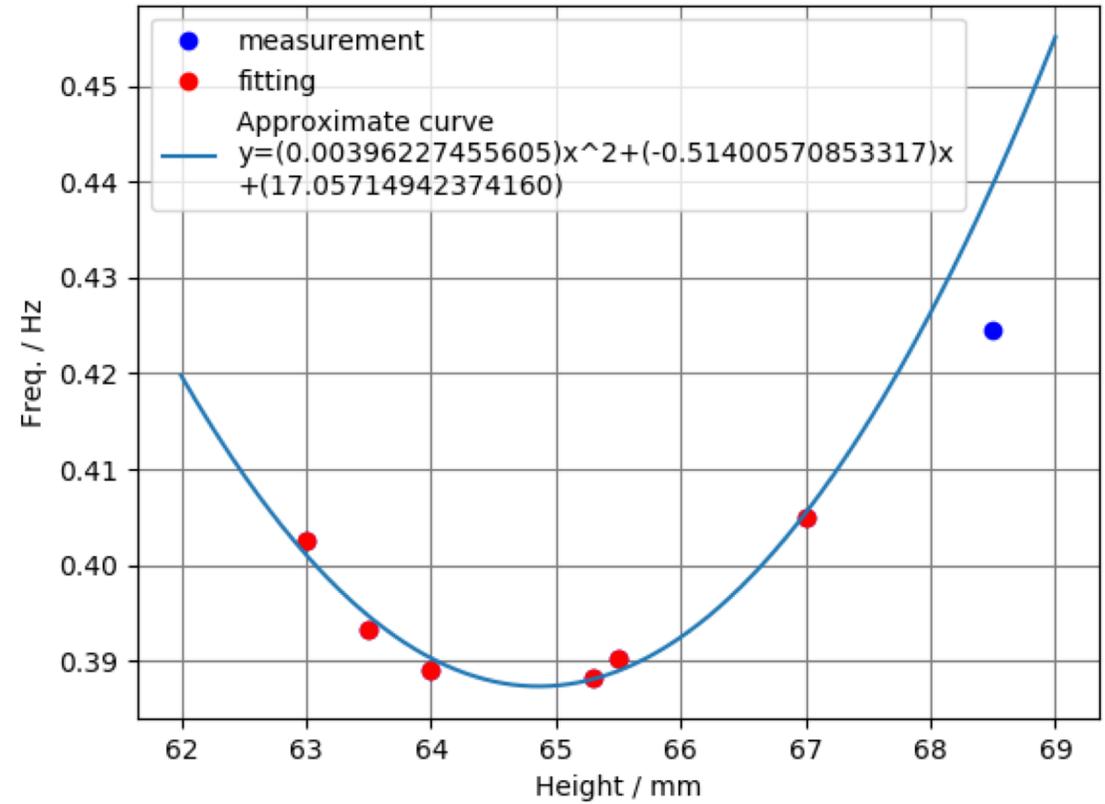
[Y. Fuji master thesis]

Calibration result: SR2 bottom filter

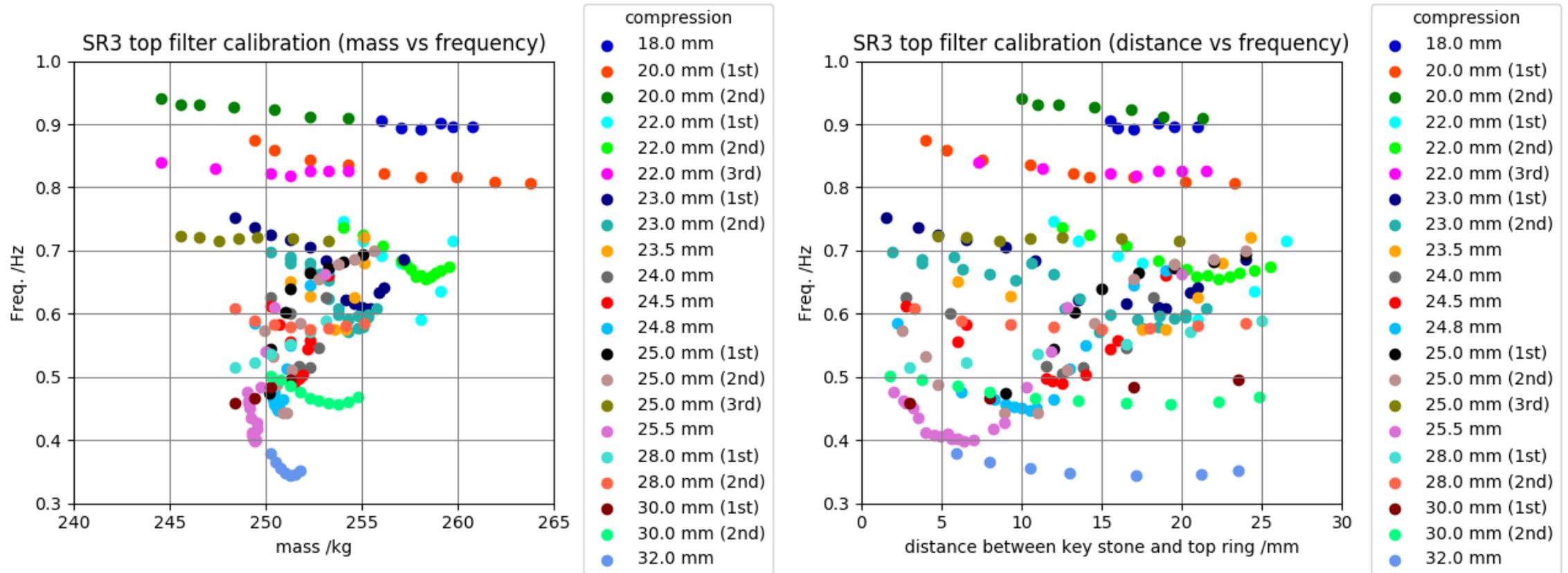
BF No.7 calibration



BF No.7 calibration

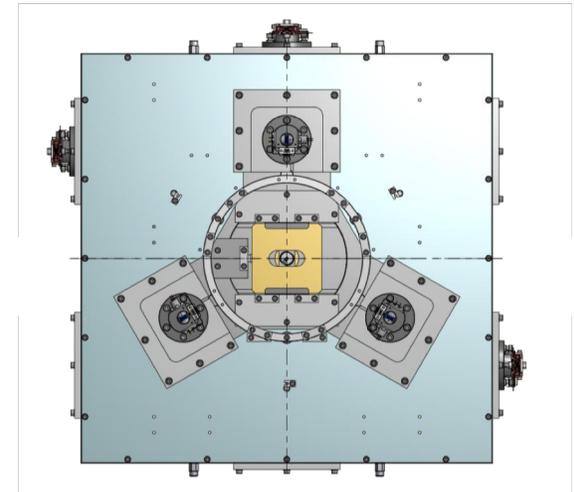
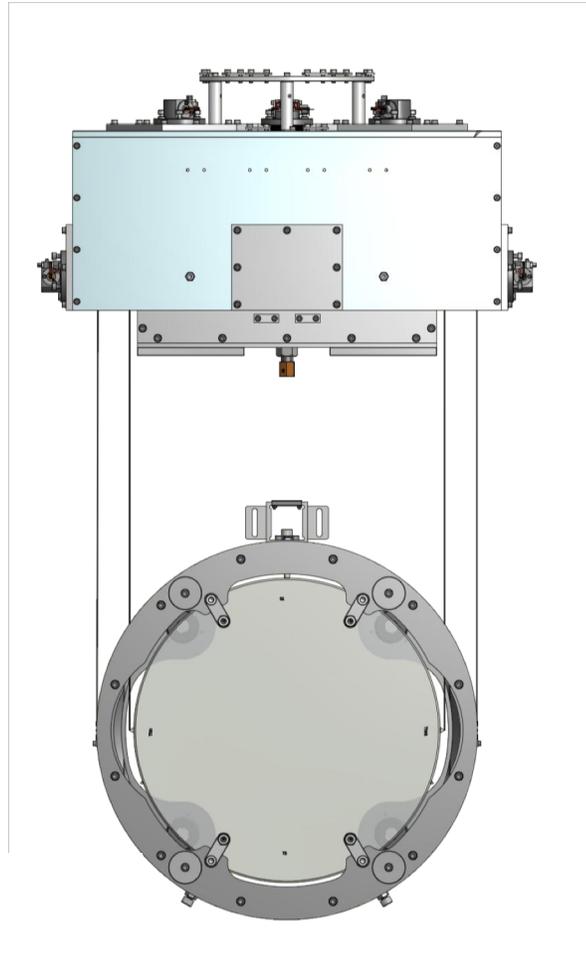
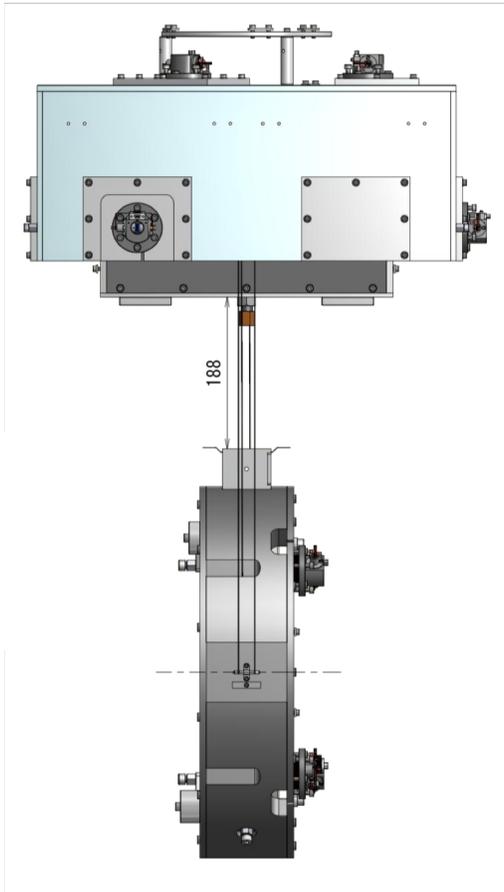


Calibration result: SR3 Top filter

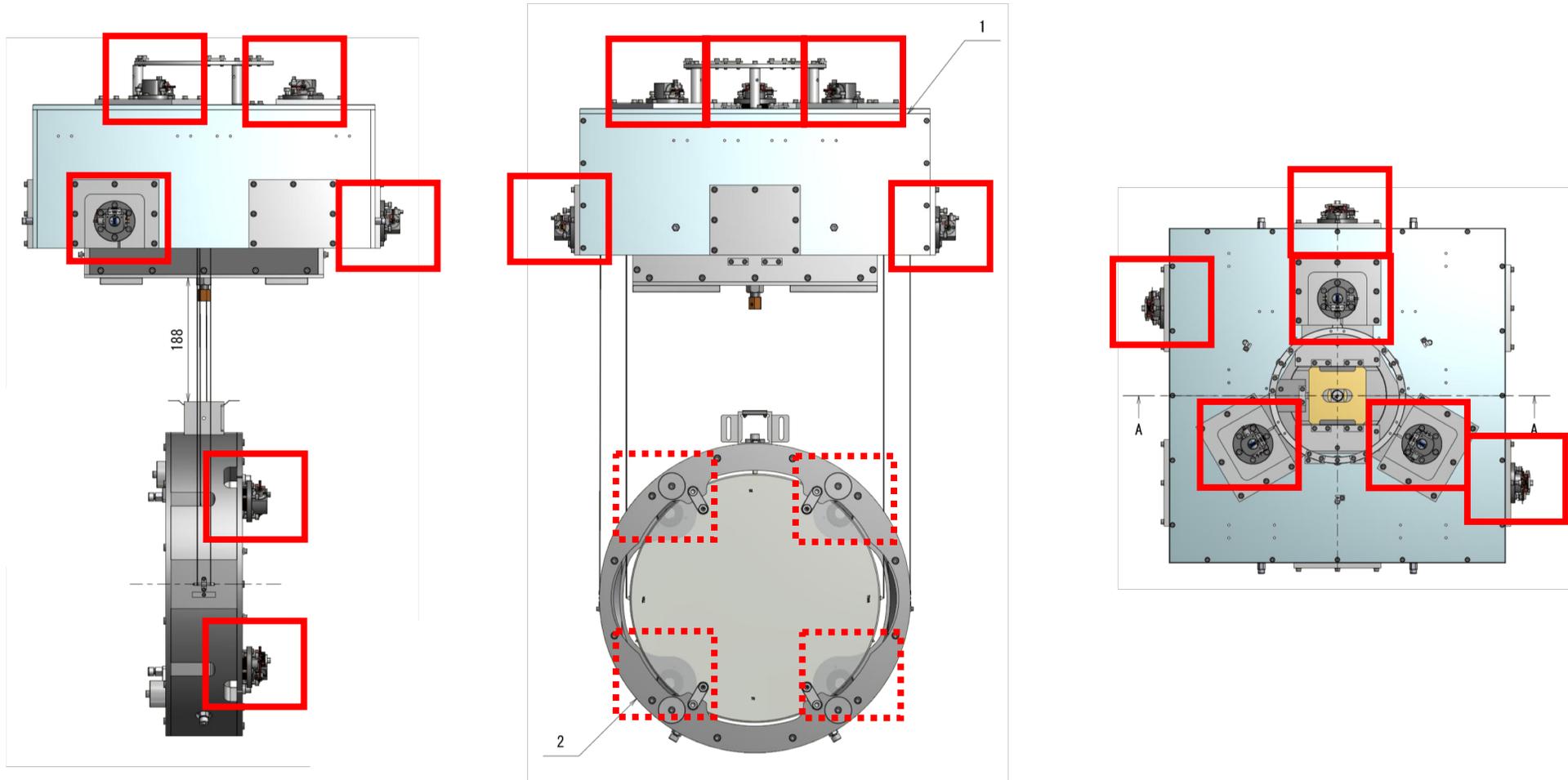


Cross Coupling Cancellation

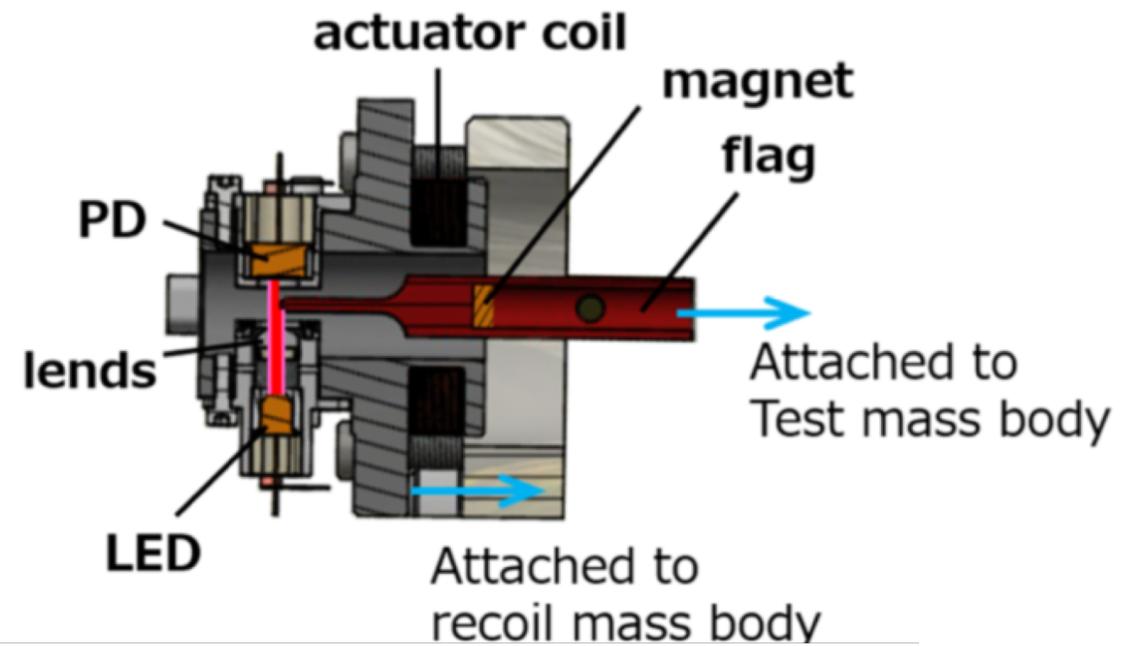
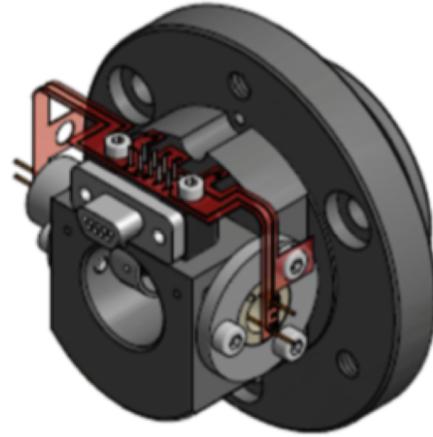
Payload



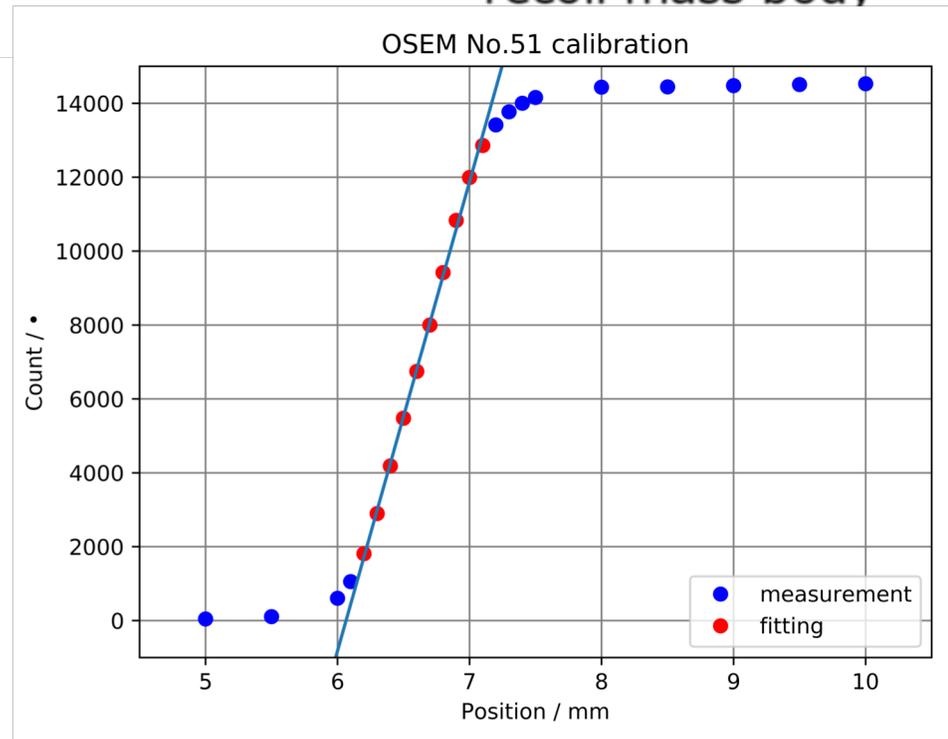
Payload actuators



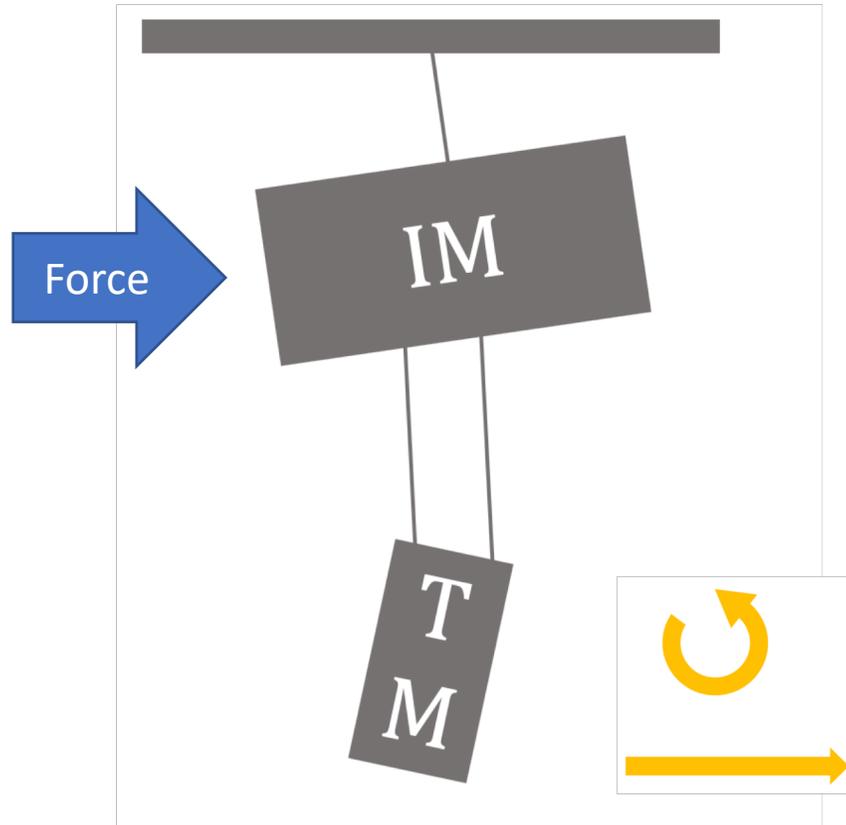
OSEM



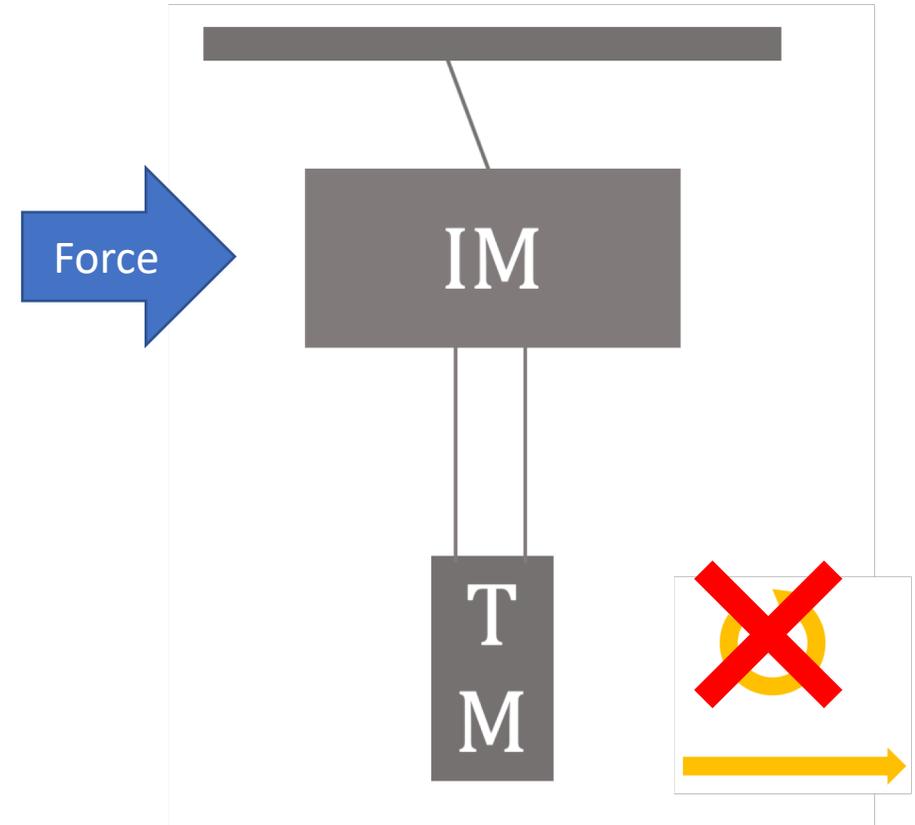
Optical Sensor ElectroMagnet (OSEM) is a sensor and actuator. It measures the relative distance of IM and actuate IM by a coil.



Cross coupling cancellation

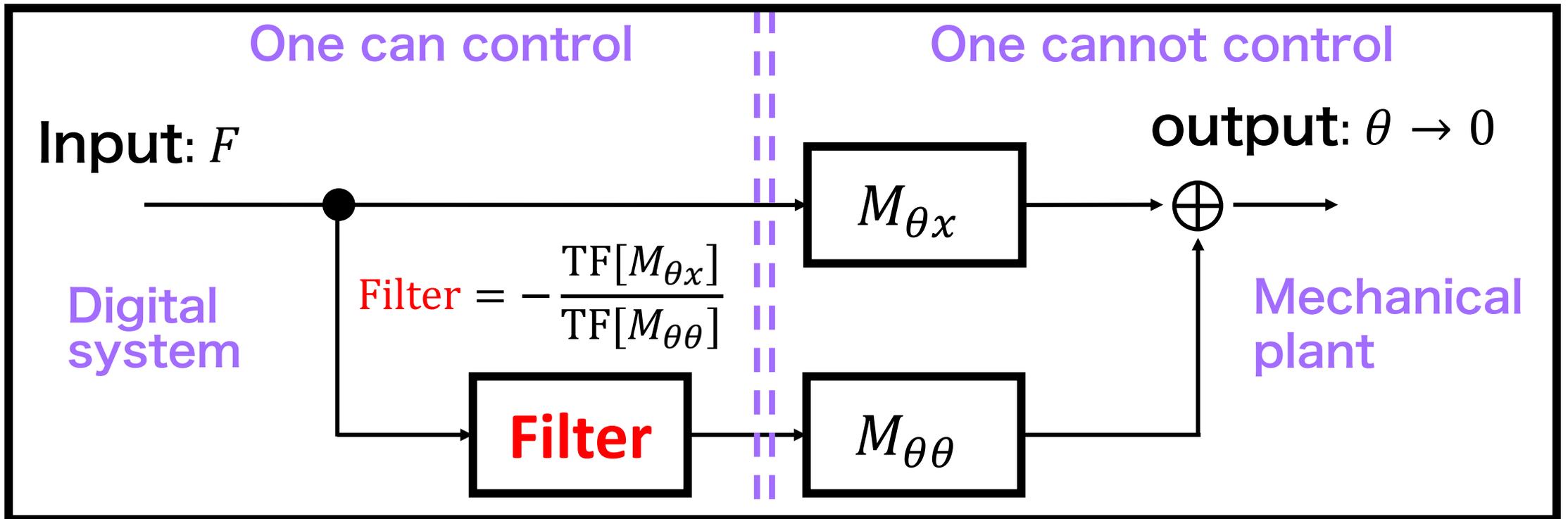


Without control filters



With control filters

How do we install a filter?

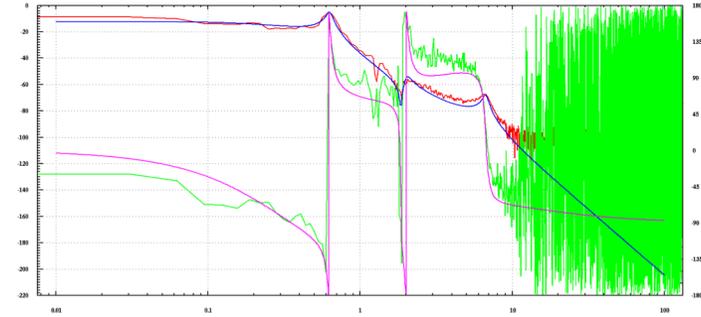
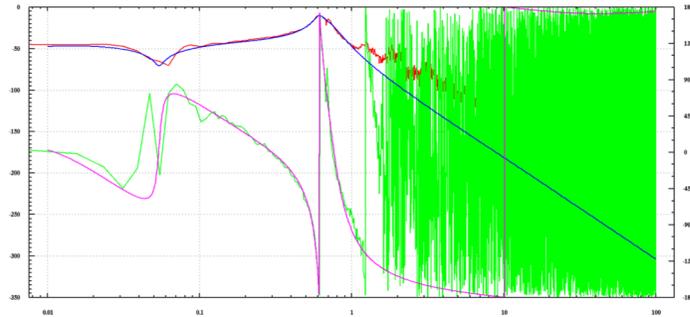


Result

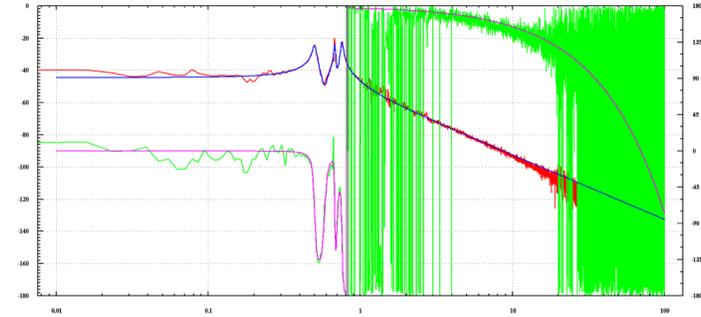
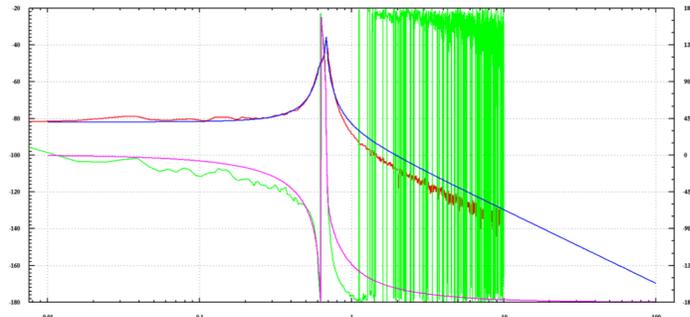
$L \rightarrow P$

$P \rightarrow P$

IM
to
TM

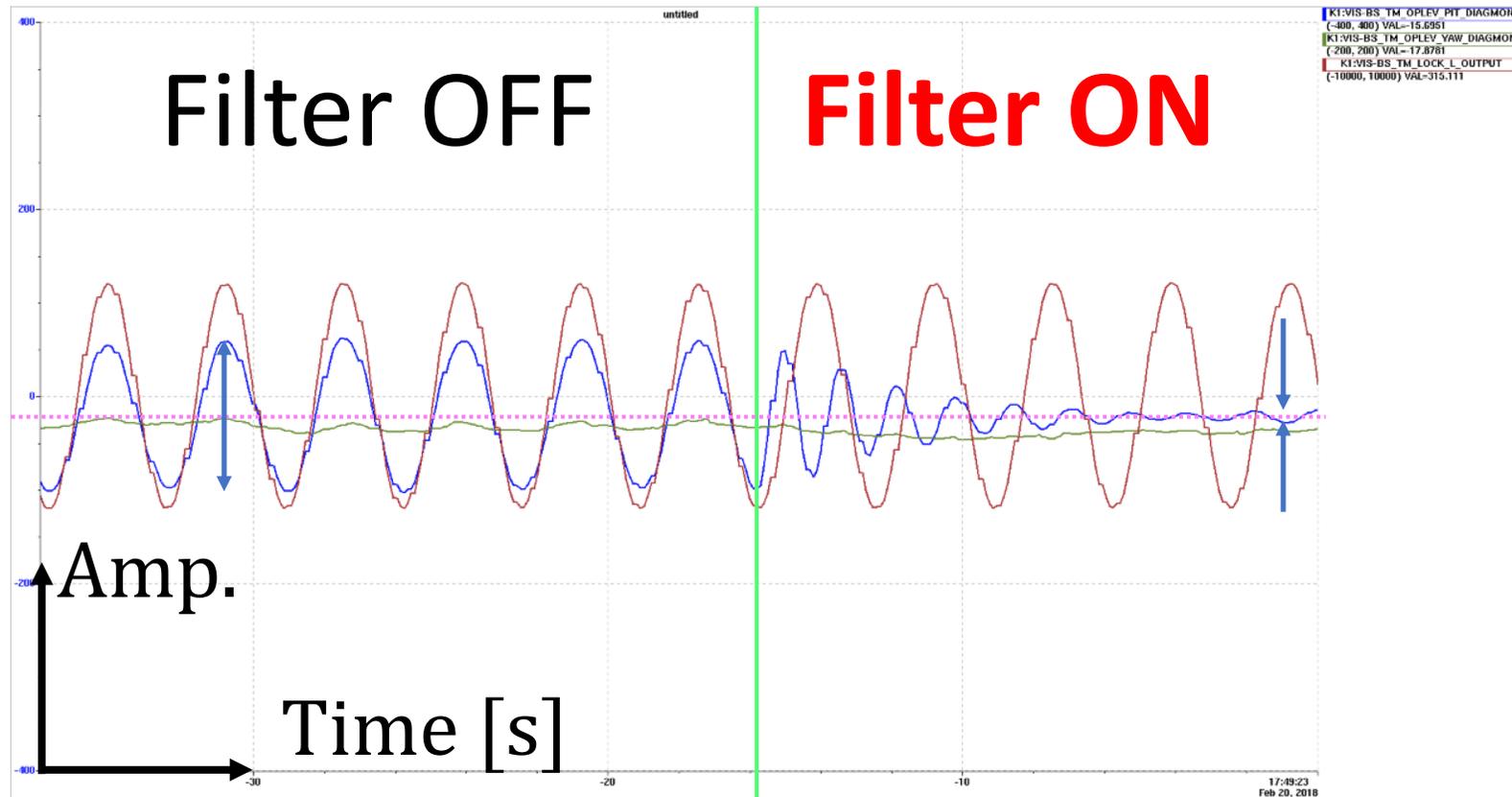


TM
to
TM



Damped transfer functions and its fitting

Result (time vs amp.)



Input signal vs TM pitch at 0.3 Hz. The amplitude became 1/10 times smaller.

State Space Approach

EOM of suspensions

- Since the suspension moves around the equilibrium points, we can use an Taylor approximate Lagrangian around the equilibrium points.

$$\frac{d}{dt} \frac{\partial \mathcal{L}_{\text{apr}}}{\partial \dot{X}} - \frac{\partial \mathcal{L}_{\text{apr}}}{\partial X} = 0$$
$$\mathcal{L}_{\text{apr}}(X) = \mathcal{L}(X_{\text{eq}}) + \left. \frac{\partial \mathcal{L}}{\partial X} \right|_{X=X_{\text{eq}}} X + \frac{1}{2} \left. \frac{\partial^2 \mathcal{L}}{\partial X^2} \right|_{X=X_{\text{eq}}} X^2.$$

EOM of suspensions

- From this approximation, one can get the linearized equation of motion around the equilibrium points.

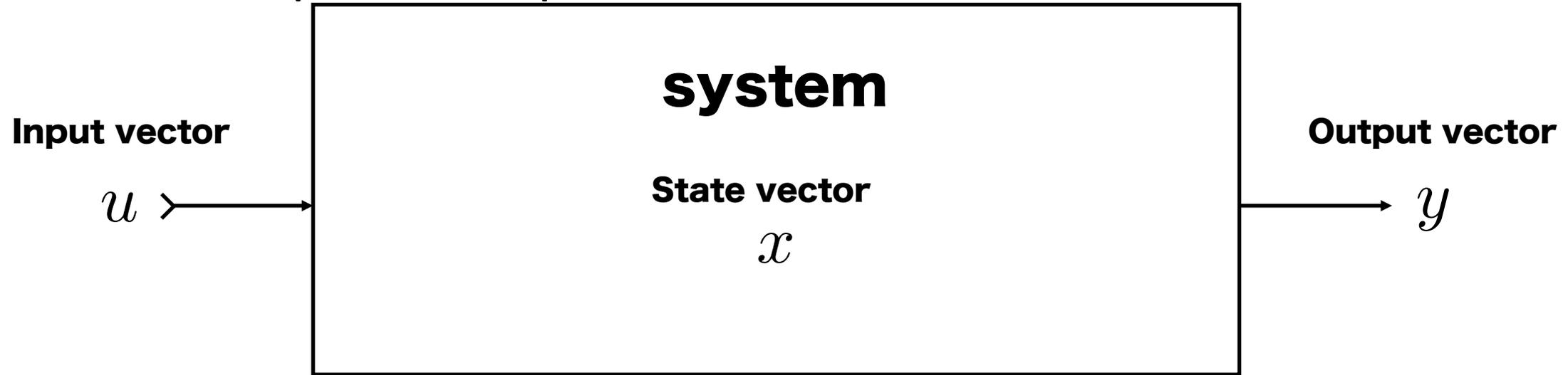
$$M\ddot{\mathbf{x}} + C\dot{\mathbf{x}} + K(\mathbf{x} - \mathbf{x}_{\text{eq}}) = 0$$

M is the inertia matrix

C is the damping matrix

K is the stiffness matrix

State space representation



$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases}$$

A : **State matrix**

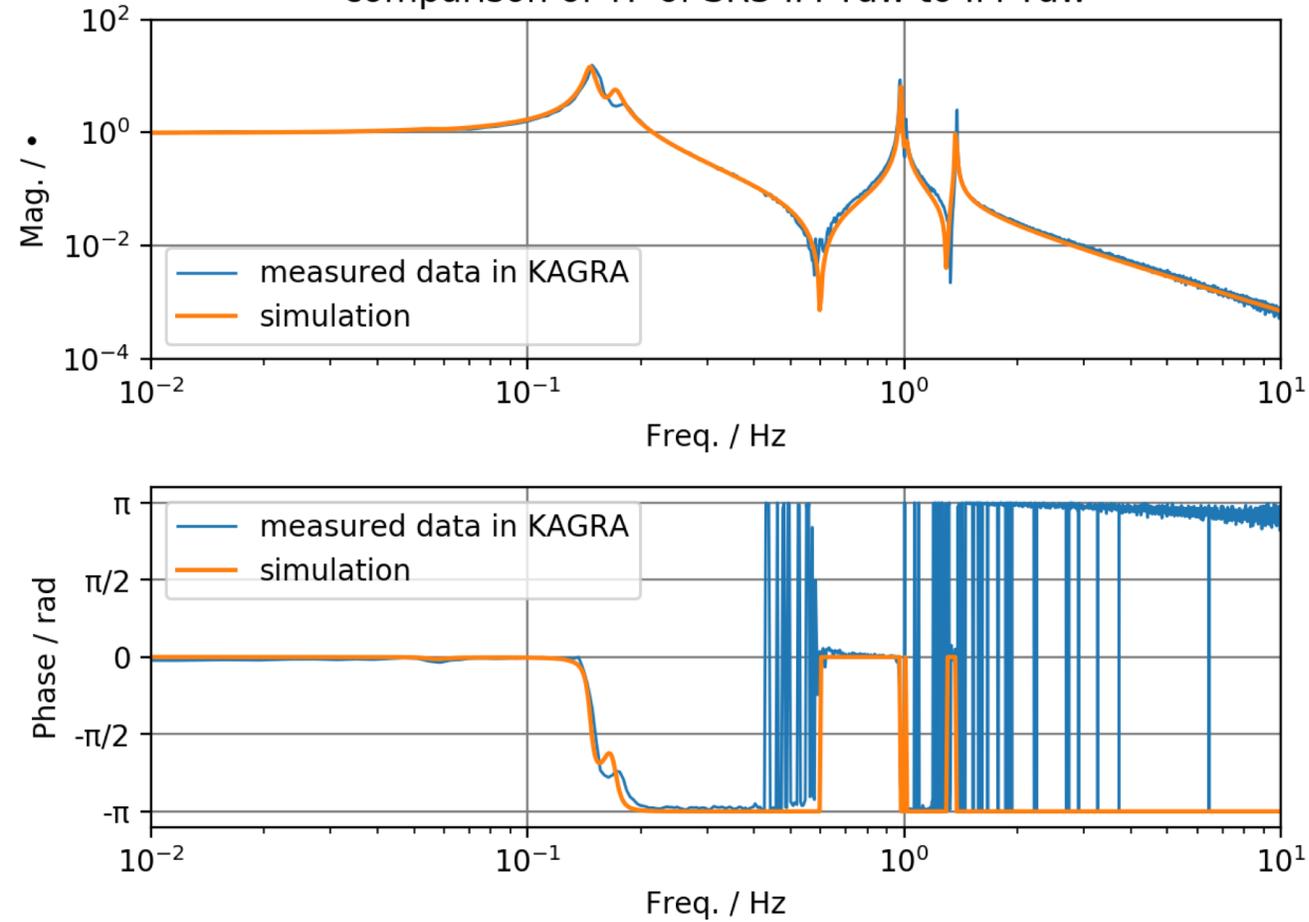
B : **Input matrix**

C : **Output matrix**

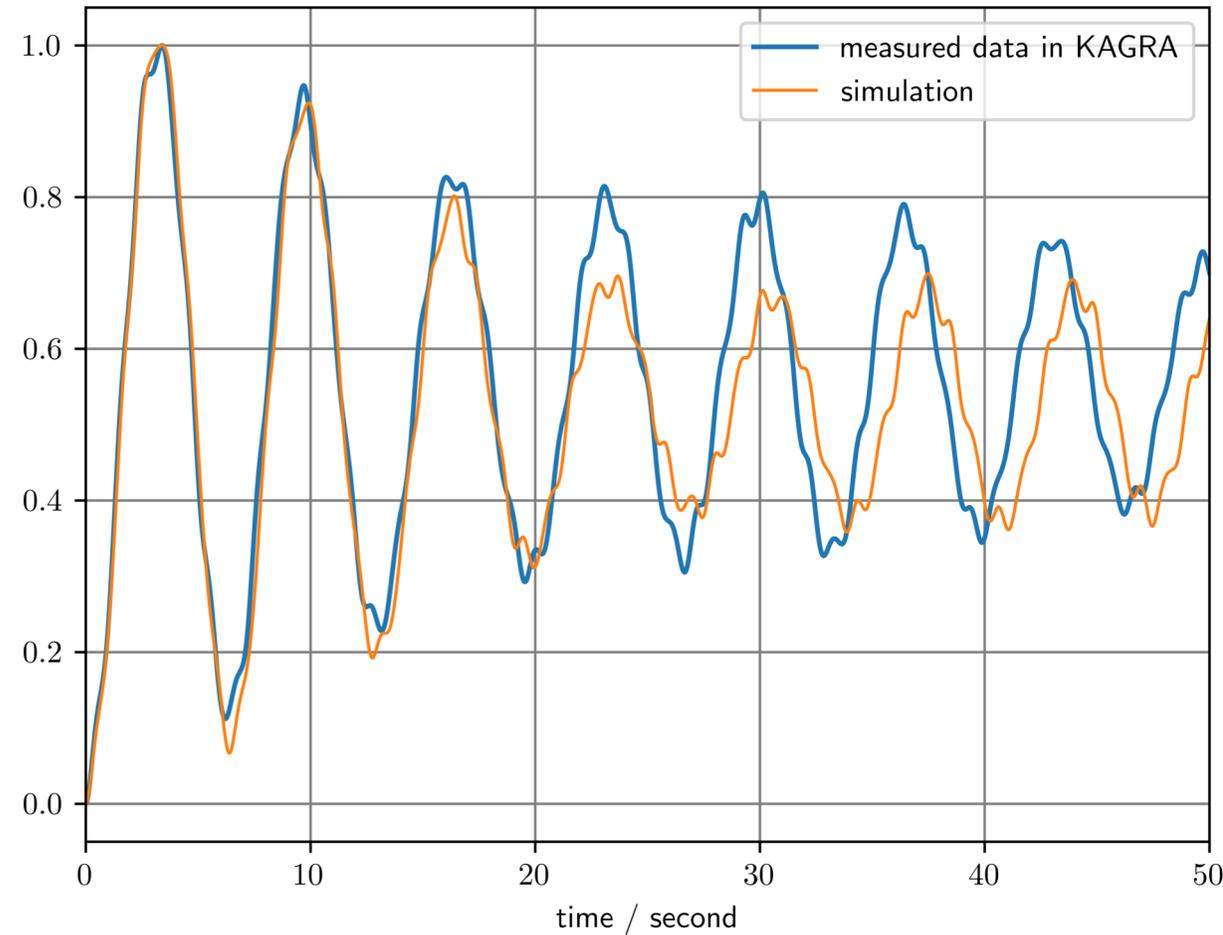
D : **Feedthrough matrix**

Transfer function(SR3 IM Yaw)

comparison of TF of SR3 IM Yaw to IM Yaw



Standardized time series of SR3 IM Yaw step response



Thank you!!
Grazie!!