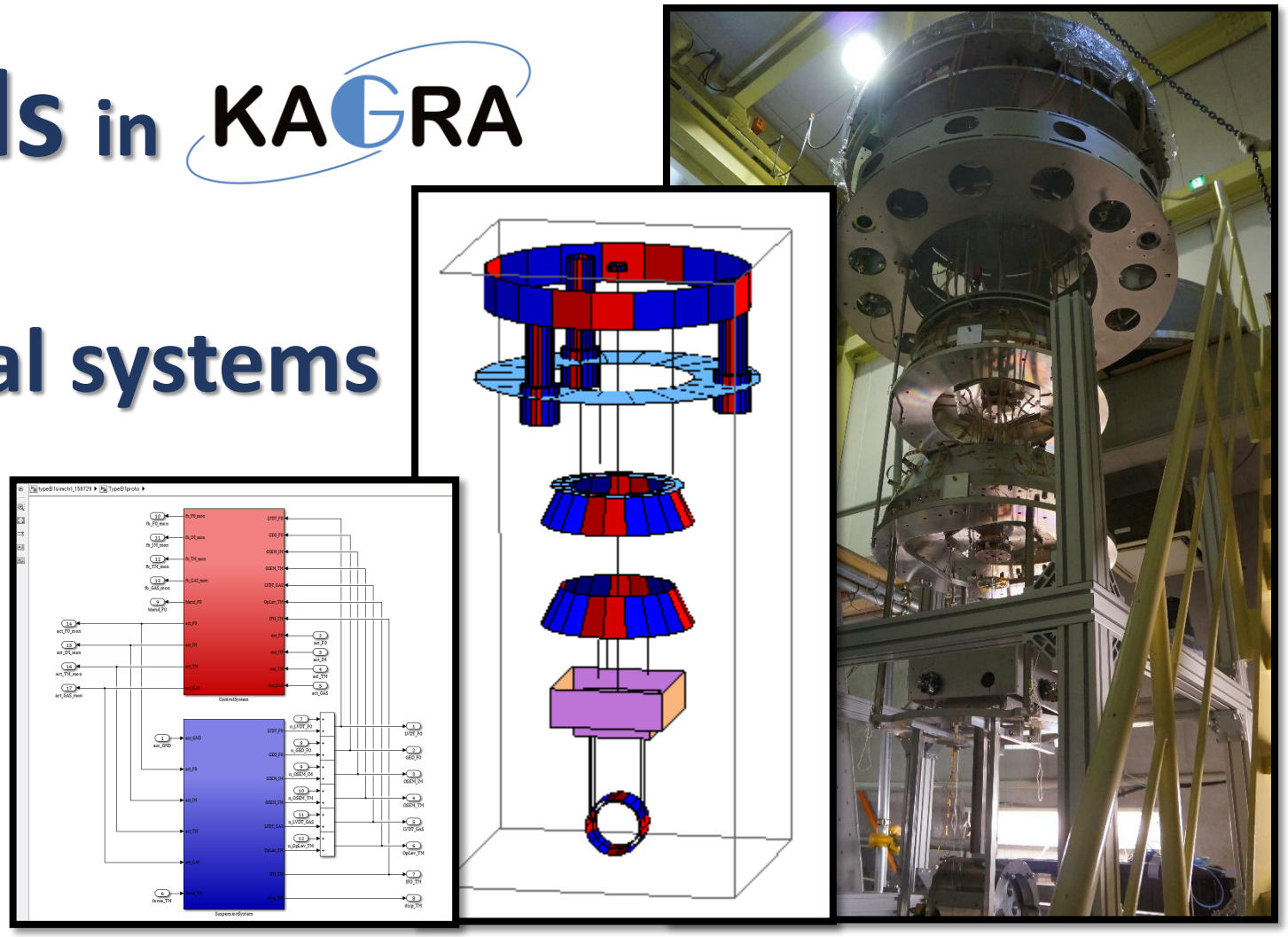
Modeling tools in KAGRA
for seismic and payload mechanical systems



Yoshinori Fujii
U. of Tokyo / NAOJ

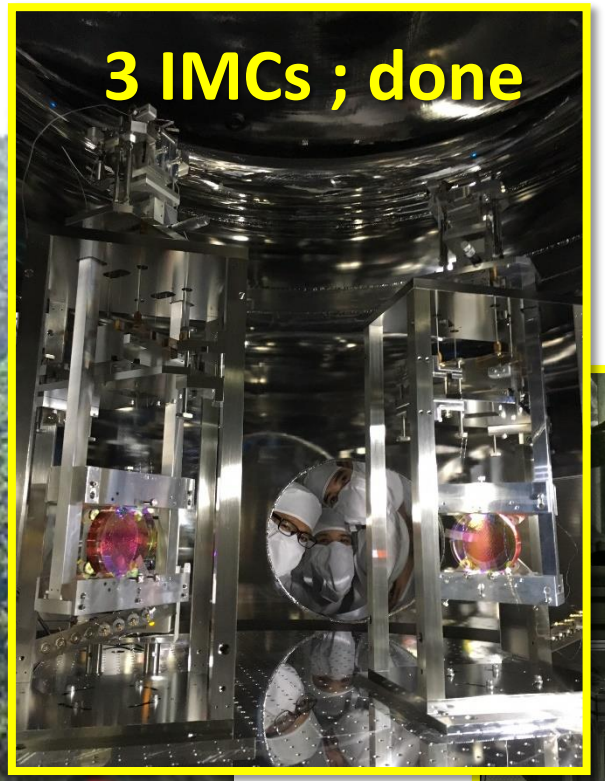
with the cooperation of KAGRA VIS team

Contents

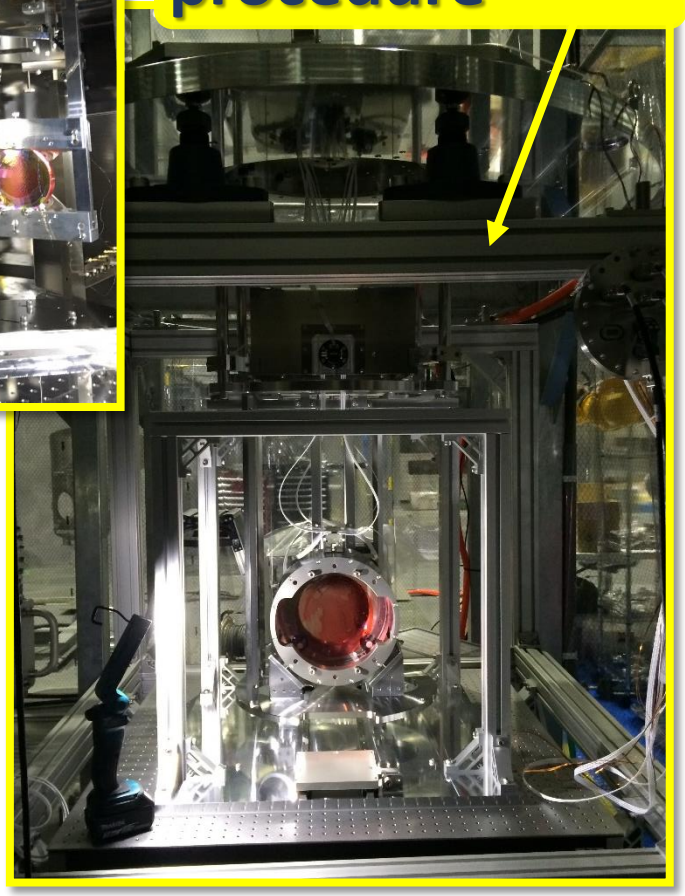
- Intro
  - KAGRA / Suspension Configuration /
- Suspension modeling
  - Modeling tools
  - Implementation to BS SAS prototype exp.

❖ Intro : KAGRA

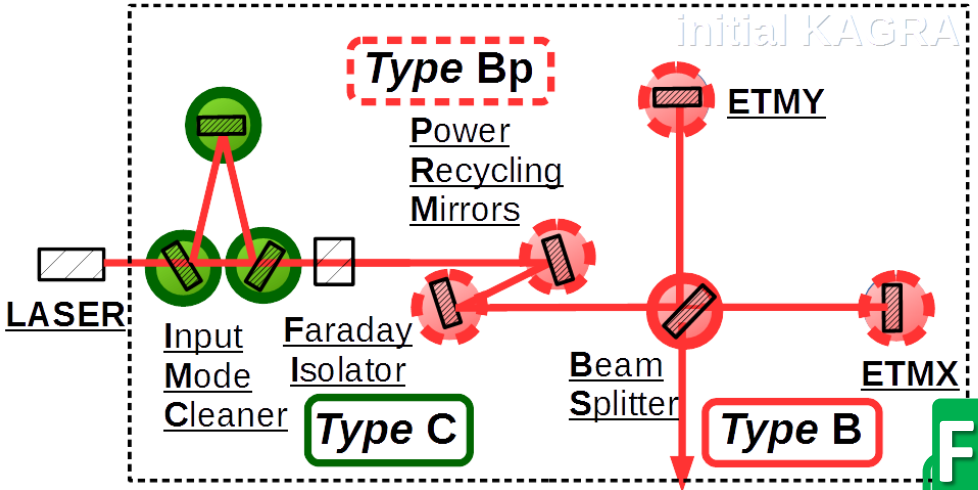
We are NOW installing
İKAGRA SASs in the tunnel!

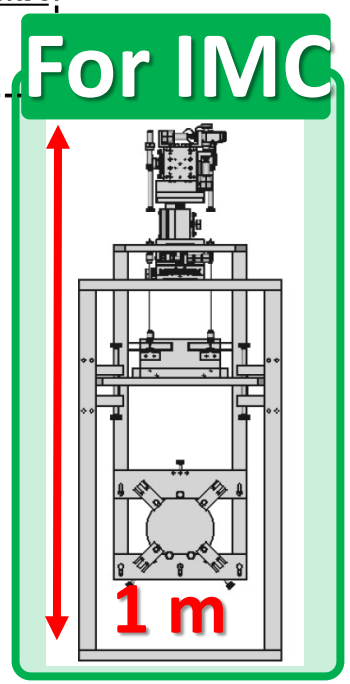


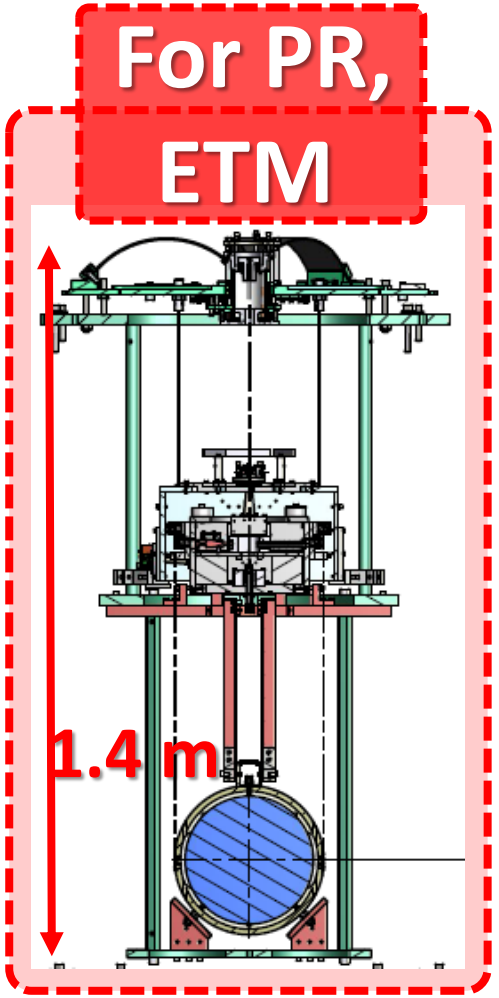
2 PRs & 2 ETMs ;
Confirming
installation
procedure

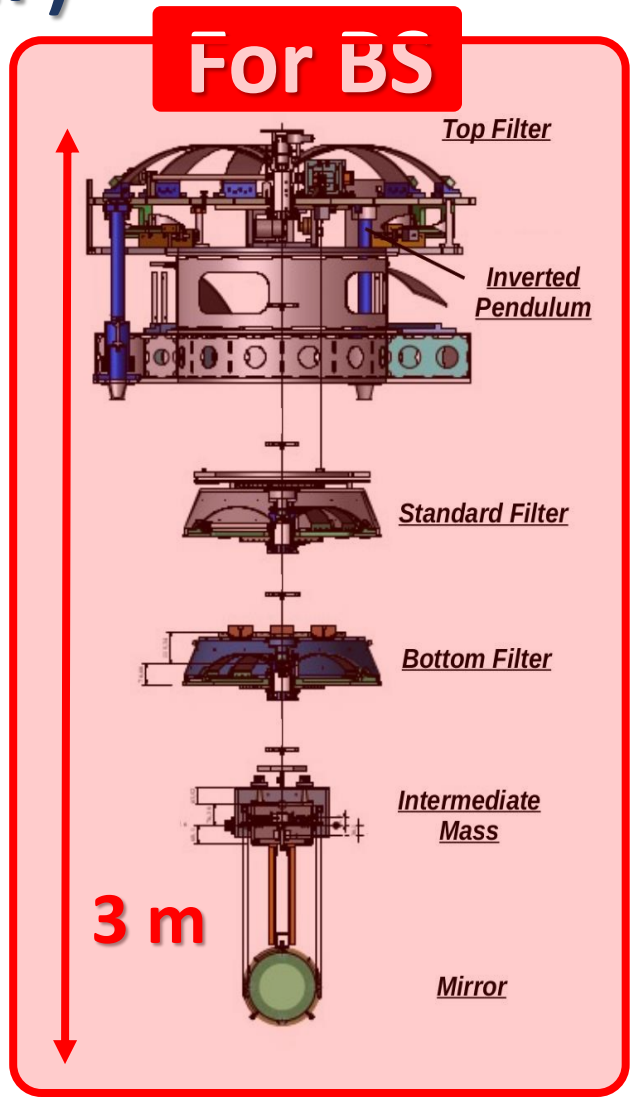


❖ iKAGRA Suspension Configuration (for a test run)

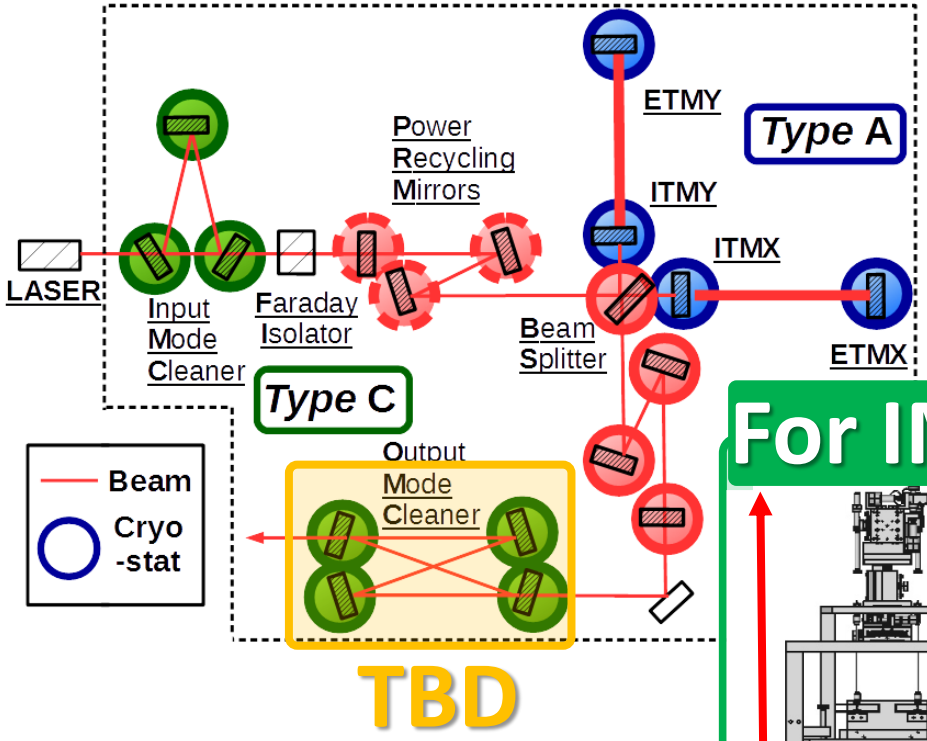


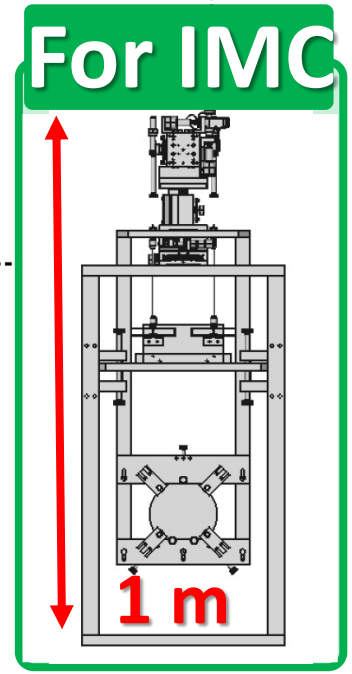


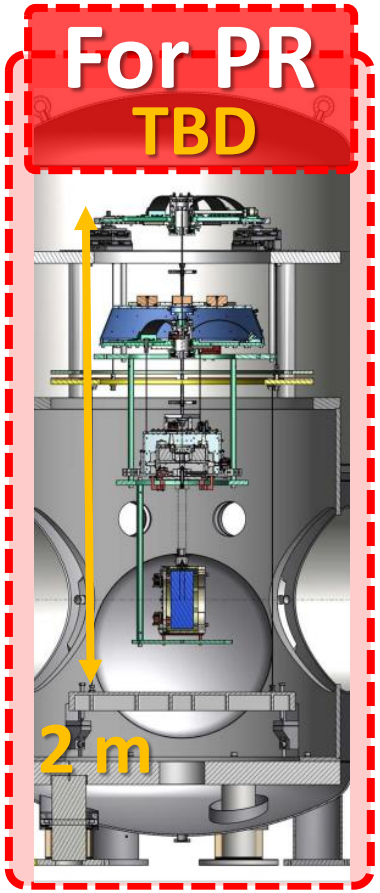


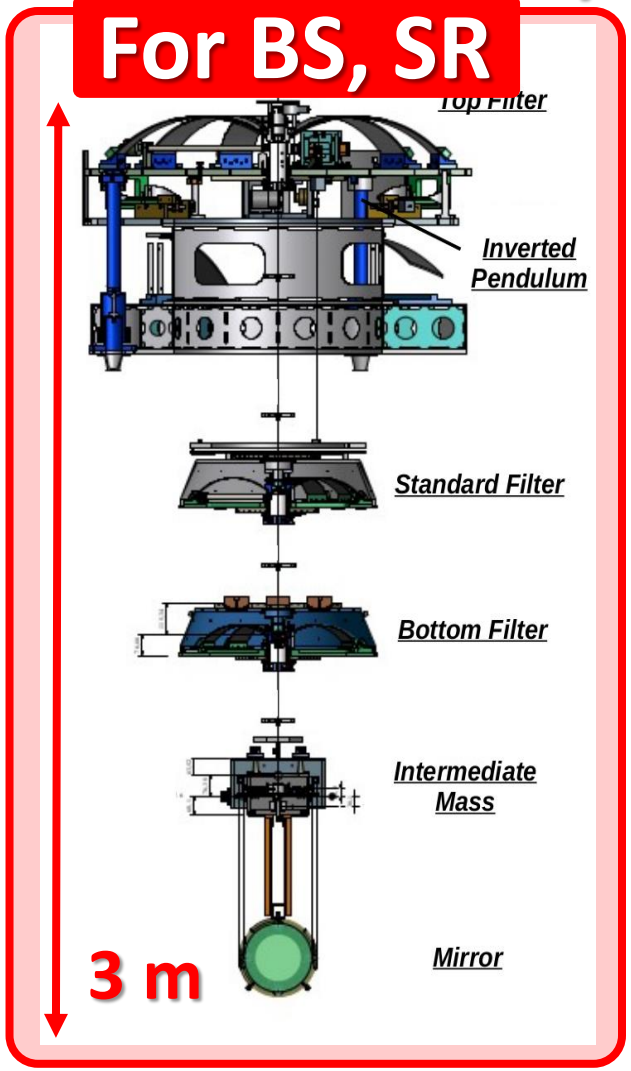


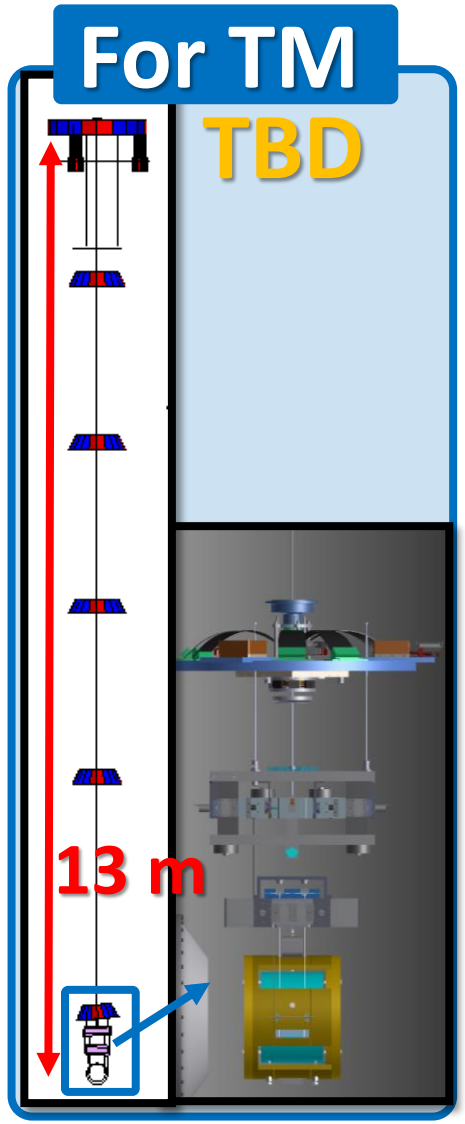
❖ bKAGRA Suspension Configuration (for observation)











Contents

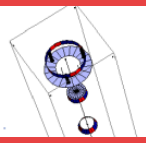
- ❒ Intro
  - ❒ KAGRA / Suspension Configuration /
- ❖ Suspension modeling
  - ❒ Modeling tools
  - ❒ Implementation to BS SAS prototype exp.

❖ Modeling tools : We have 2 ways.

Passive Model

Mechanical Model

SUMCON spension odel structor in Mathematica



Main Concern :
- Seismic noise
- Vibration from heat links
- Eddy current damping
- Suspension thermal noise

State-Space Model

COMSOL MULTIPHYSICS

Main Concern :
- Heat link
Transfer func.

Passive Model
Active Model

Control Model

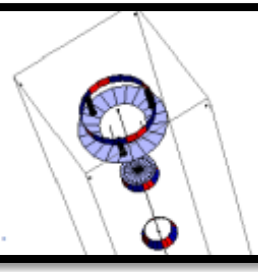
MATLAB SIMULINK

Main Concern :
- Controllability
- Servo filter design
- Sensor / Actuator noise
- SUMCON's main concern

❖ Modeling tools : Mechanical model

SUMCON *in Mathematica*

spension odel structor



is ***3D rigid body modeling software*** created by T Sekiguchi.

More detailed information is here :

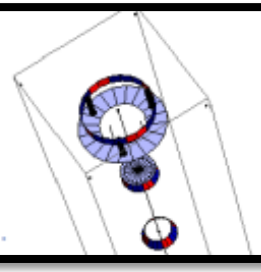
T sekiguchi, *LCGT internal Document* : **JGW-P1200770** (2012)

http://gwdoc.icrr.u-tokyo.ac.jp/DocDB/0007/P1200770/002/MasterThesis.pdf

❖ Modeling tools : Mechanical model

SUMCON *in Mathematica*

spension odel structor



Required information

- Mass & MoI
- Wire
- Vertical spring
- IP
- Heat link
- Eddy current damper

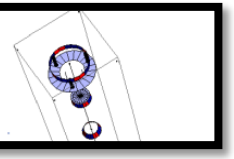
→ **Construct linearized Eq of M** →

Main outcomes

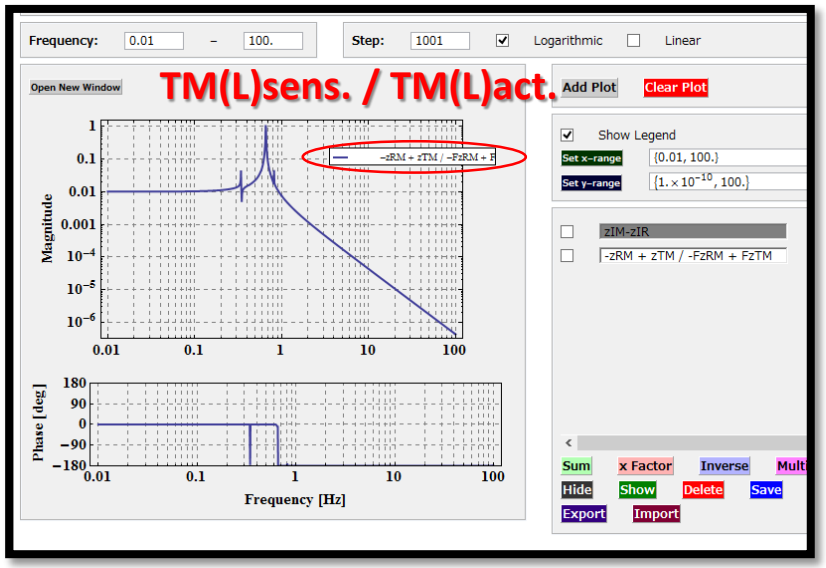
- Transfer function : Displacement & Force / Torque
- Eigen mode List & 3D shape
- Thermal & Seismic noise plot

❖ Modeling tools : Mechanical model

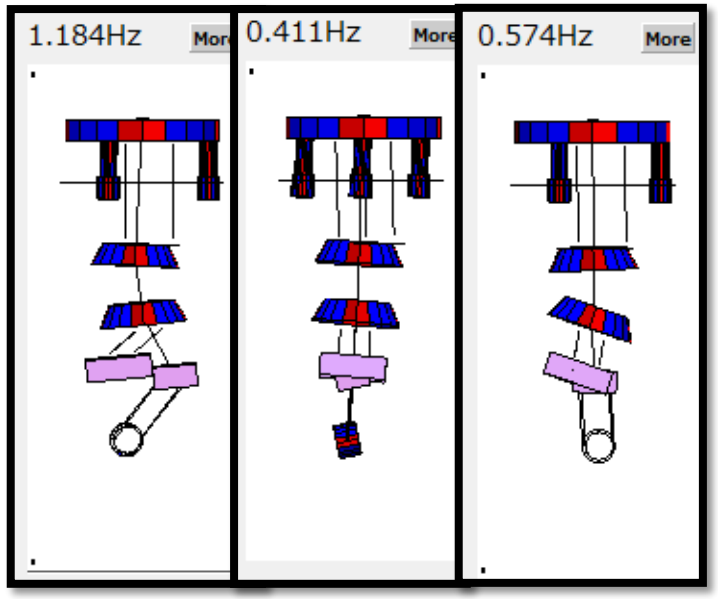
SUMCON in Mathematica
spension odel structor



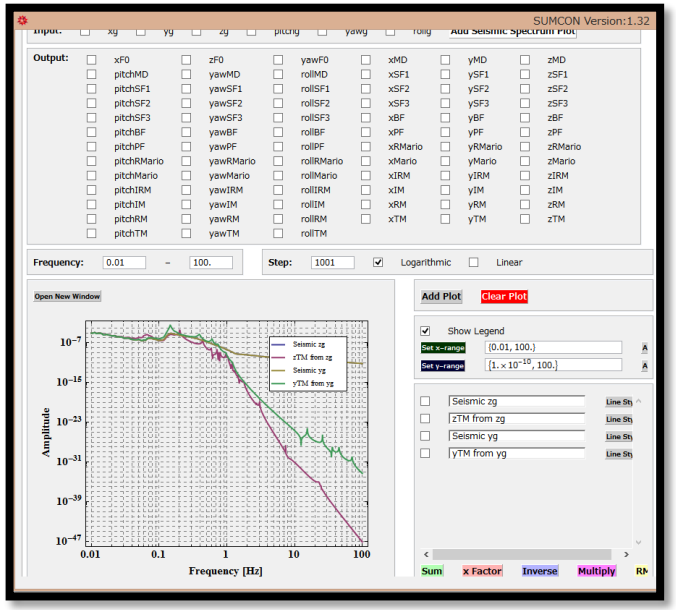
Displacement & Force / Torque Transfer function



Eigen frequency / Eigen mode shape



Thermal & Seismic noise plot



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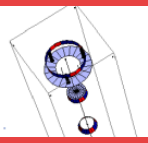
Passive Model

Mechanical Model

SUMCON spension odel structor in Mathematica



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State-Space Model

COMSOL MULTIPHYSICS

Main Concern :
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Passive Model
Active Model

Control Model

MATLAB SIMULINK

Main Concern :
- Controllability
- Servo filter design
- Sensor / Actuator noise
- SUMCON's main concern

❖ Modeling tools : Active model

MATLAB SIMULINK

is used in ***active controlling simulation***

Required information

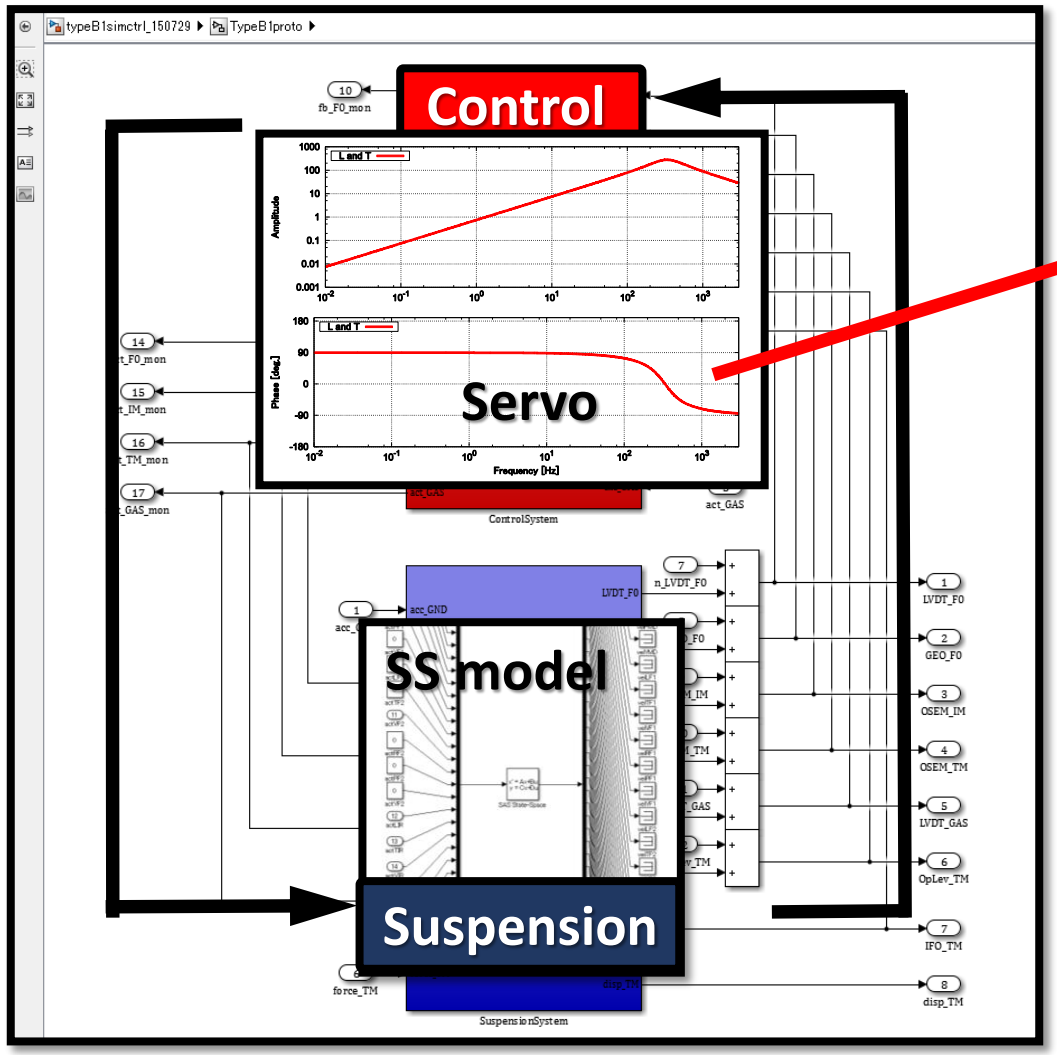
- Mass & MoI
- Wire
- Vertical spring
- IP
- Heat link
- Eddy current damper
- Servo filter

→ Construct State-space model →

Main outcomes

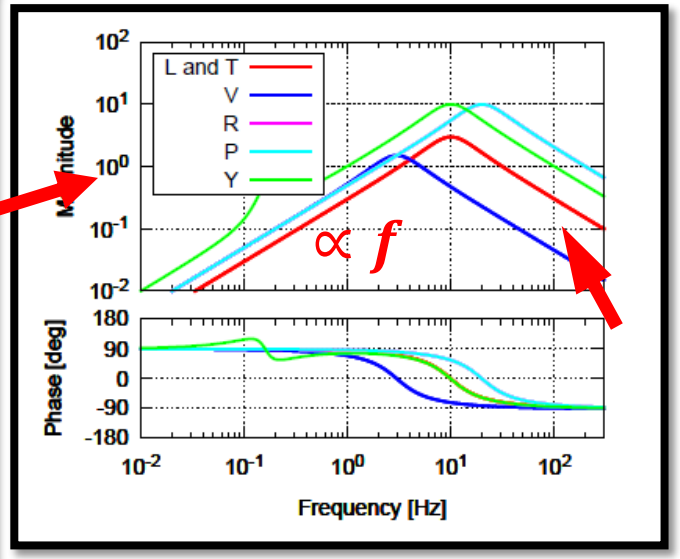
- Open loop / Closed loop TF
- Q factor
- Sensor noise coupling
- Mirror angular fluctuation

❖ Modeling tools : Active model



MATLAB SIMULINK

NOTE



IM servo filters <u>for damping</u> using OSEMs (displacement sensor)

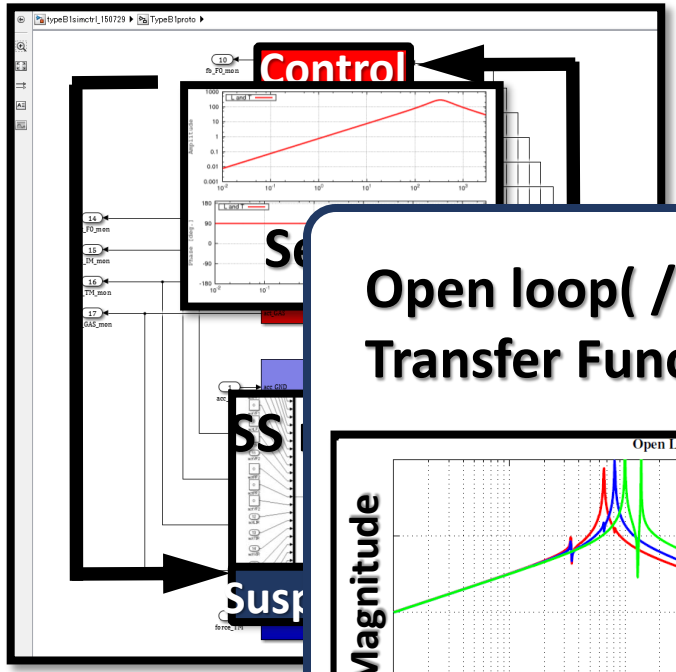
Viscous damping filter using displacement

→ $\propto f$

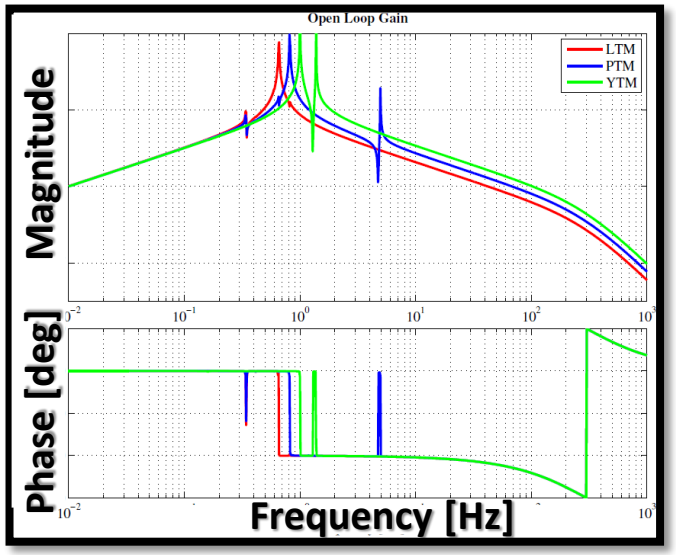
Infinite gain at $f \to \infty$ is not applicable!

→ Need to add a low-pass filter with cut-off.

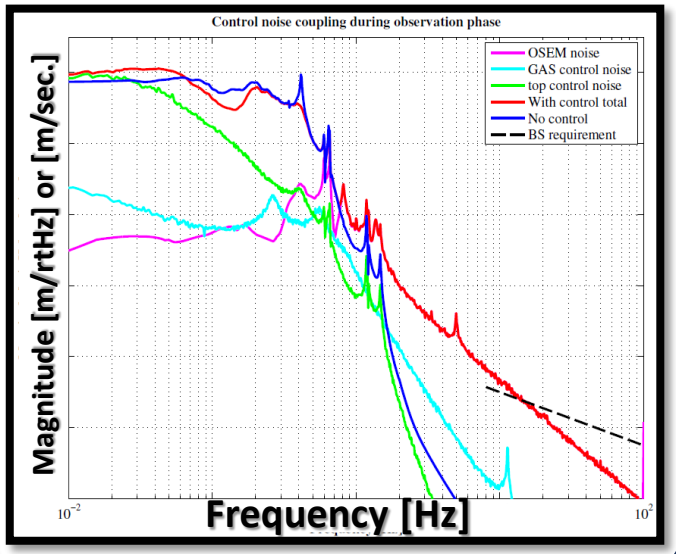
❖ Modeling tools : Active model



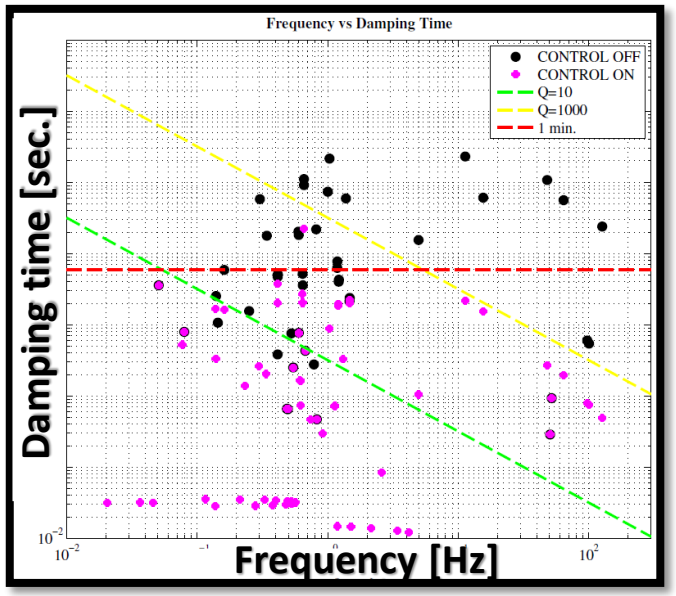
Open loop(/ Closed loop) Transfer Function



Noise coupling



Q factor



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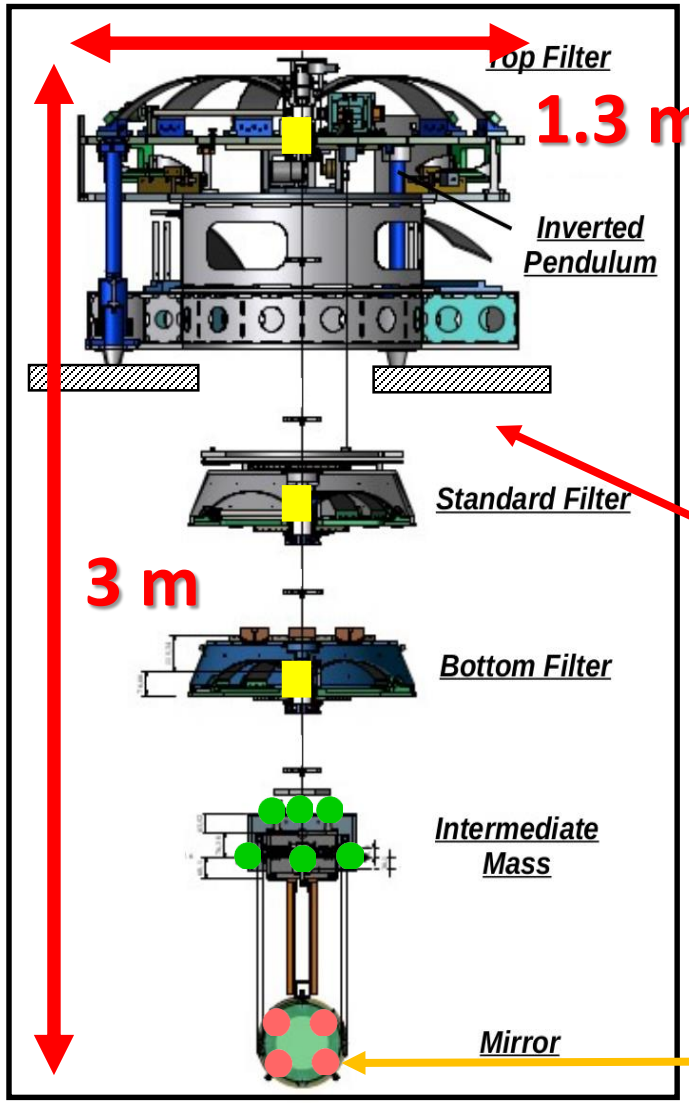
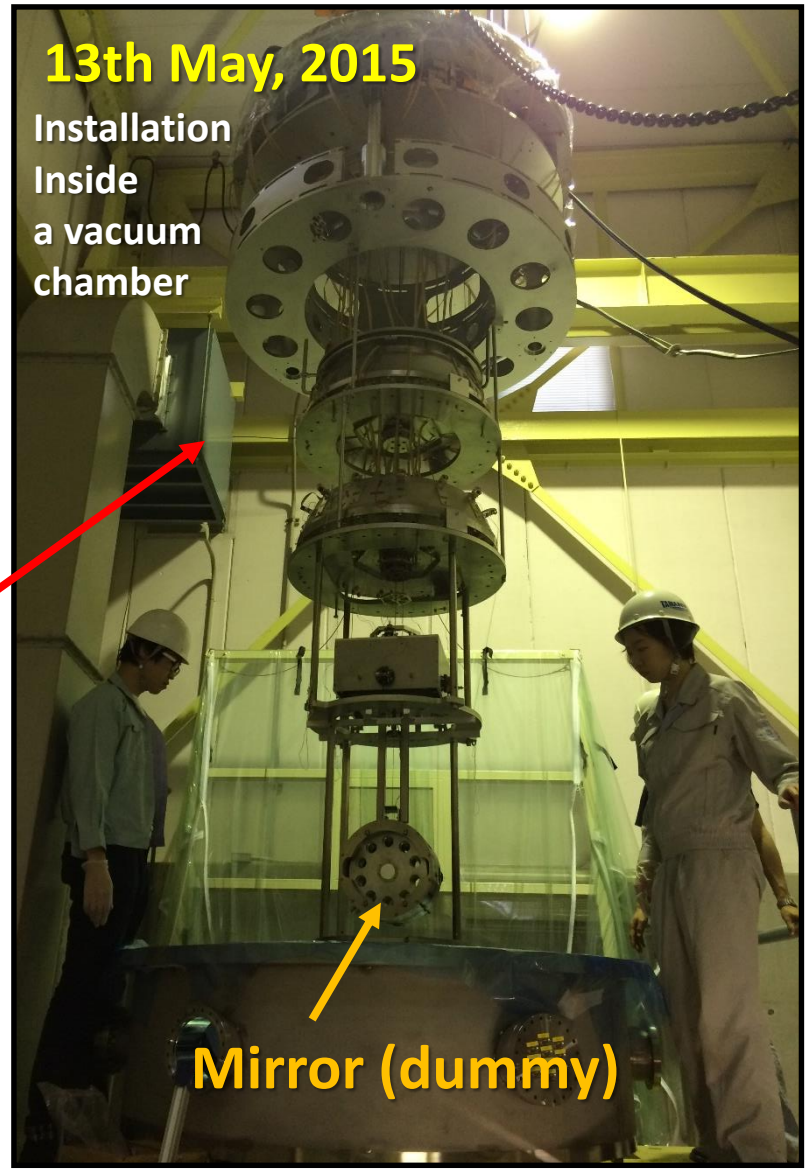
❖ Implementation to BS SAS prototype exp.



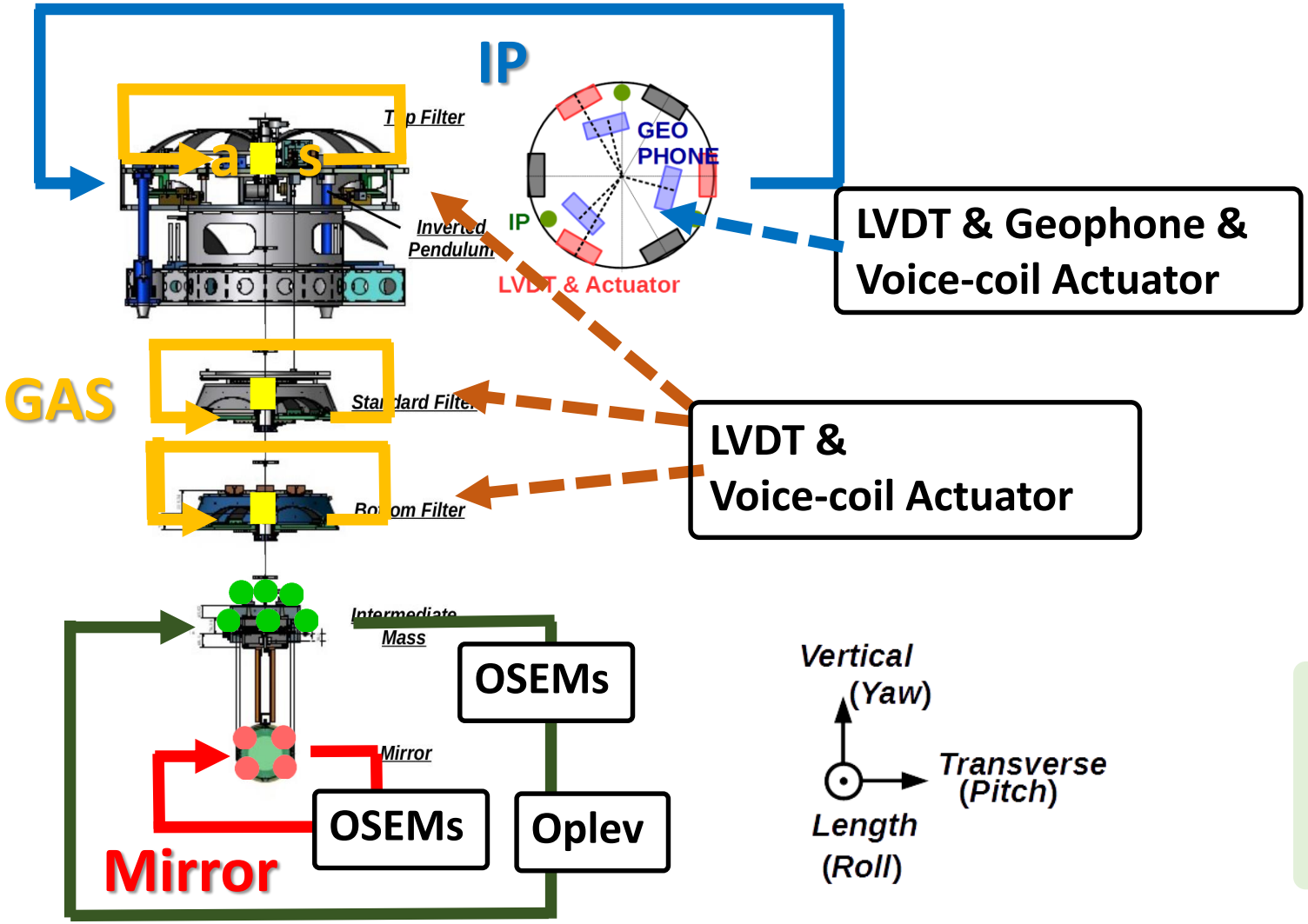
KAGRA SAS for BS, SR

5-stage pendulum

with IP, 3 GAS filters



❖ Implementation to BS SAS prototype exp. ; Local control overview



IP servo :
DC position control (L, T)
Thermal drift control
Pendulum mode damping

GAS filter servo
DC position control (V)
Thermal drift control
GAS filter mode damping

Payload servo :
DC alignment control
Pendulum / rotational mode damping

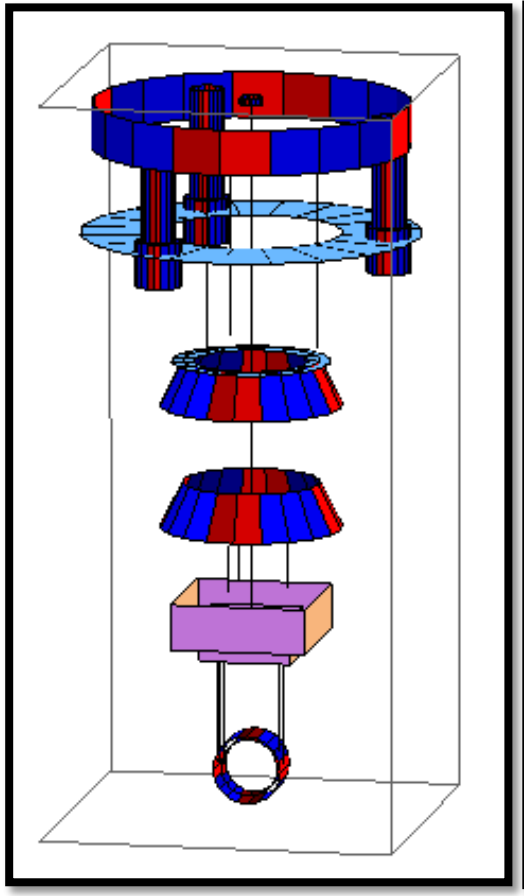
❖ Implementation to BS SAS prototype exp.

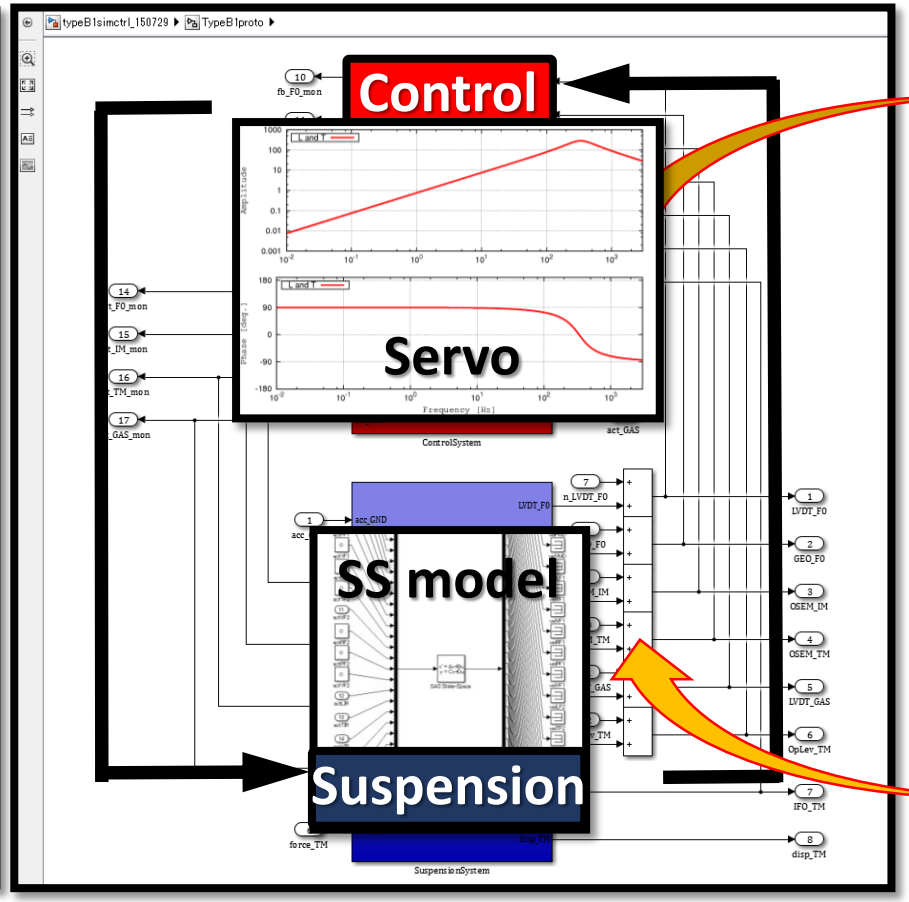
Main flow

1. Make a model and do simulation on Simulink, Mathematica (and FEM)
2. Assemble suspension system with Frequency response test
3. Tune servo filters on Simulink from measured Transfer Functions
4. implement the servo filters to the actual system
5. Test SAS performances

❖ Implementation to BS SAS prototype exp.

How were the simulation tools used in the experiment ?

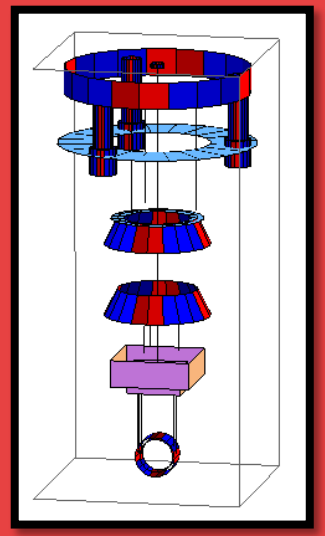




❖ Implementation to BS SAS prototype exp.

Visual part

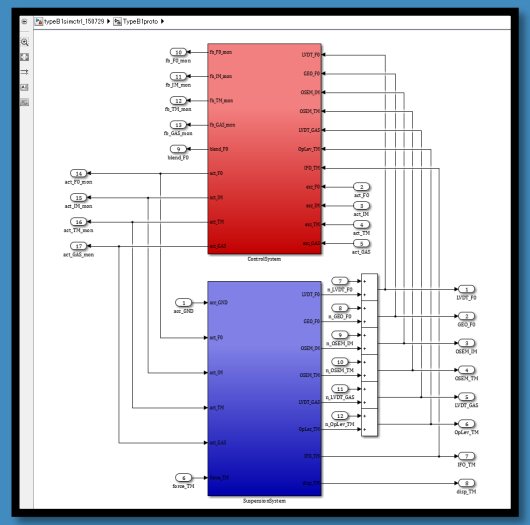
SUMCON
spension odel structor



VS.

Numerical part

MATLAB
SIMULINK



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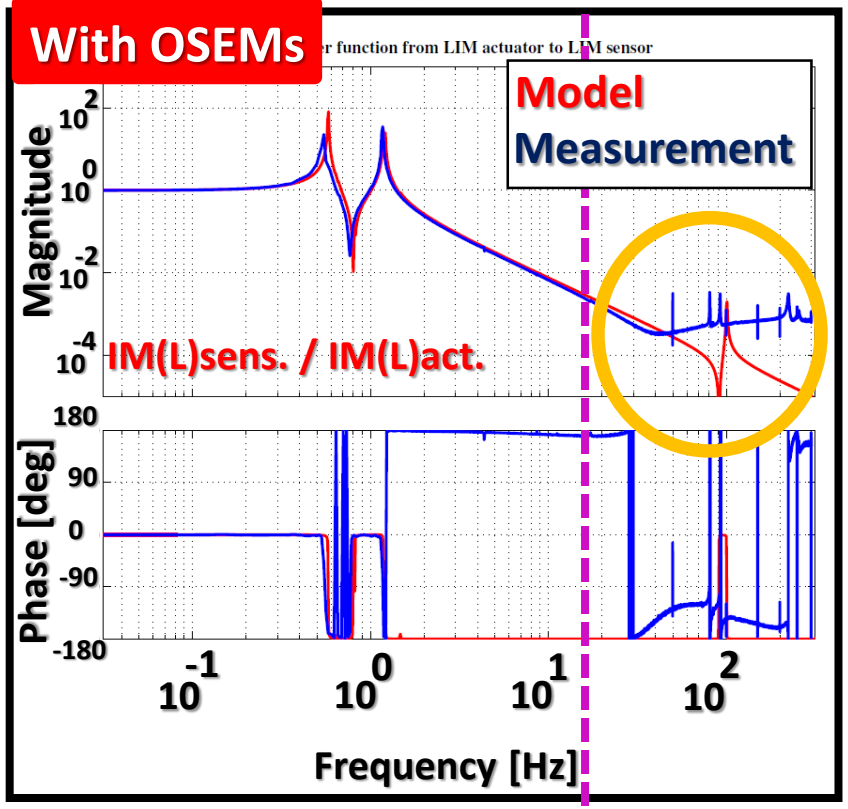
❖ Implementation to BS SAS prototype exp.

In tuning servo filters

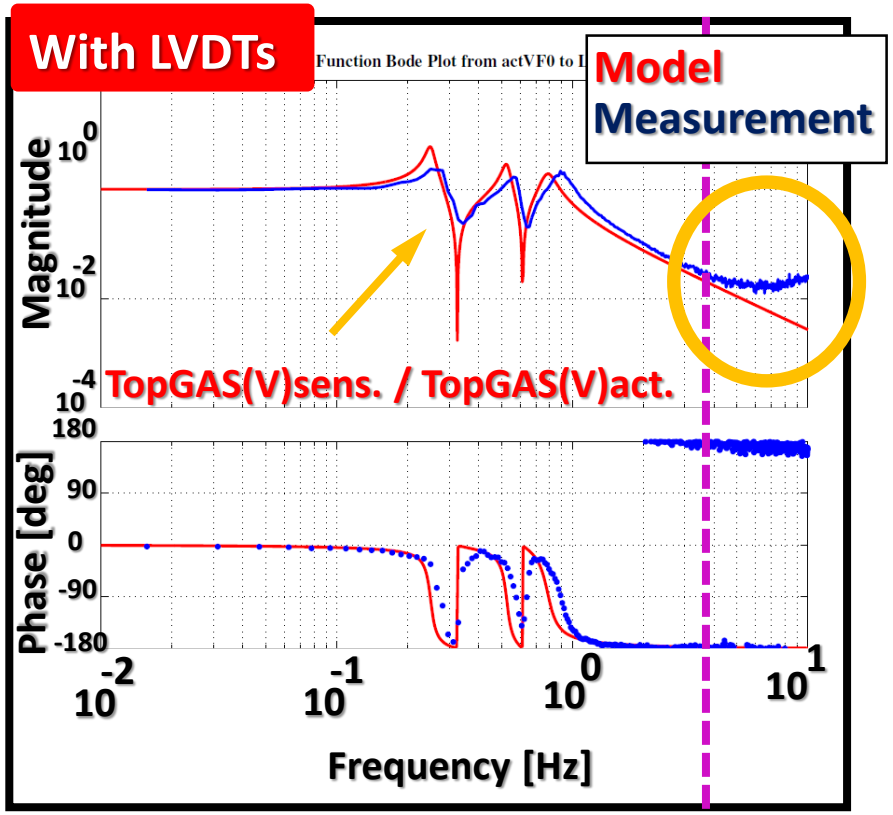
Force / Torque transfer function

With OSEMs



Correspond to the Model

With LVDTs



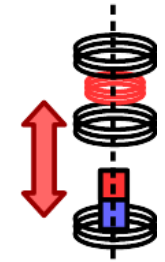
Correspond to the Model

Discrepancies

- EM coupling

OSEM : above 5 Hz

LVDT : above 50 Hz



- Resonance frequency
- Q factor

Hanging condition

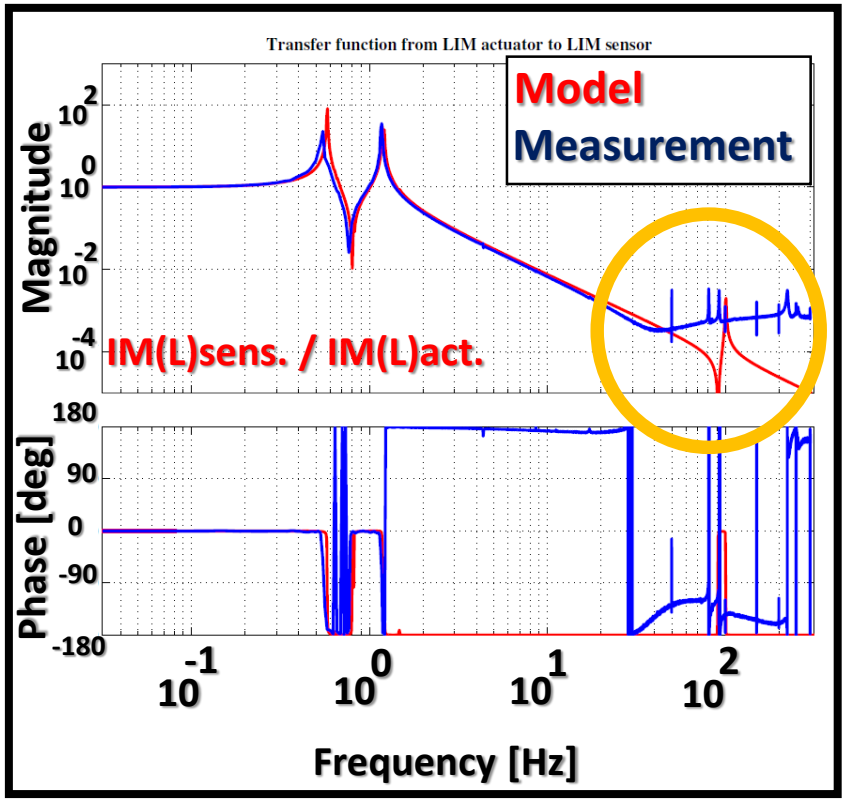
Asymmetry in IP stiffness

Ham noise

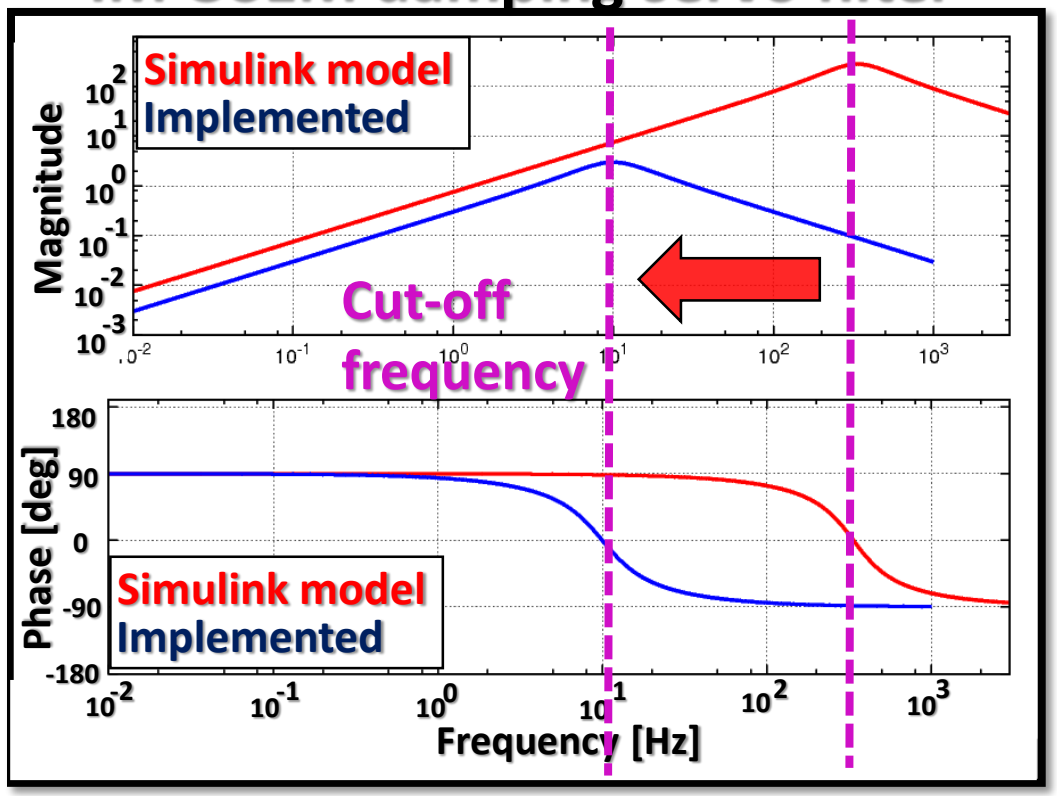
wire violin mode

❖ Implementation to BS SAS prototype exp.

In tuning servo filters Ex.)



IM OSEM damping servo filter



Simulink

- <u>Cut-off frequency</u>
  → High Q peak at high frequency in simulation
  → couldn't set it at lower frequency.

- <u>Gain</u>
  → manually investigated

❖ Implementation to BS SAS prototype exp.

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❖ Implementation to BS SAS prototype exp.

In testing SAS performances

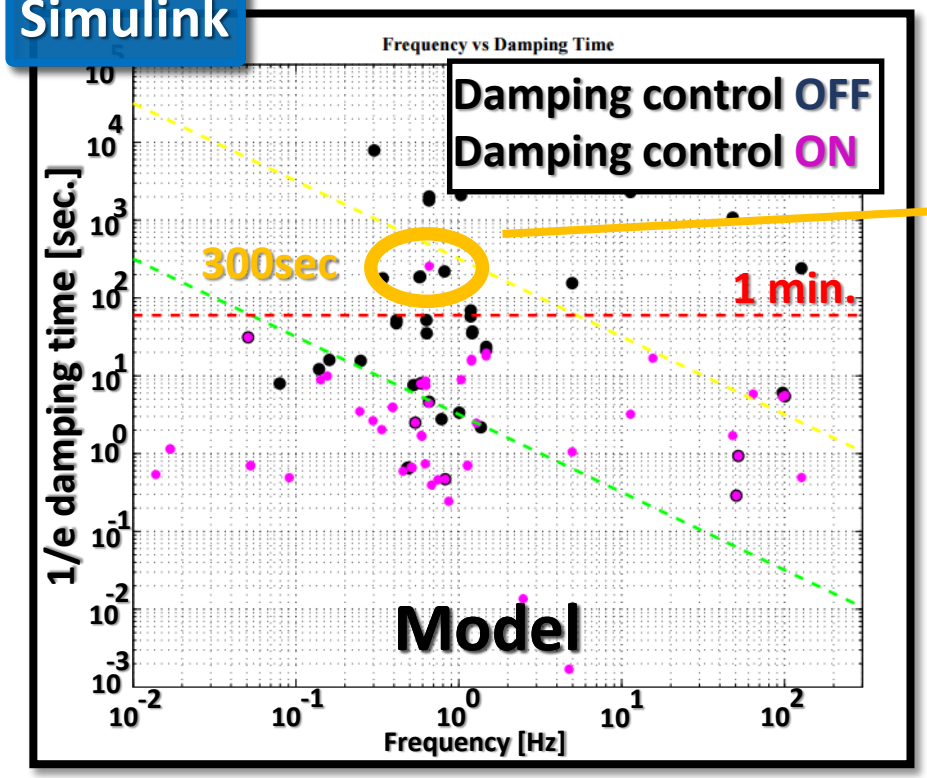
- Mechanical response test
- Damping control performance test → For Calming the SAS down
- Long term stability test

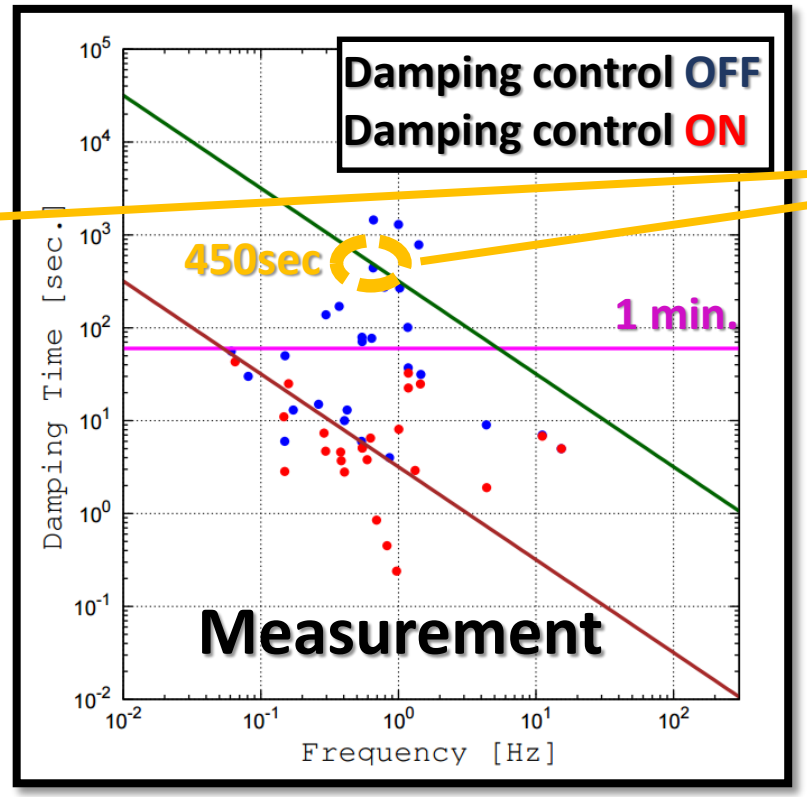
❖ Implementation to BS SAS prototype exp.

In testing SAS performances

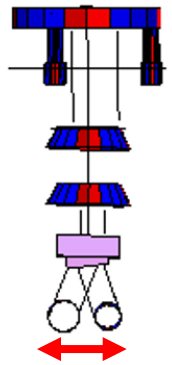
Damping control performance test for Calming the SAS down

Simulink





SUMCON



"this mode doesn't contribute to lock acquisition."

Summary

- 2 modeling tools are used in KAGRA SAS :
  - SUMCON for visual confirming
  - Simulink for numerical confirming

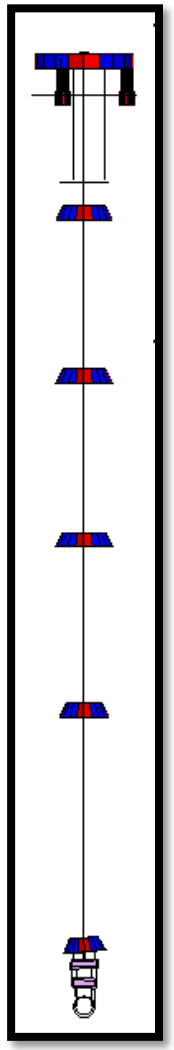
→ both tools worked well in actual system !

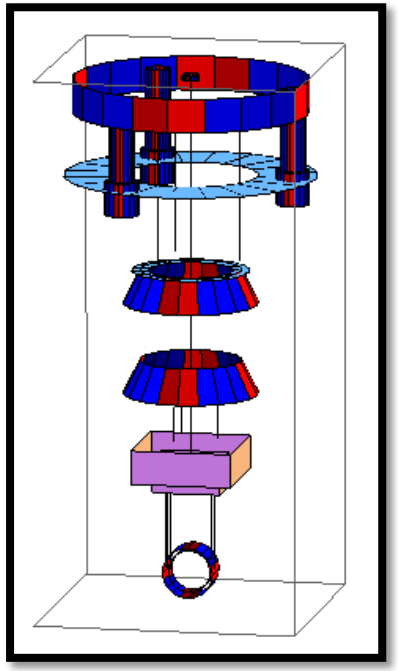
- We implemented those tools into actual SAS.
  - Mechanical system : Rigid body model can explain actual system at low frequency.
  - Control system : servo filters need to be tuned according to actual system, due to uncertainty of actual Q factor.

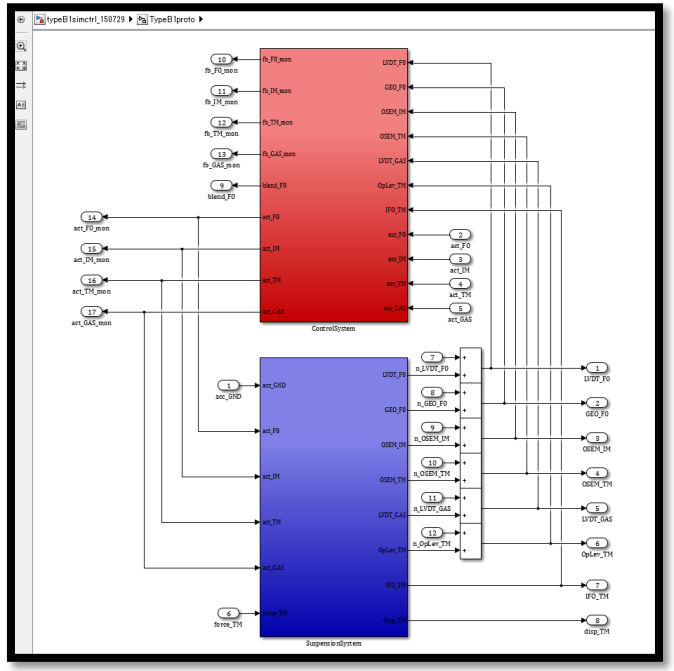
Next step

- Continue building the SAS for iKAGRA using these tools.
- Construct current bKAGRA TM SAS model as soon as possible.

You can use the modeling tools : SUMCON and Simulink !







http://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/DocDB/ShowDocument?docid=3729
http://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/DocDB/ShowDocument?docid=3606

NOTE : we don't have any manuals, though.

If you have any problems, please contact me :
yoshinori.fujii AT nao.ac.jp

Thank you for your attention.

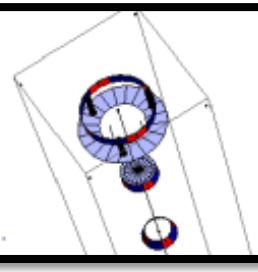
Back up

Water is now preparing to spring,,,,?

❖ Modeling tools : Mechanical model

SUMCON *in* **Mathematica**

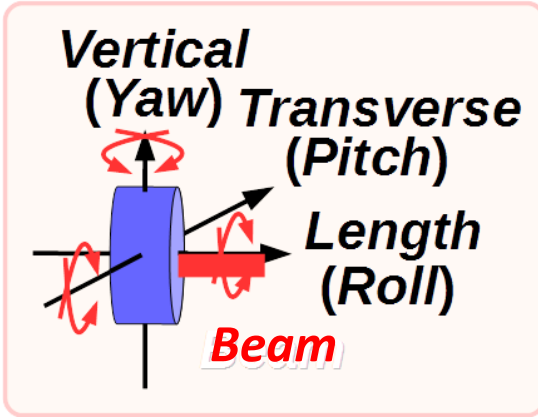
spension odel structor



is ***3D rigid body modeling software*** created by T Sekiguchi.

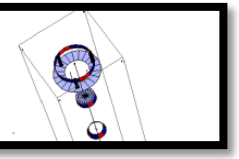
Assuming

- ❒ 6 DoFs(3 translation, 3 rotation) for each mass
- ❒ No deformation of masses
- ❒ Non-mass wire / No wire string vibration
- ❒ GAS → vertical spring moving for only one direction



❖ Modeling tools : Mechanical model

SUMCON in Mathematica
spension odel structor



Main flow

1. Express

$U(x)$: potential energy

$F(x, \dot{x})$: dissipation function

$T(x, \dot{x})$: kinetic energy

2. Find x_e : equilibrium position

$$\left.\frac{\partial U}{\partial x_i}\right|_{x=x_e} = 0$$

(for each U, F, T)

3. Calculate matrix

$$\boldsymbol{K}: K_{ij} = \left.\frac{\partial^2 U}{\partial x_i \partial x_j}\right|_{x=x_e} \quad \text{: stiffness matrix}$$

$$\boldsymbol{C}: C_{ij} = \left.\frac{\partial^2 F}{\partial \dot{x}_i \partial \dot{x}_j}\right|_{x=x_e} \quad \text{: damping matrix}$$

$$\boldsymbol{M}: M_{ij} = \left.\frac{\partial^2 T}{\partial \dot{x}_i \partial \dot{x}_j}\right|_{x=x_e} \quad \text{: inertia matrix}$$

4. Construct

Linearized Eq of motion

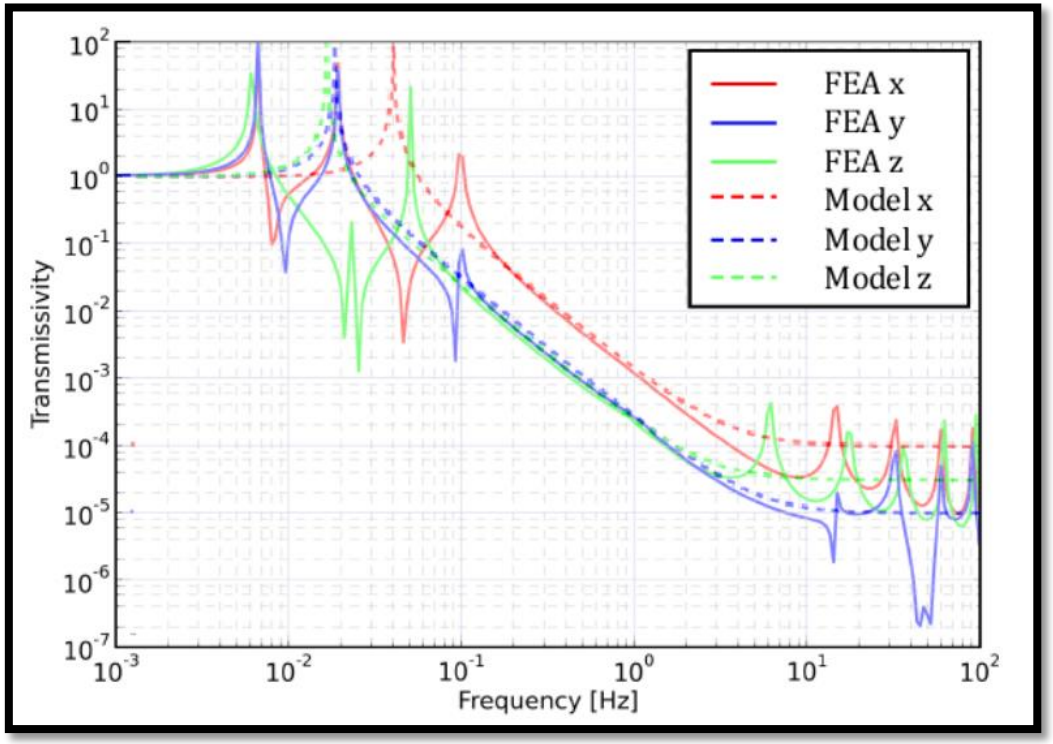
$$\boldsymbol{K}\ddot{x} + \boldsymbol{C}\dot{x} + \boldsymbol{K}(x - x_e) = f$$

f : external force

Assuming the vibration is small so that we can linearize the system

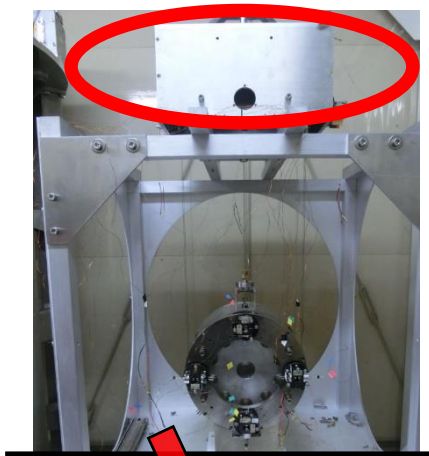
❖ Modeling tools : Mechanical model

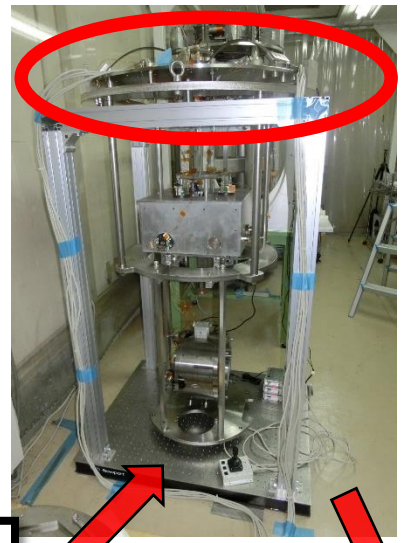
Heat links

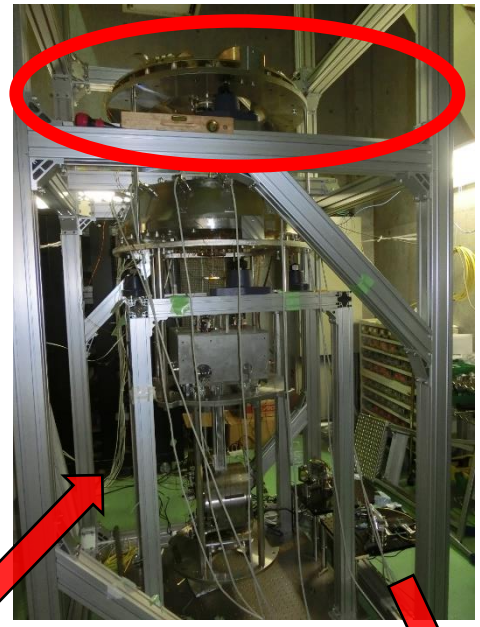


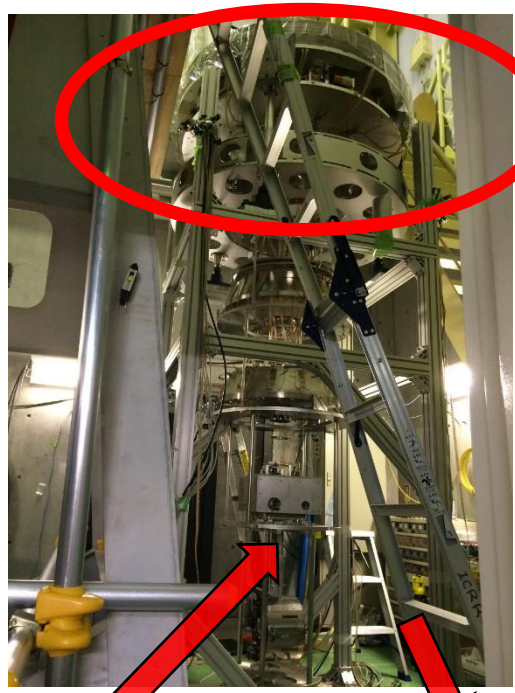
❖ Implementation to BS SAS prototype exp.

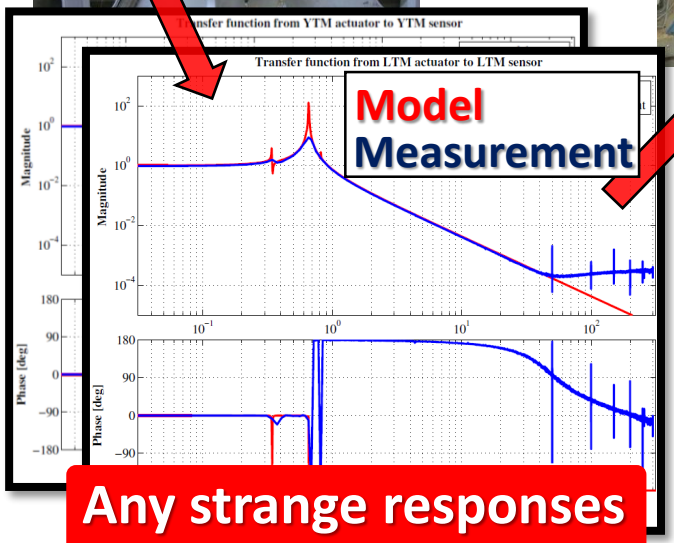
In assembly











No

No

No

Any strange responses against the model ?

Any strange responses against the model ?

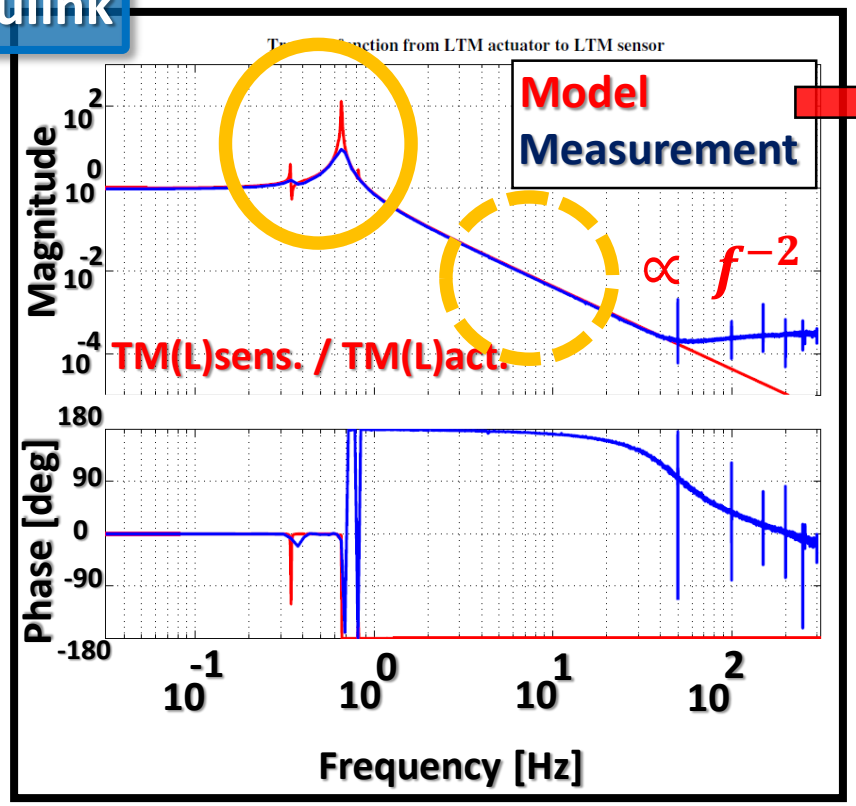
Any strange responses against the model ?

❖ Implementation to BS SAS prototype exp.

In assembly

Force / Torque transfer function with No controls

Simulink

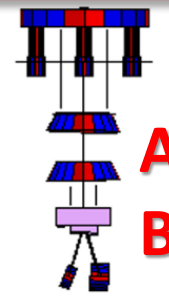


Large discrepancy against the model in
- **resonance frequencies ?**
- **Q factor ?**

If, Yes

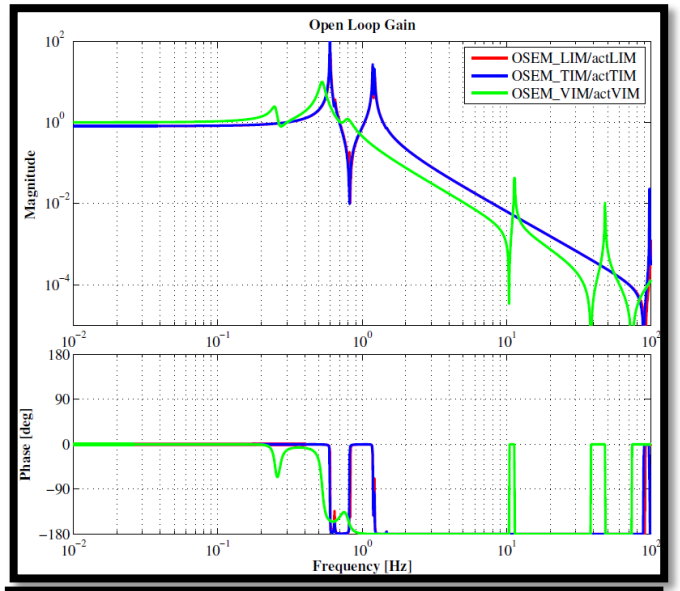
Investigate the reason
with Eigen mode shape etc.

SUMCON

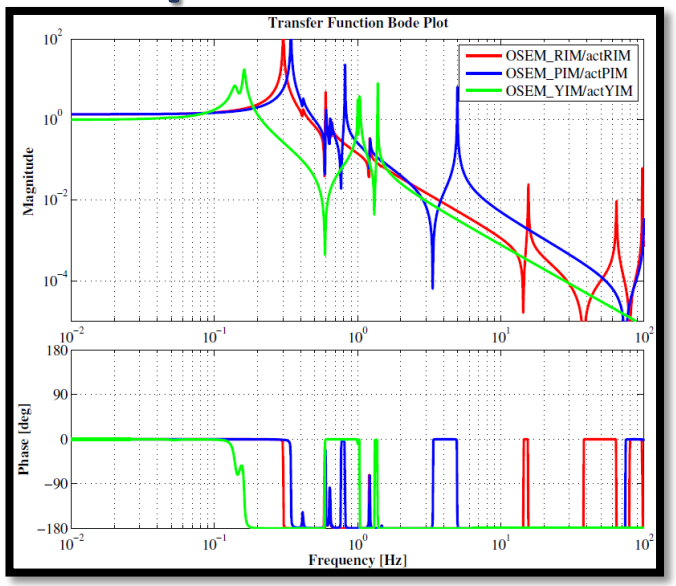


Any friction?
Broken parts?

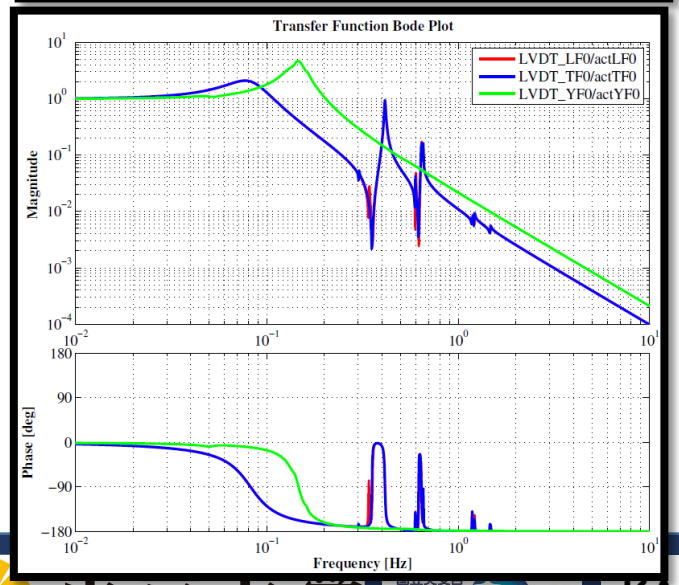
❖ Modeling tools : modeled Force / Torque transfer function



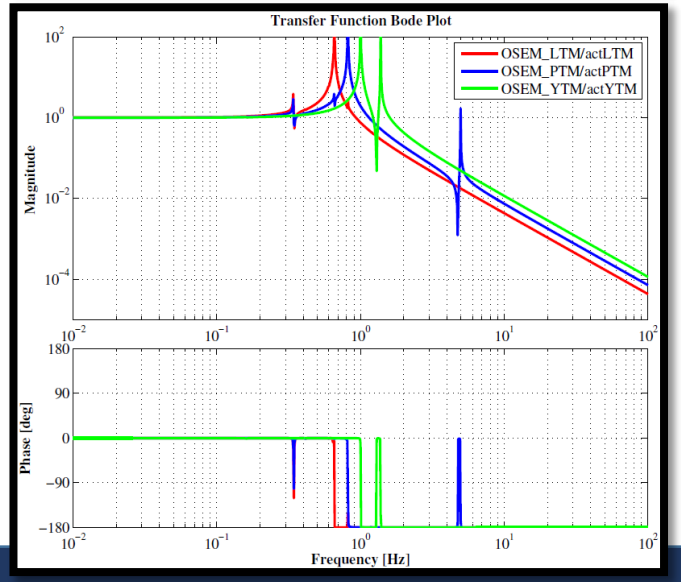
Transfer function
For IM OSEM
L, T, V



Transfer function
For IM OSEM
P, R, Y

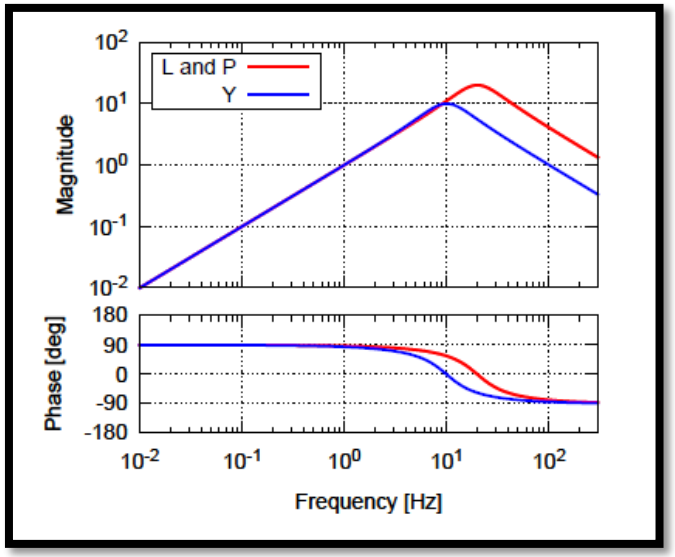


Transfer function
For F0
L, T, Y

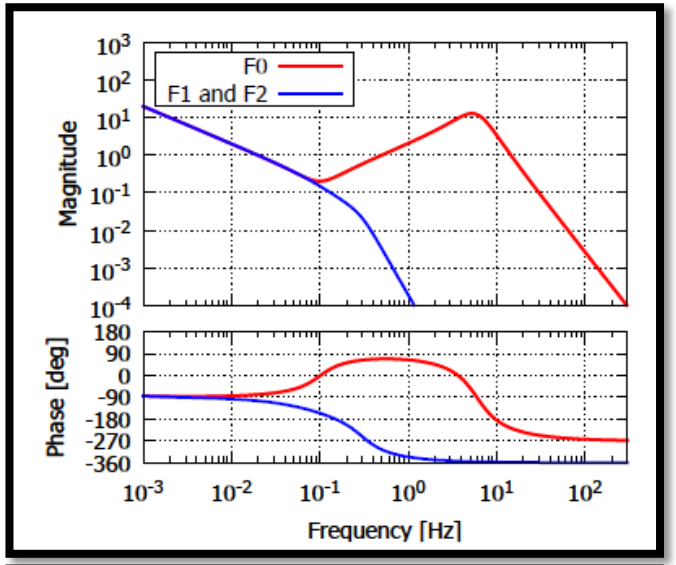


Transfer function
For TM
L, P, Y

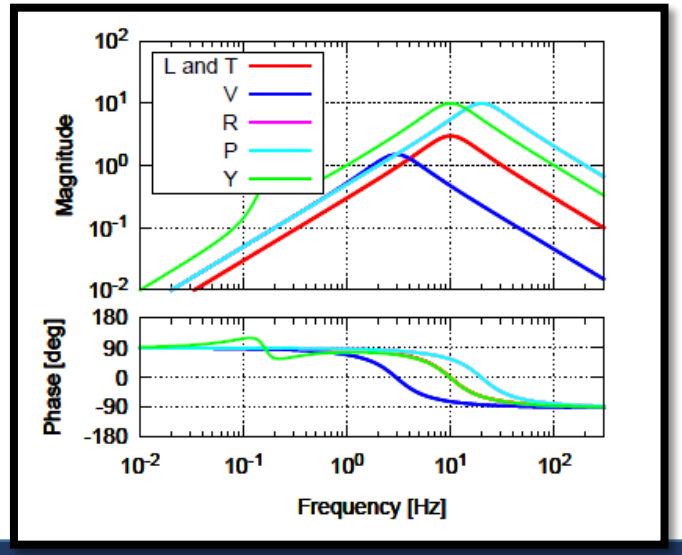
❖ Modeling tools : actual servo filters for damping



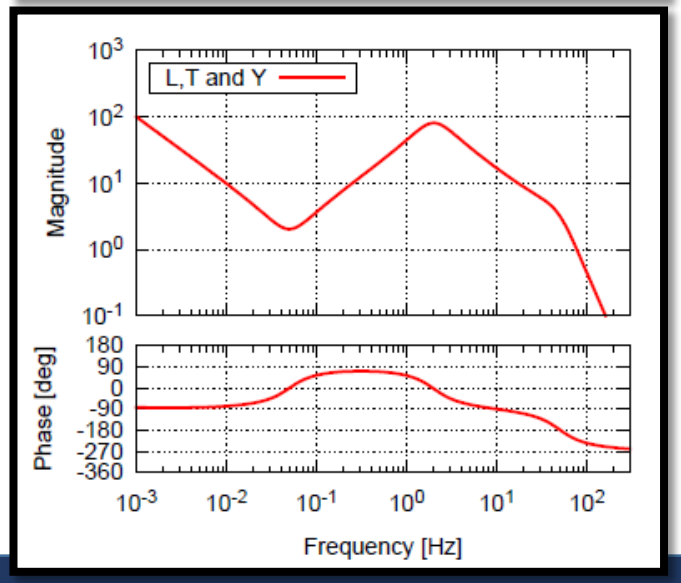
Servo filter
For TM OSEM



Servo filter
For GAS filter

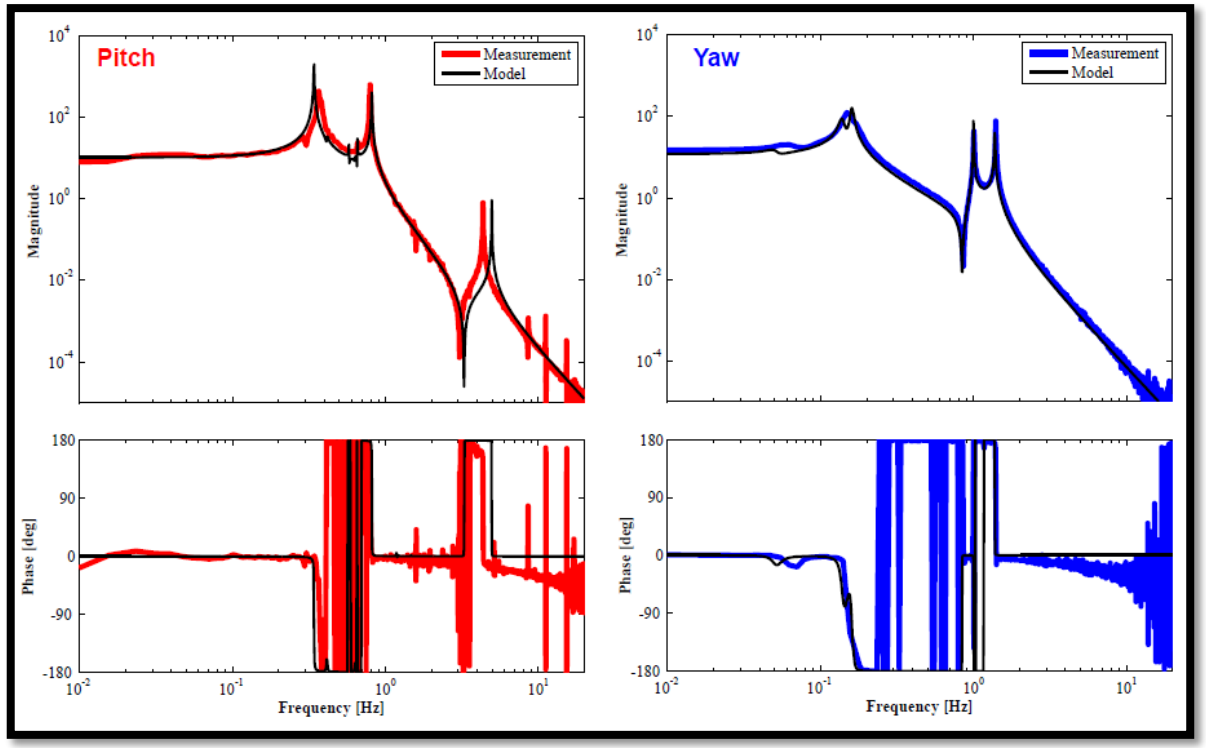


Servo filter
For IM OSEM

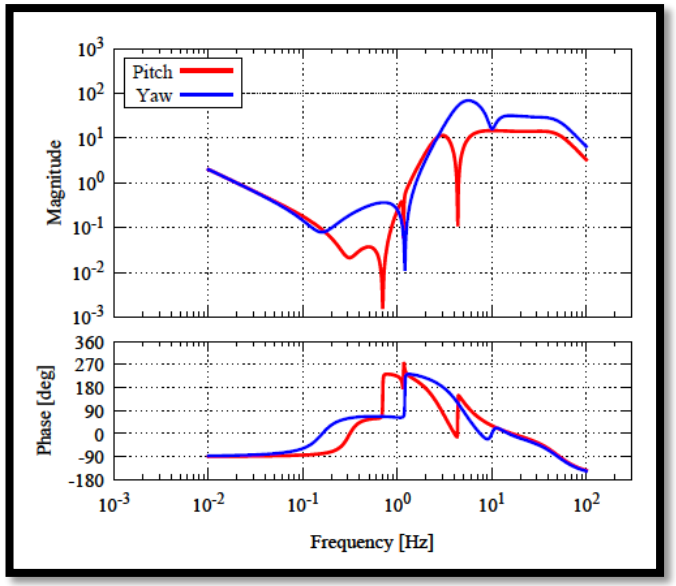


Servo filter
For IP

❖ Modeling tools : actual servo filters for damping



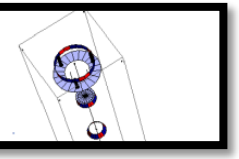
Transfer function from TM act. to Oplev



Servo filter for Oplev (in front of TM)

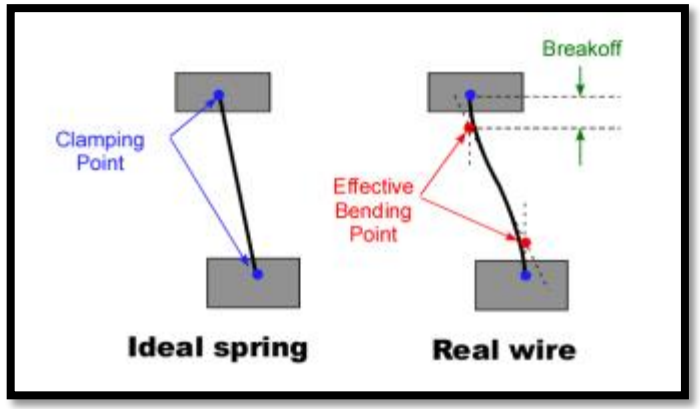
❖ Modeling tools : Mechanical model

SUMCON in Mathematica
spension odel structor



in the modeling,

Effective bending point

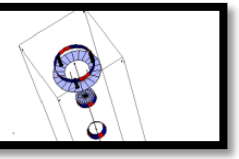


Dissipation dilution effects are reflected;

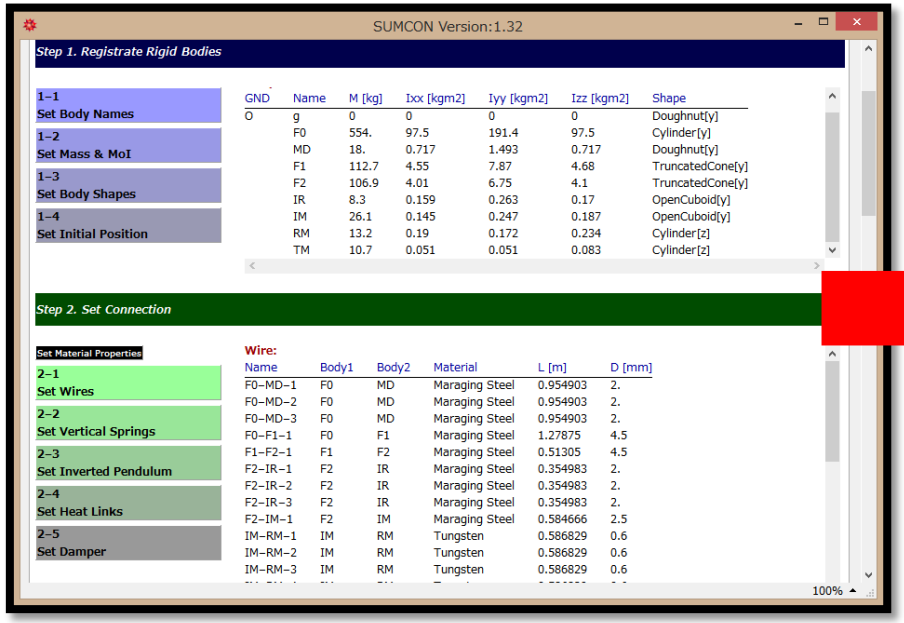
$$\varphi_{pen} = \Delta\, 2L\, \varphi_{wire},$$

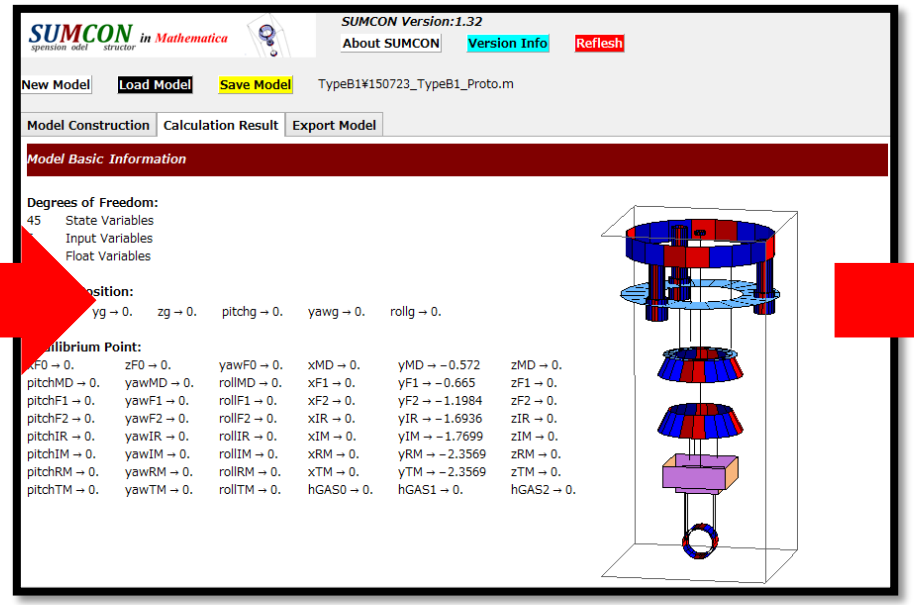
❖ Modeling tools : Mechanical model

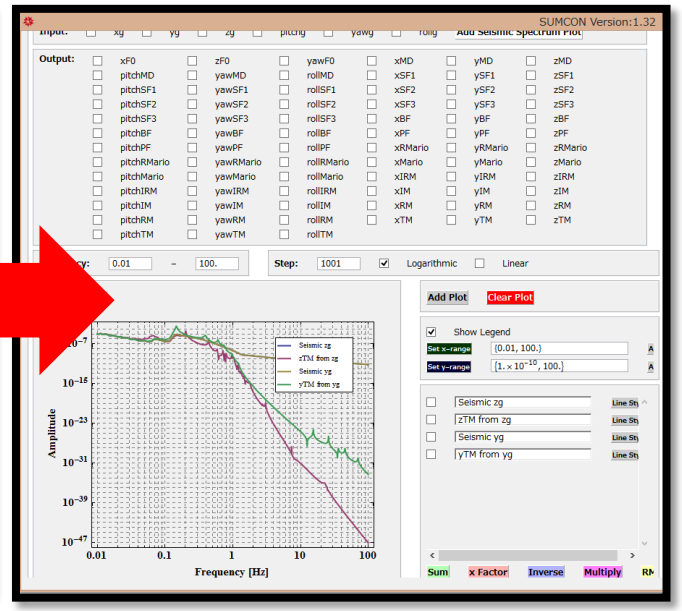
SUMCON spension odel structor **in Mathematica**



For instance,

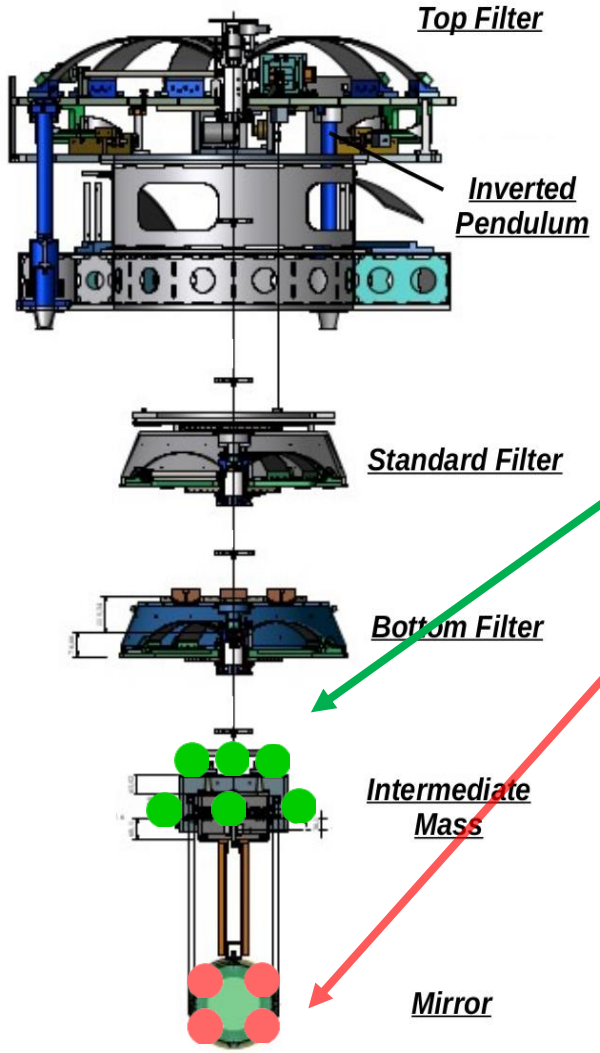


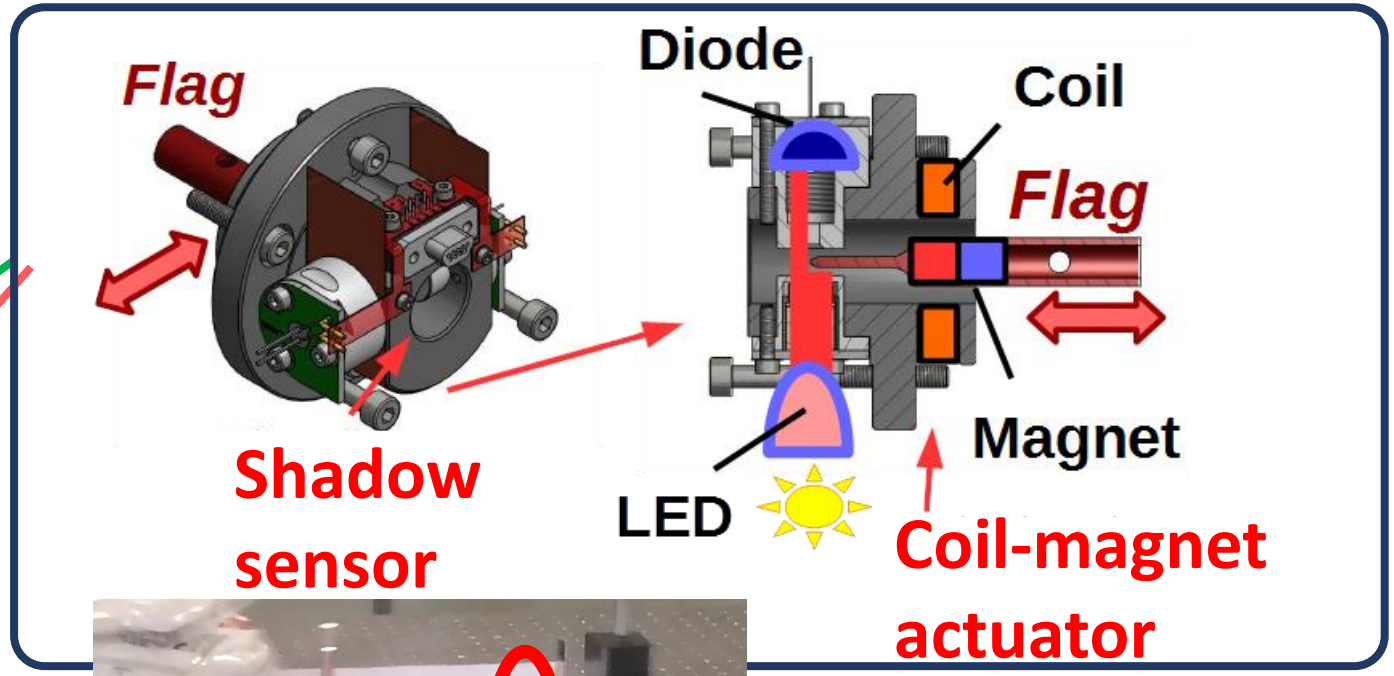


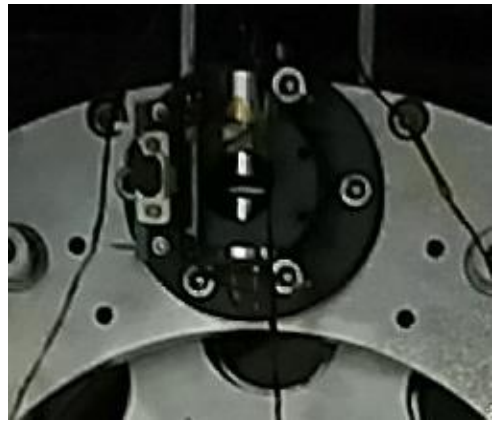


❖ BS SAS proto : OSEM

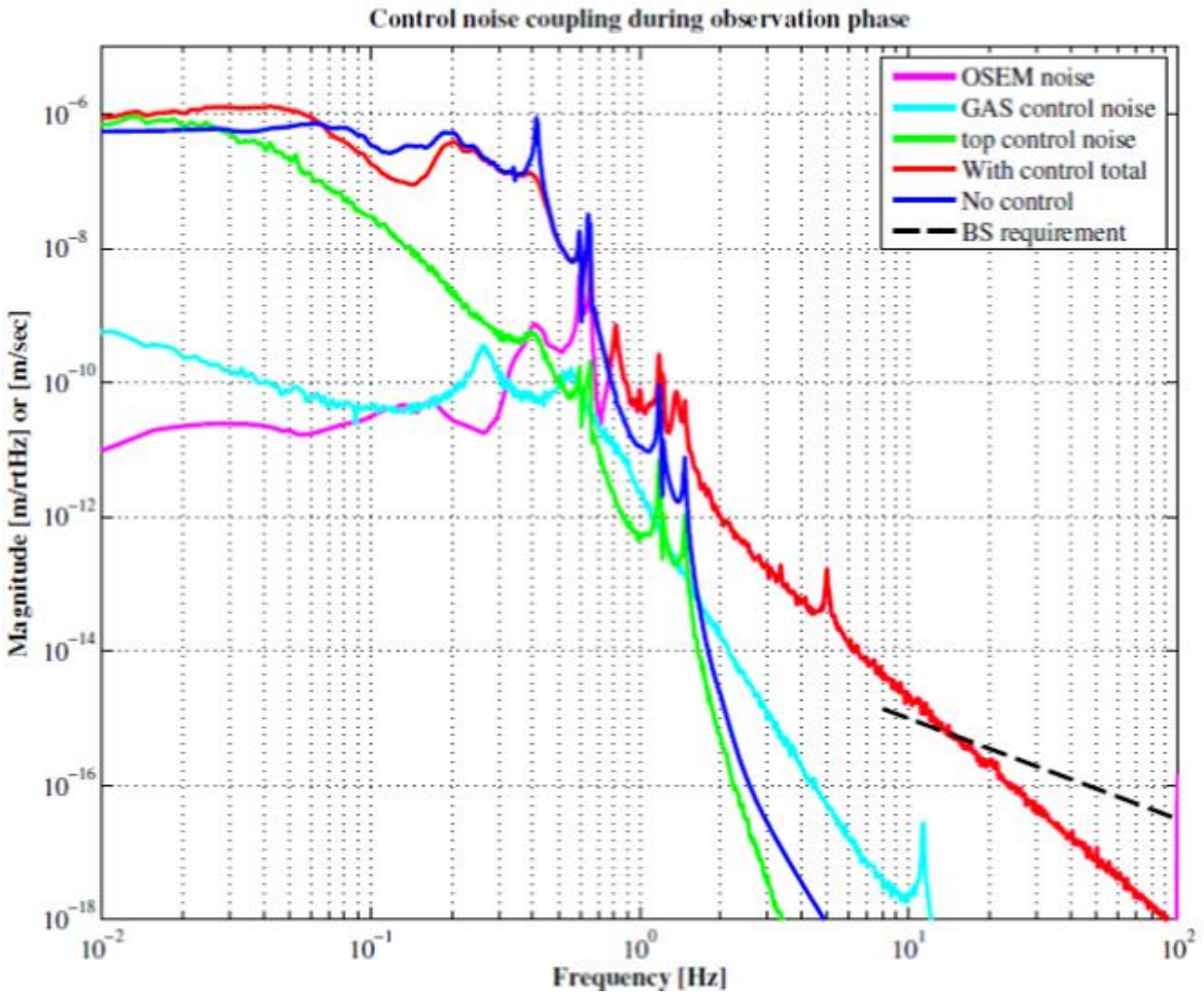
Shadow sensor & Coil-magnet actuator unit







❖はじめに：懸架装置



Type B の防振比のsimulation