Modeling tools in KAGRA for seismic and payload mechanical systems

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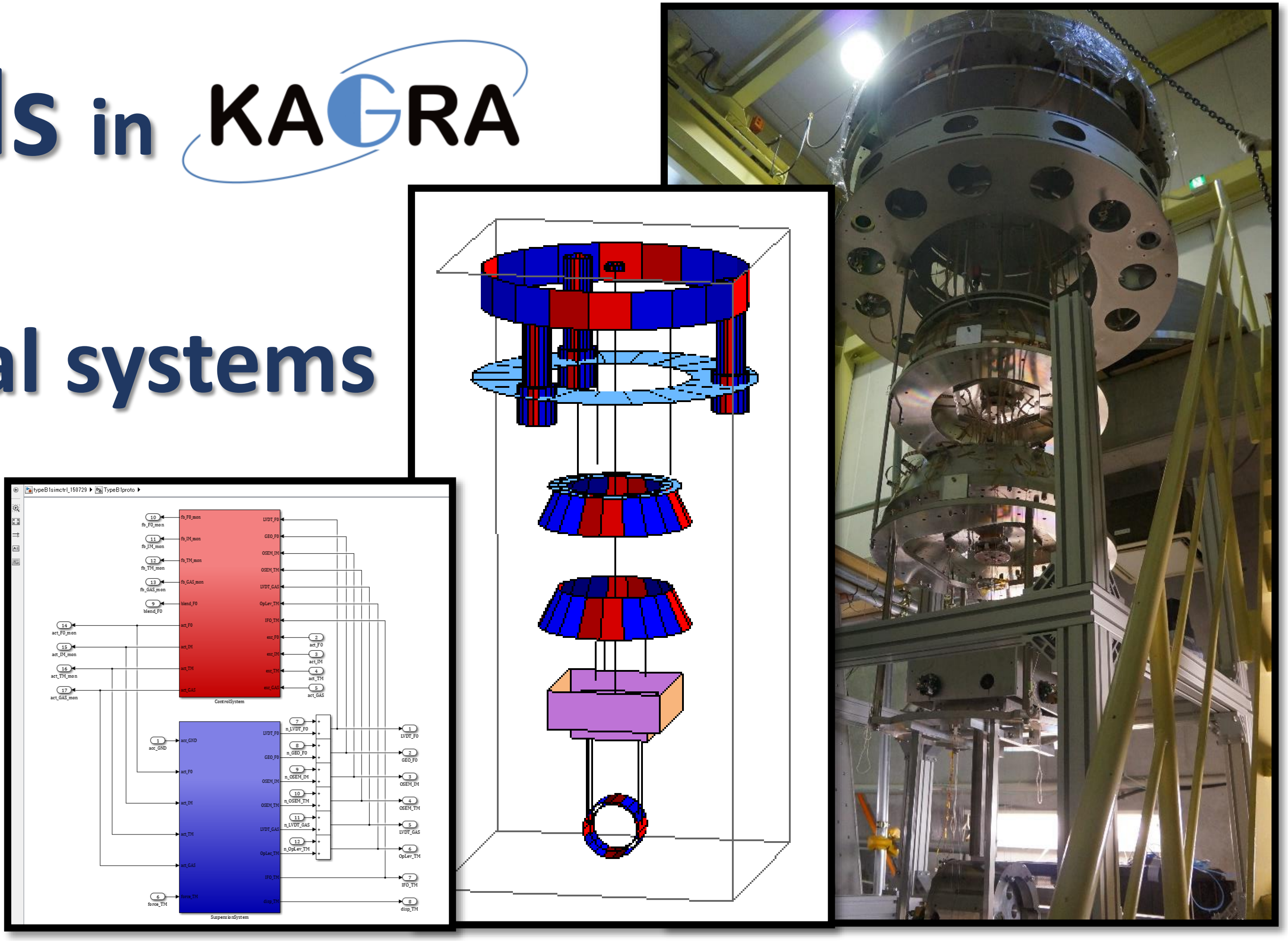
U. of Tokyo / NAOJ

with the cooperation of KAGRA VIS team

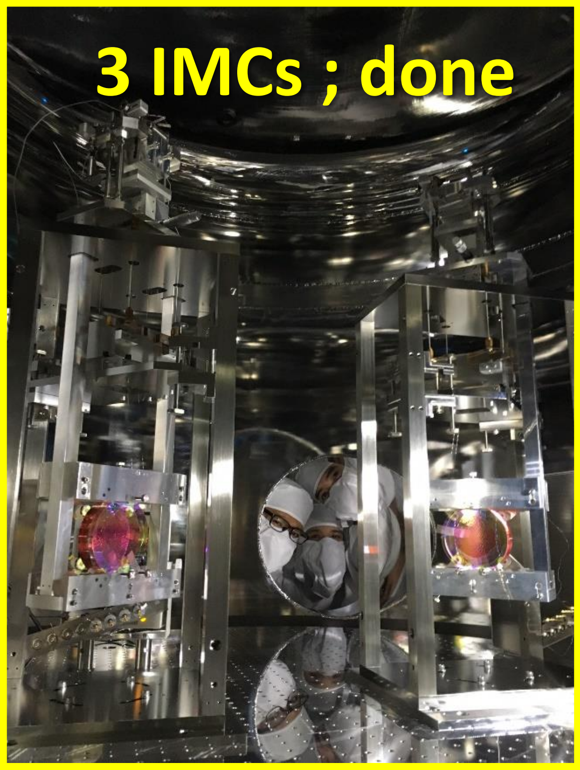


Contents

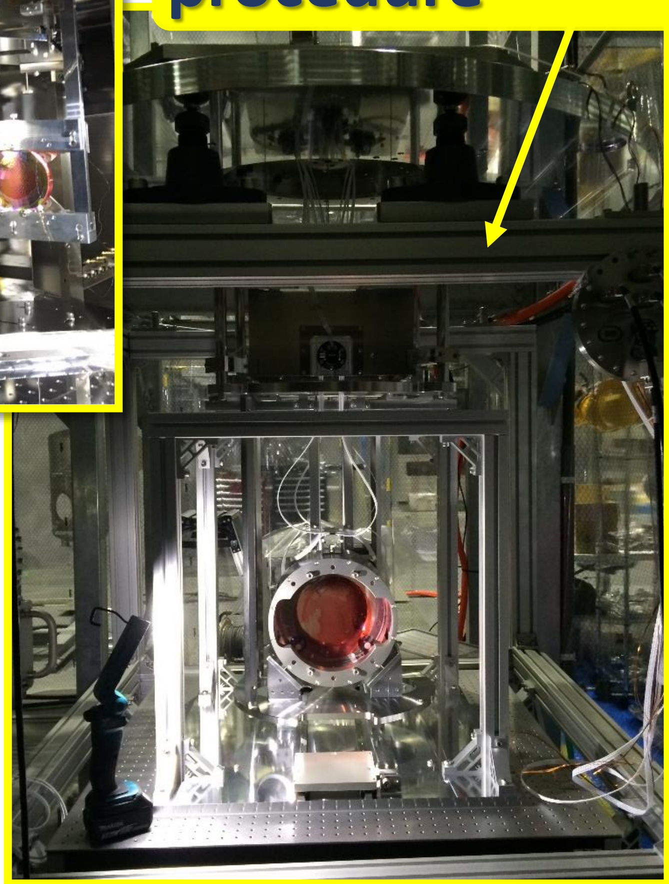
- Intro
  - KAGRA / Suspension Configuration /

- Suspension modeling
  - Modeling tools
  - Implementation to BS SAS prototype exp.

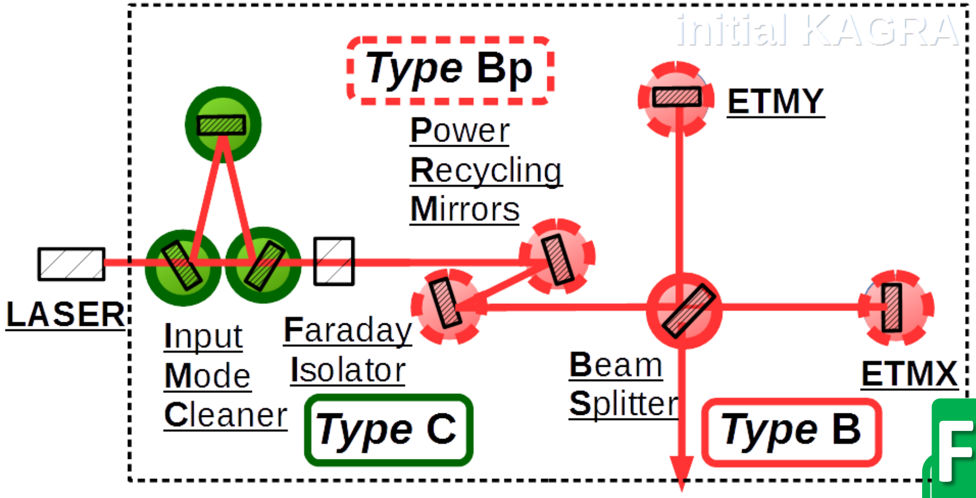
❖ Intro : KAGRA

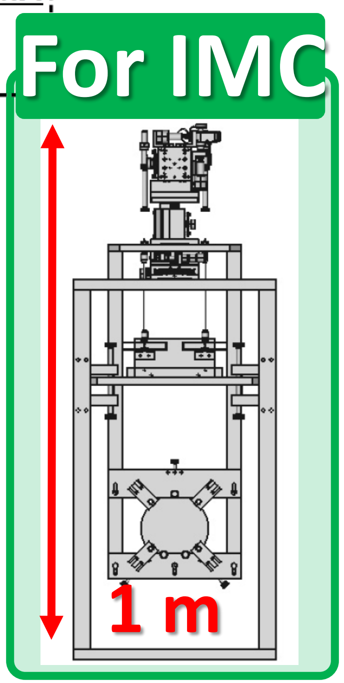


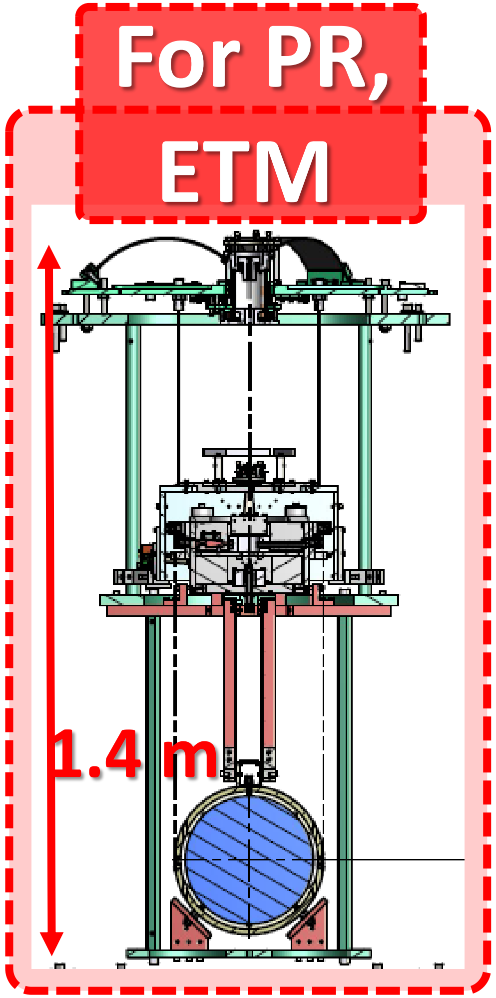
2 PRs & 2 ETMs ; Confirming installation procedure

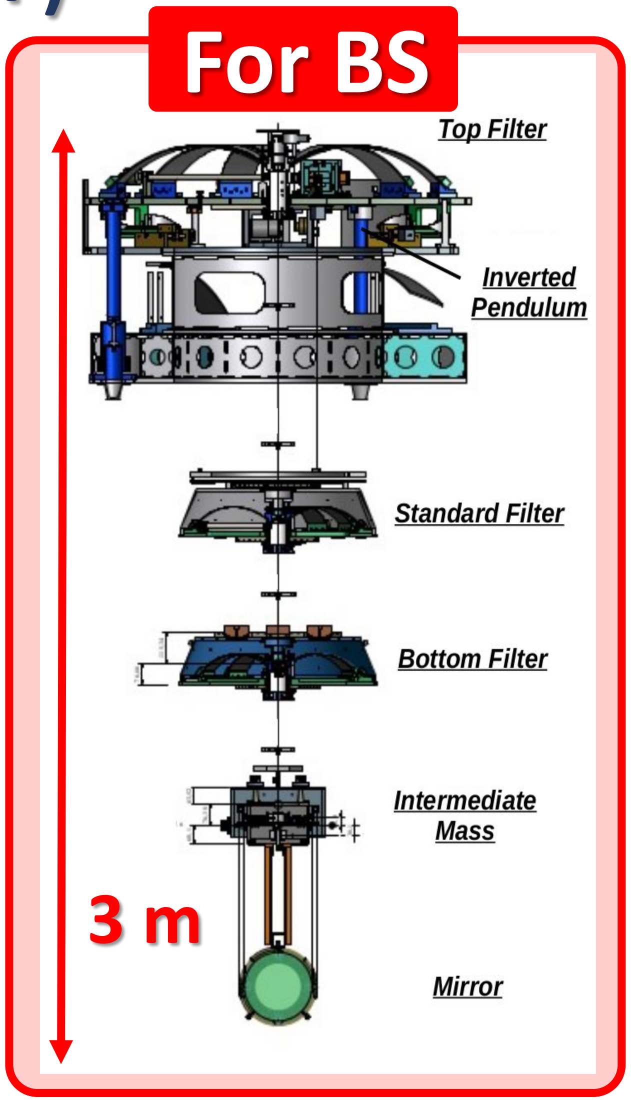


❖ iKAGRA Suspension Configuration (for a test run)

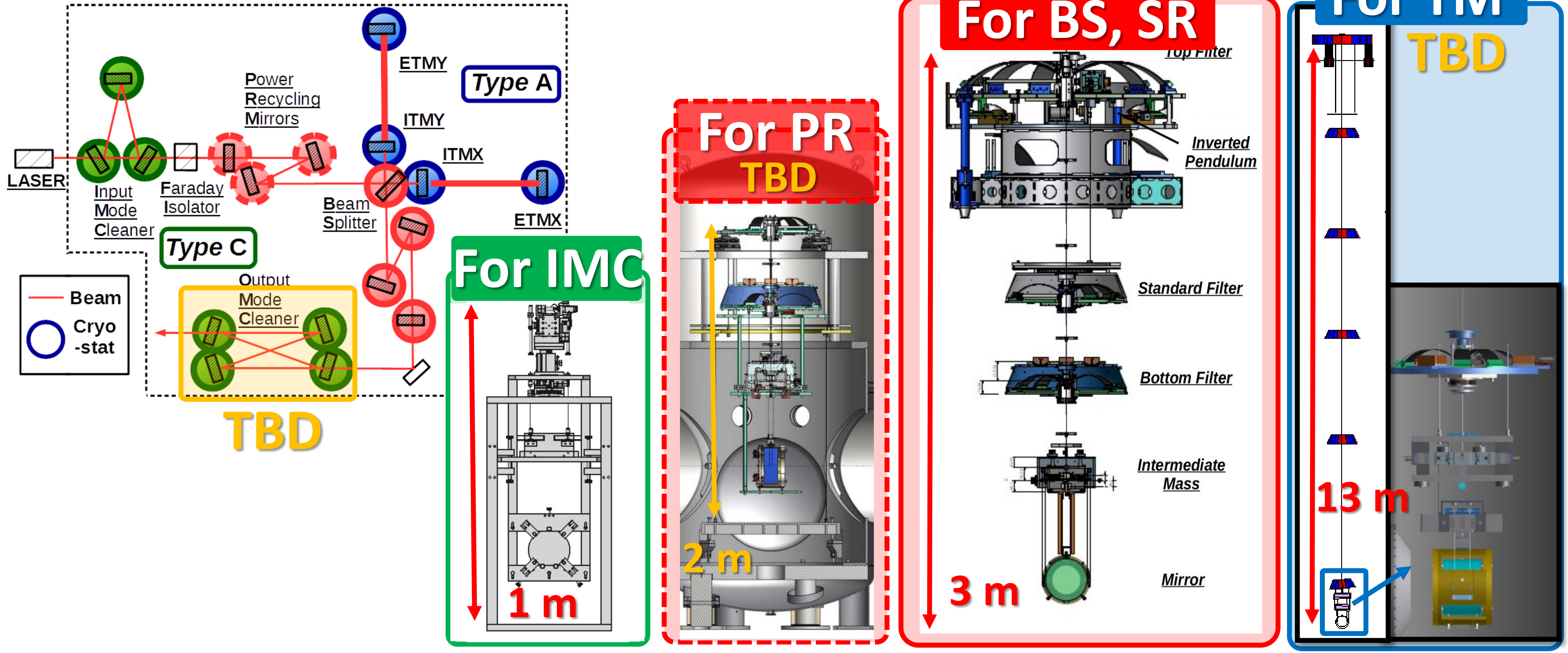








❖ bKAGRA Suspension Configuration (for observation)



Contents

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

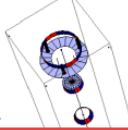
❖ Modeling tools : We have 2 ways.

Passive Model

Passive Model
Active Model

Mechanical Model

SUMCON in *Mathematica*
spension odel structor



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

COMSOL MULTIPHYSICS

Main Concern :
- Heat link
Transfer func.

State-Space Model

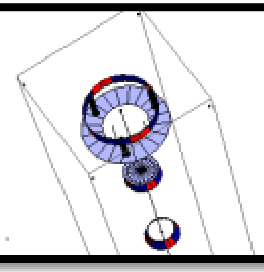
Control Model

MATLAB SIMULINK

Main Concern :
- Controllability
- Servo filter design
- Sensor / Actuator noise

❖ Modeling tools : Mechanical model

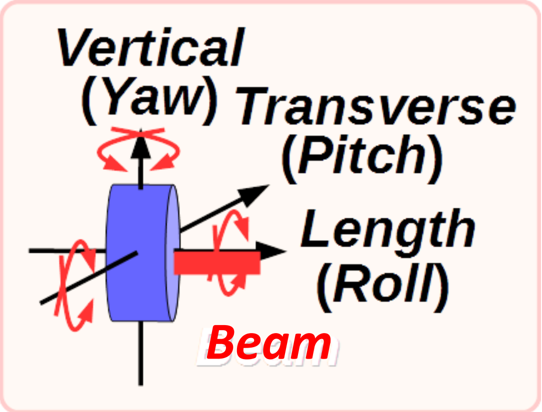
SUMCON in *Mathematica*
spension odel structor



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

Assuming

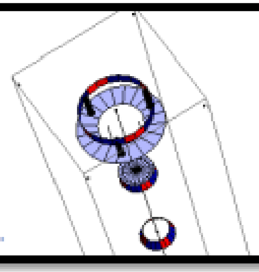
- ❐ 6 DoFs(3 translation, 3 rotation) for each mass
- ❐ No deformation of masses
- ❐ Non-mass wire / No wire string vibration
- ❐ GAS → vertical spring moving for only one direction



❖ Modeling tools : Mechanical model

SUMCON *in Mathematica*

spension odel structor



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

Assuming

More detailed information is here :

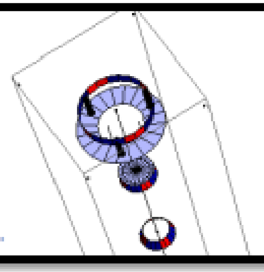
T sekiguchi, *LCGT internal Document* : **JGW-P1200770** (2012)

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** →

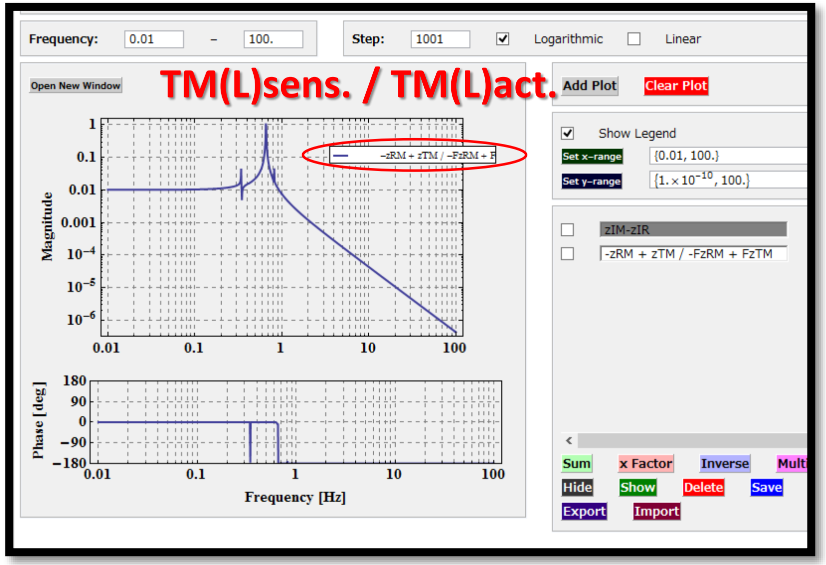
Main outcomes

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

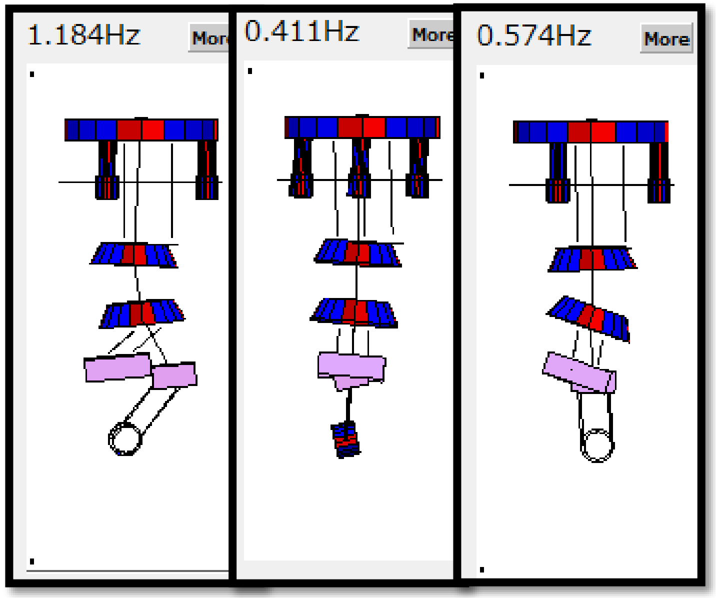
❖ Modeling tools : Mechanical model

SUMCON spension odel structor *in Mathematica*

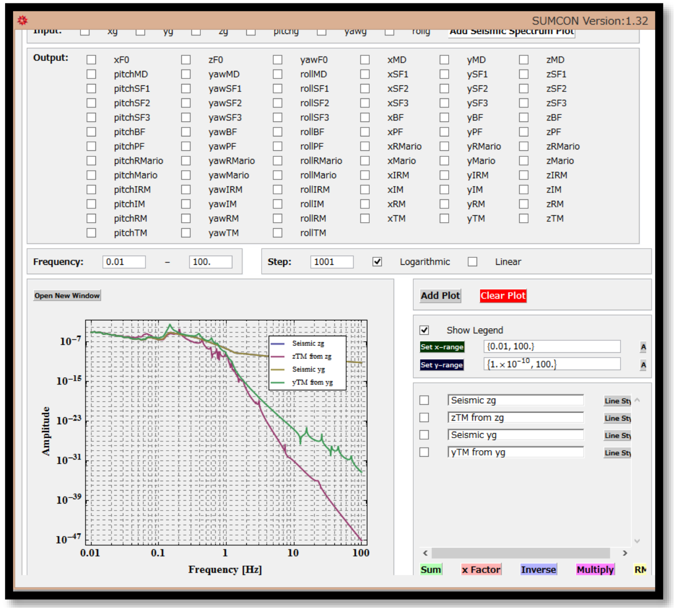
Displacement & Force / Torque Transfer function



Eigen frequency / Eigen mode shape



Thermal & Seismic noise plot



❖ Modeling tools : We have 2 ways.

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Mechanical Model

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spension odel structor

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COMSOL MULTIPHYSICS

Main Concern :

- Heat link

Transfer func.

State-Space Model

Passive Model
Active Model

Control Model

MATLAB SIMULINK

Main Concern :

- Controllability
- Servo filter design
- Sensor / Actuator noise

❖ 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

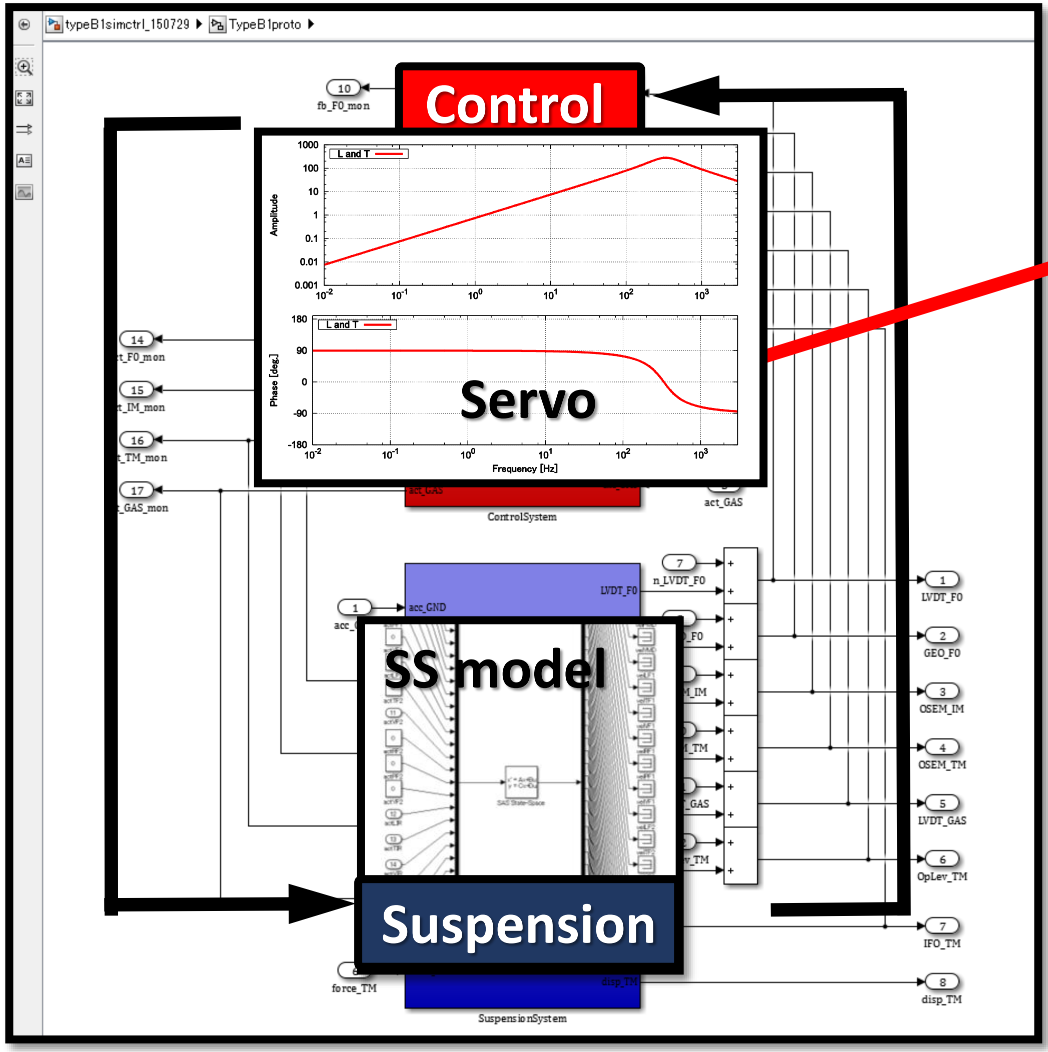
→ **Construct State-space model** →

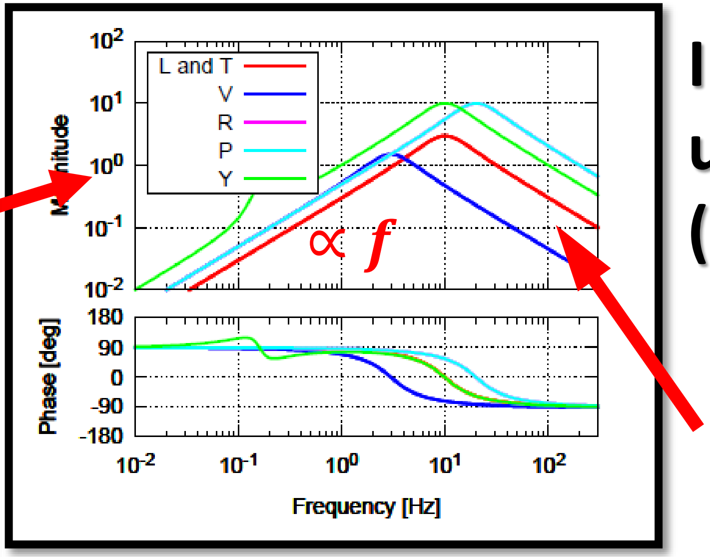
Main outcomes

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

❖ Modeling tools : Active model

MATLAB SIMULINK





IM servo filters using OSEMs (displacement sensor)

Viscous damping filter using displacement

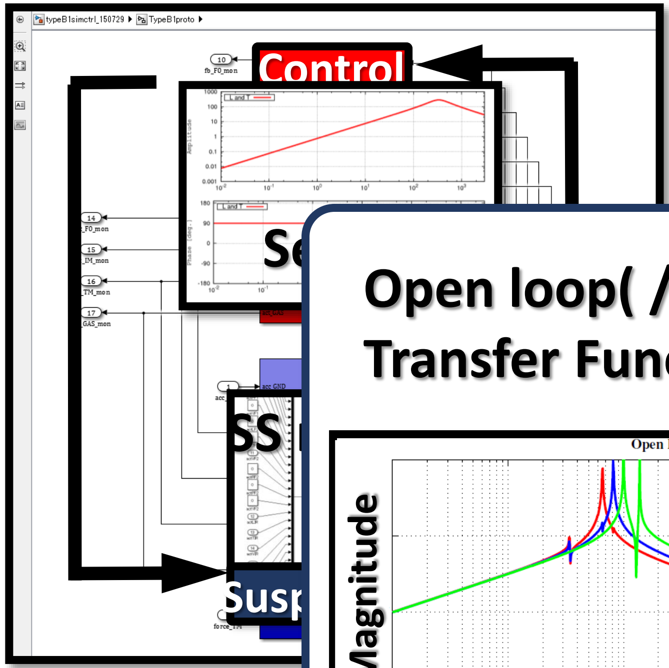
→ $\propto f$

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

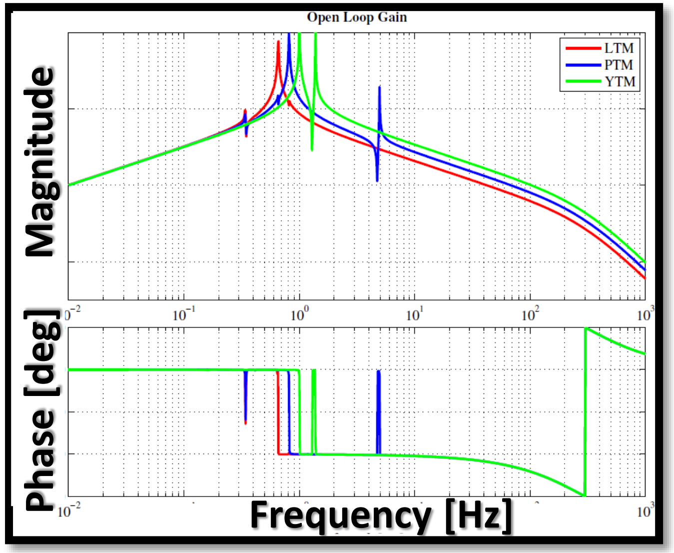
→ Need to add a low-pass filter with cut-off.

❖ Modeling tools : Active model

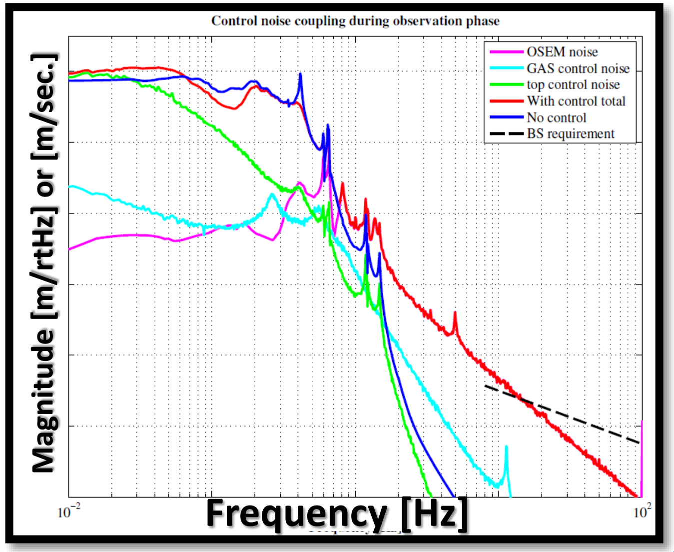
MATLAB SIMULINK



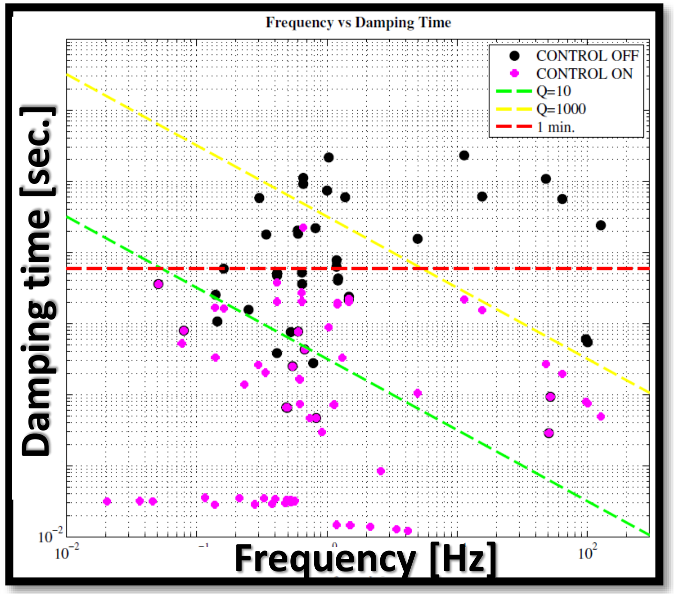
Open loop(/ Closed loop) Transfer Function



Noise coupling



Q factor



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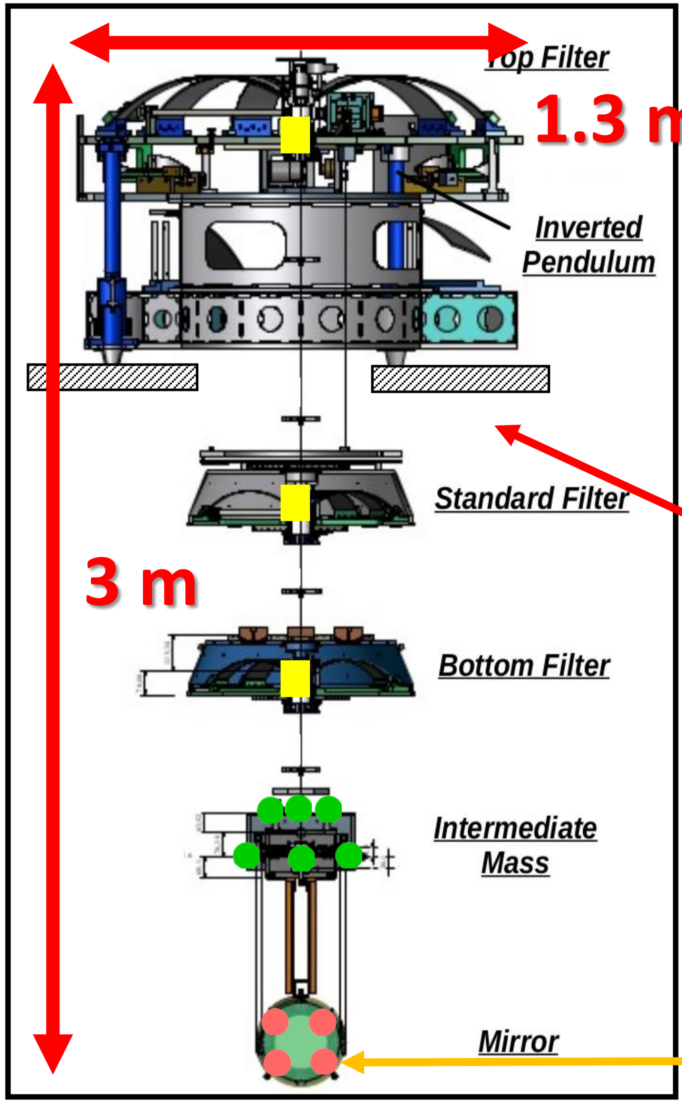
❖ Implementation to BS SAS prototype exp.

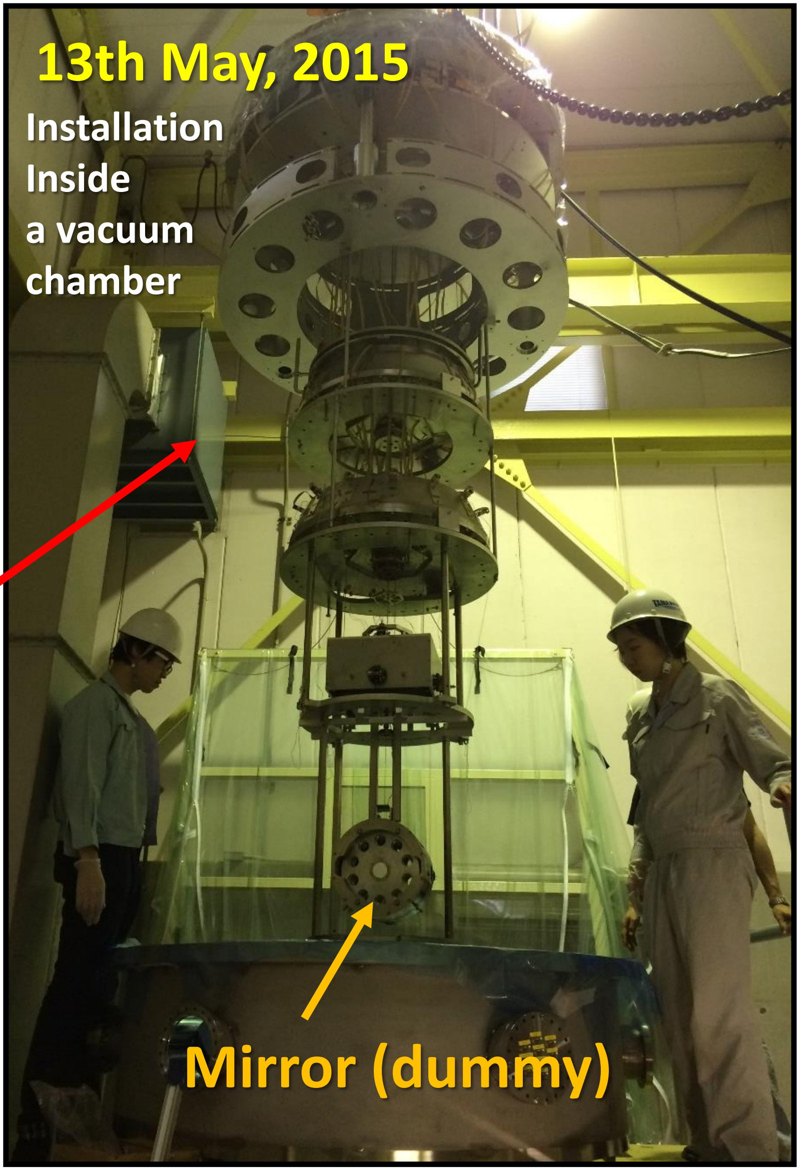


Mirror

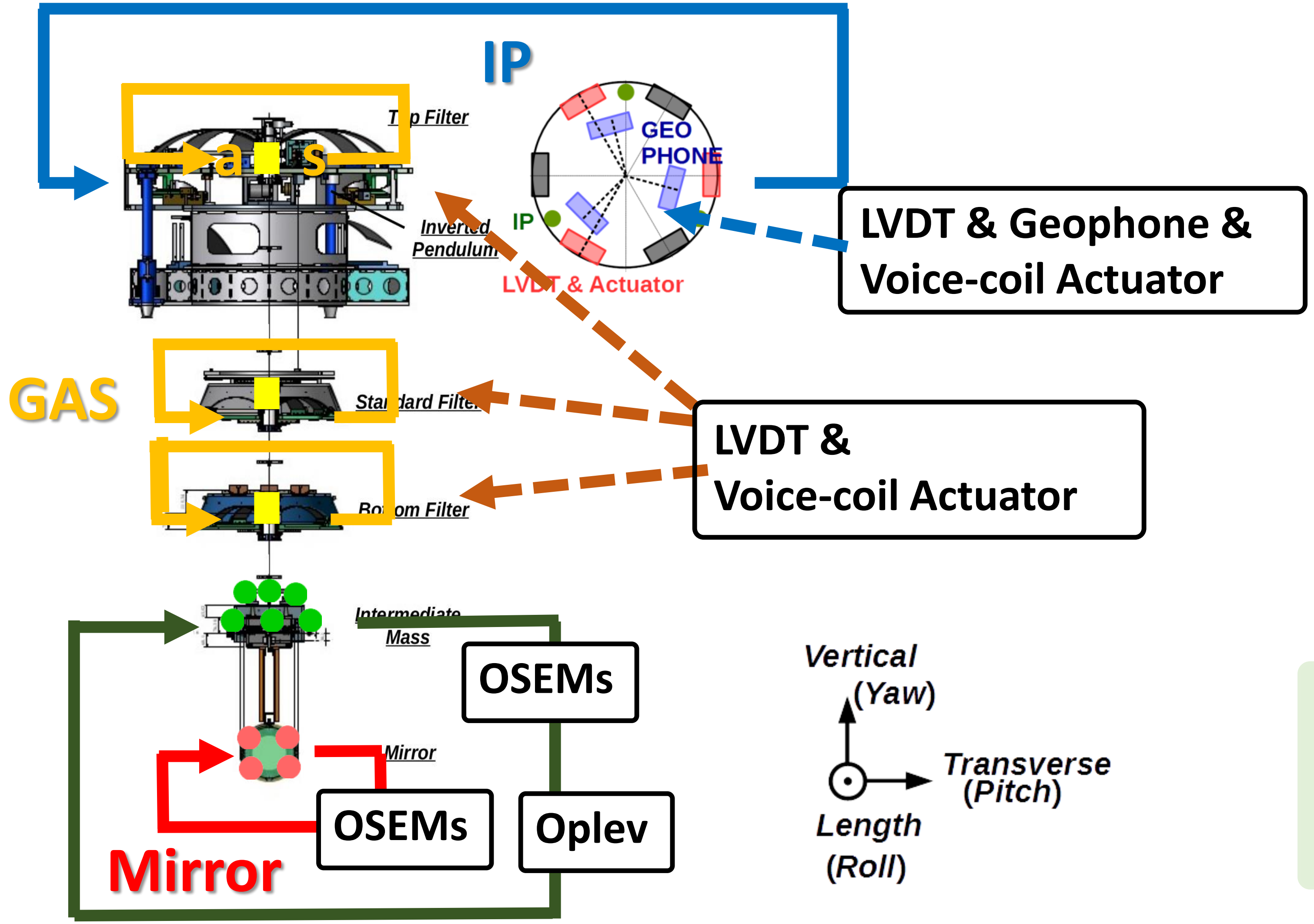
KAGRA SAS for BS, SR

5th 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

⇩

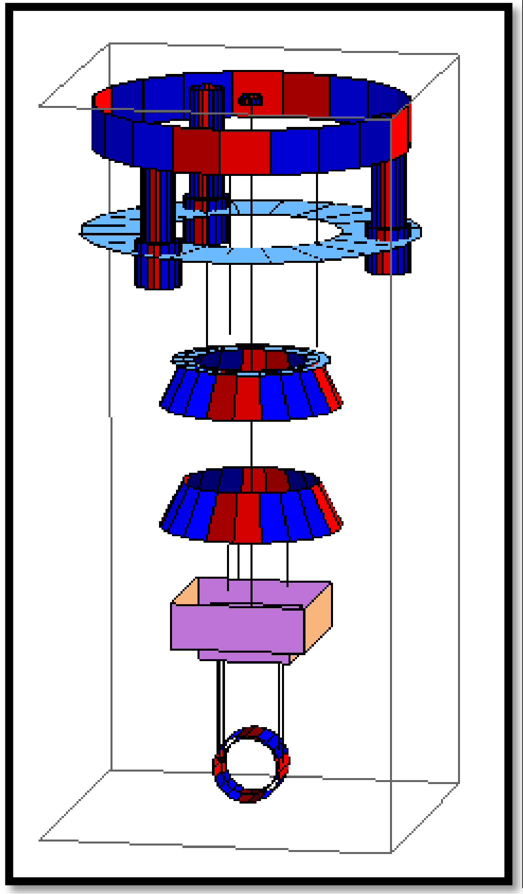
4. implement the servo filters to the actual system

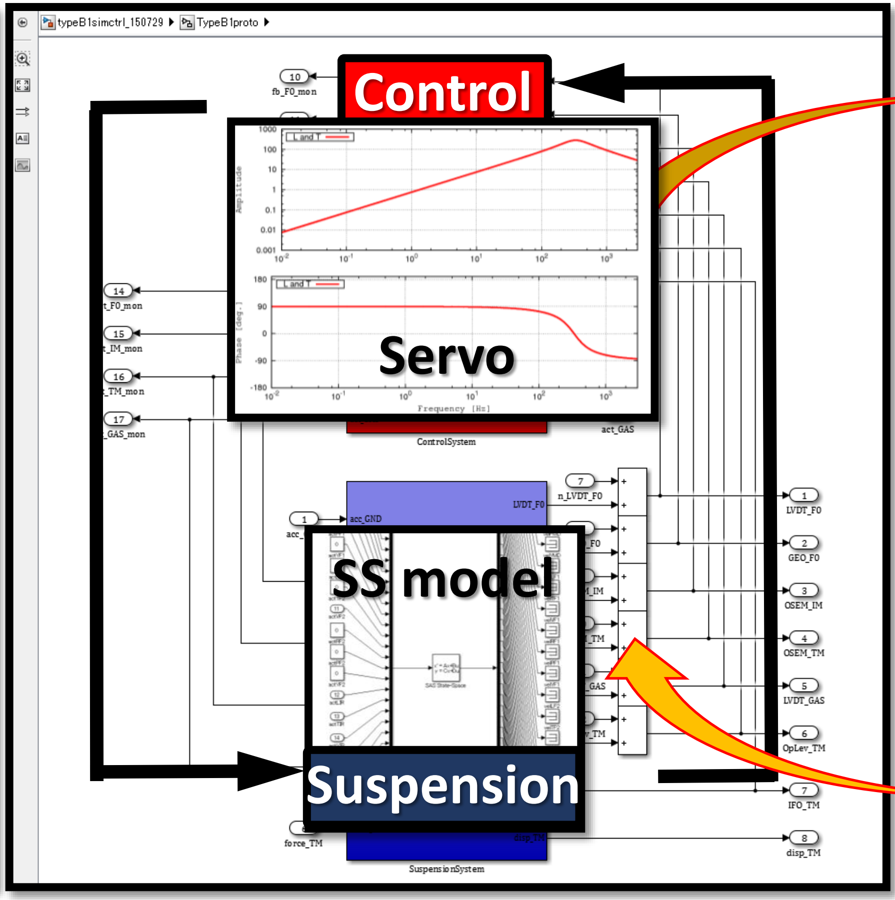
⇩

5. Test SAS performances

❖ Implementation to BS SAS prototype exp.

How was the simulation used in the experiment ?

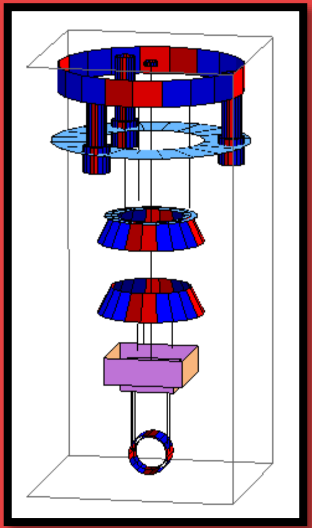




❖ Implementation to BS SAS prototype exp.

Visual part

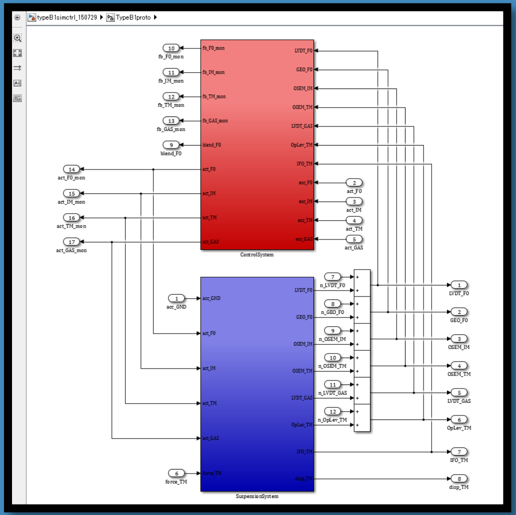
SUMCON
spension odel structor



VS.

Numerical part

MATLAB SIMULINK



❖ Implementation to BS SAS prototype exp.

Main flow

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⇓

2. Assemble suspension system with Frequency response test

⇓

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⇓

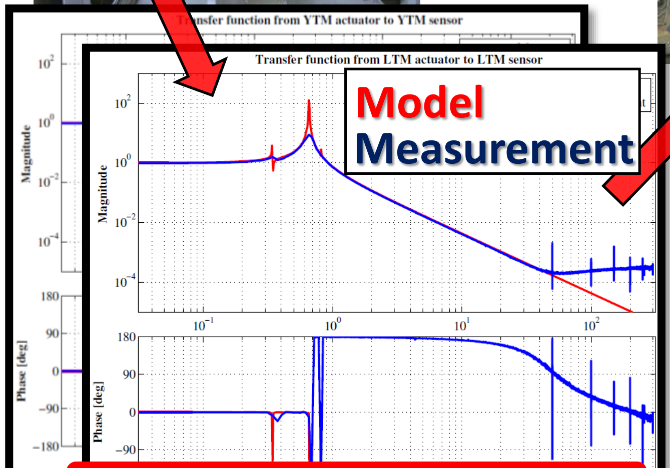
4. implement the servo filters to the actual system

⇓

5. Test SAS performances

❖ Implementation to BS SAS prototype exp.

In assembly

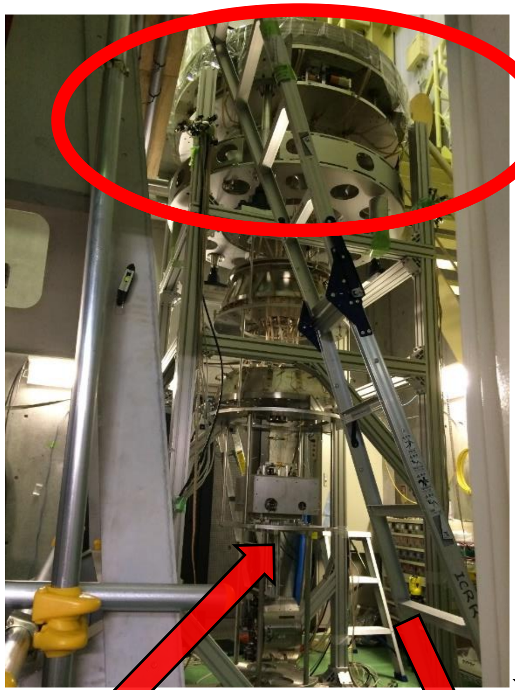


Any strange responses against the model ?

No

No

Any strange responses against the model ?



No

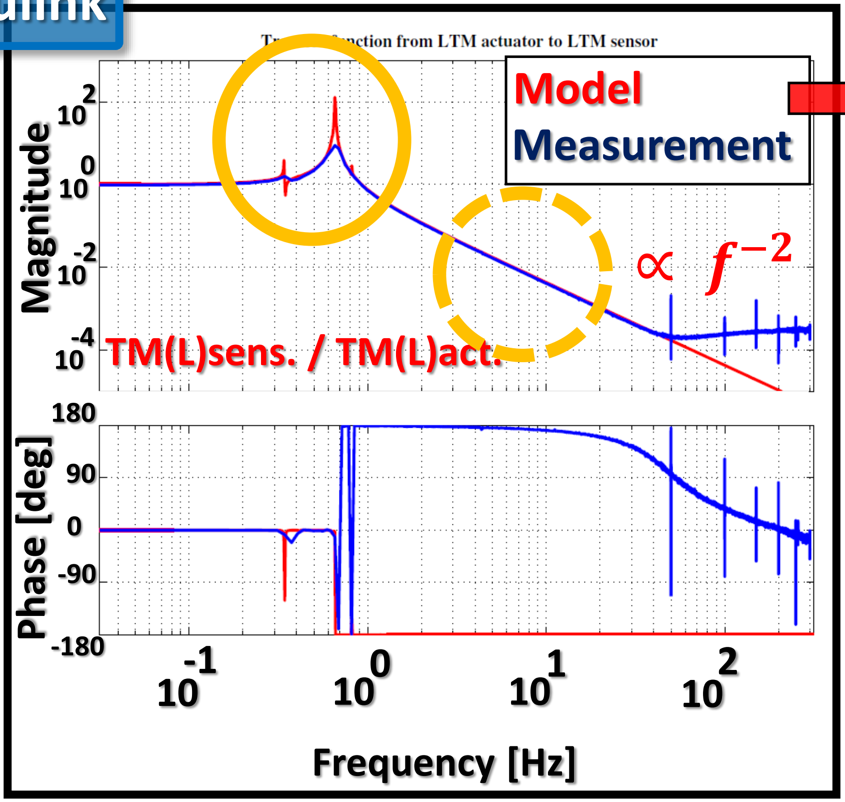
Any strange responses against the model ?

❖ Implementation to BS SAS prototype exp.

In assembly

Force / Torque transfer function with No controls

Simulink

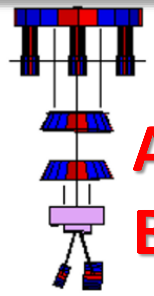


Large discrepancy against the model in
- resonance frequencies ?
- Q factor ?

If, Yes

Investigate the reason
with Eigen mode shape etc.

SUMCON



Any friction?
Broken parts?

❖ 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

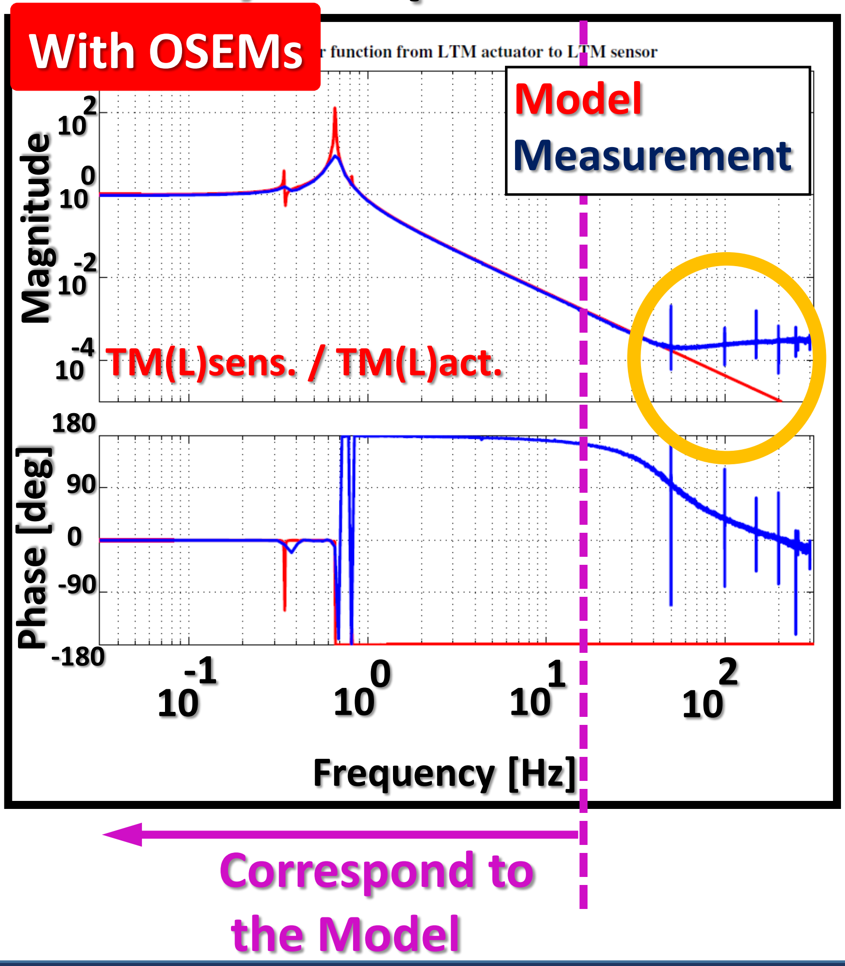
↓

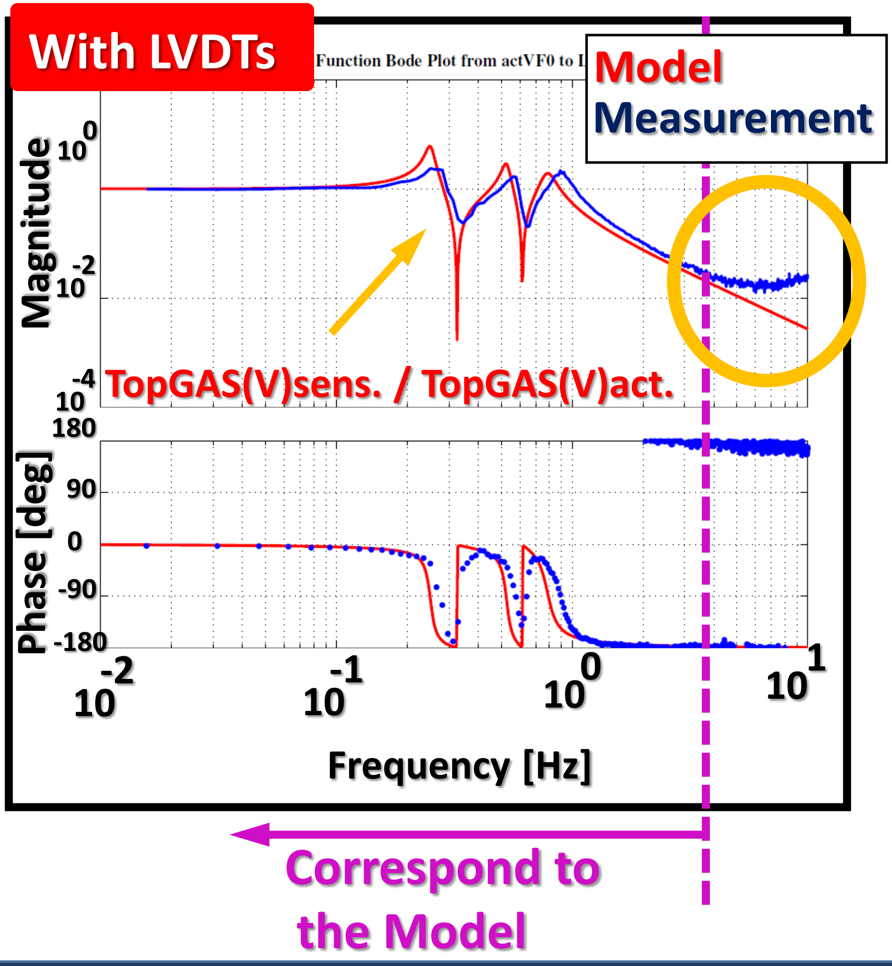
5. **Test SAS performances**

❖ Implementation to BS SAS prototype exp.

In tuning servo filters

Force / Torque transfer function



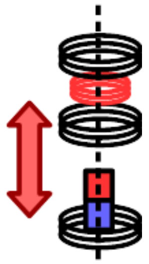


Discrepancies

- EM coupling

OSEM : above 5 Hz

LVDT : above 50 Hz



- Resonance frequency
- Q factor

Hanging condition

Asymmetry in IP stiffness

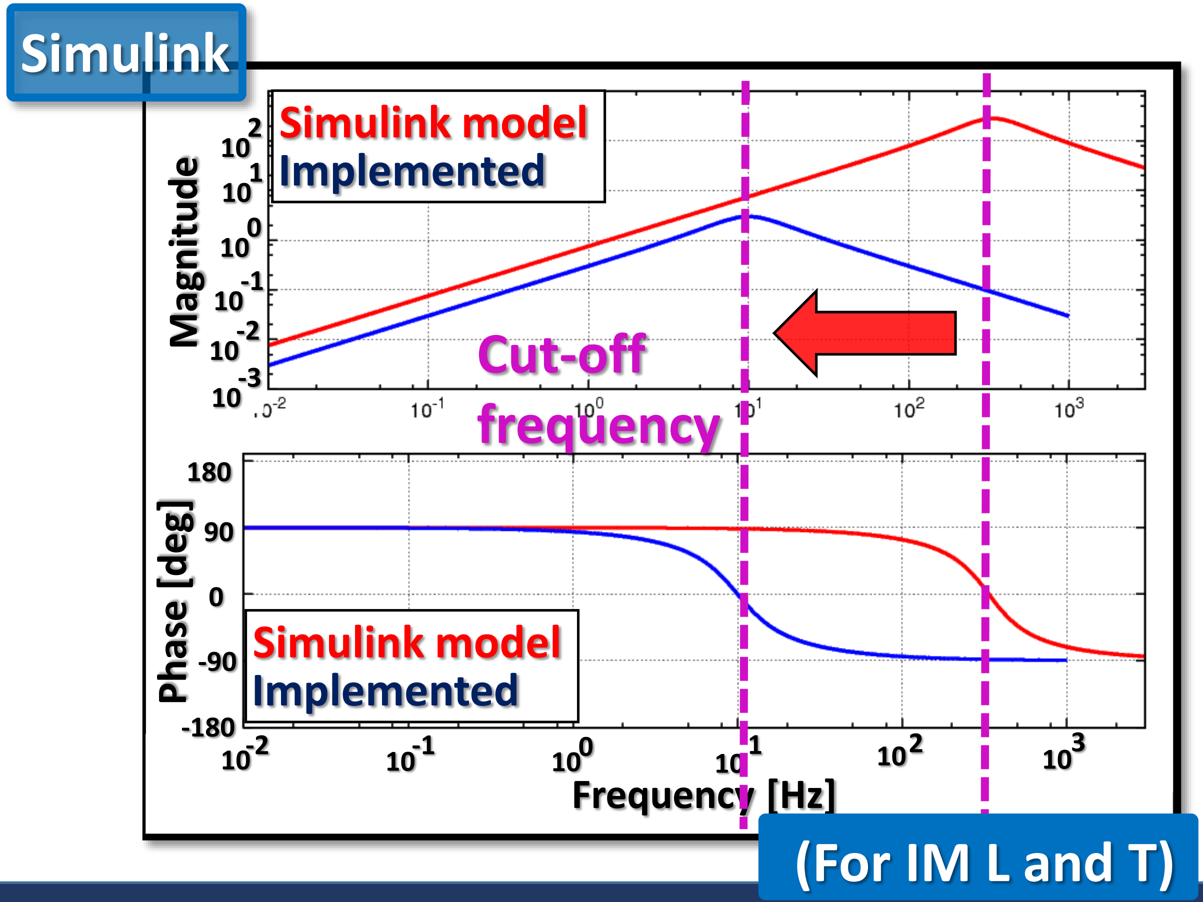
Ham noise

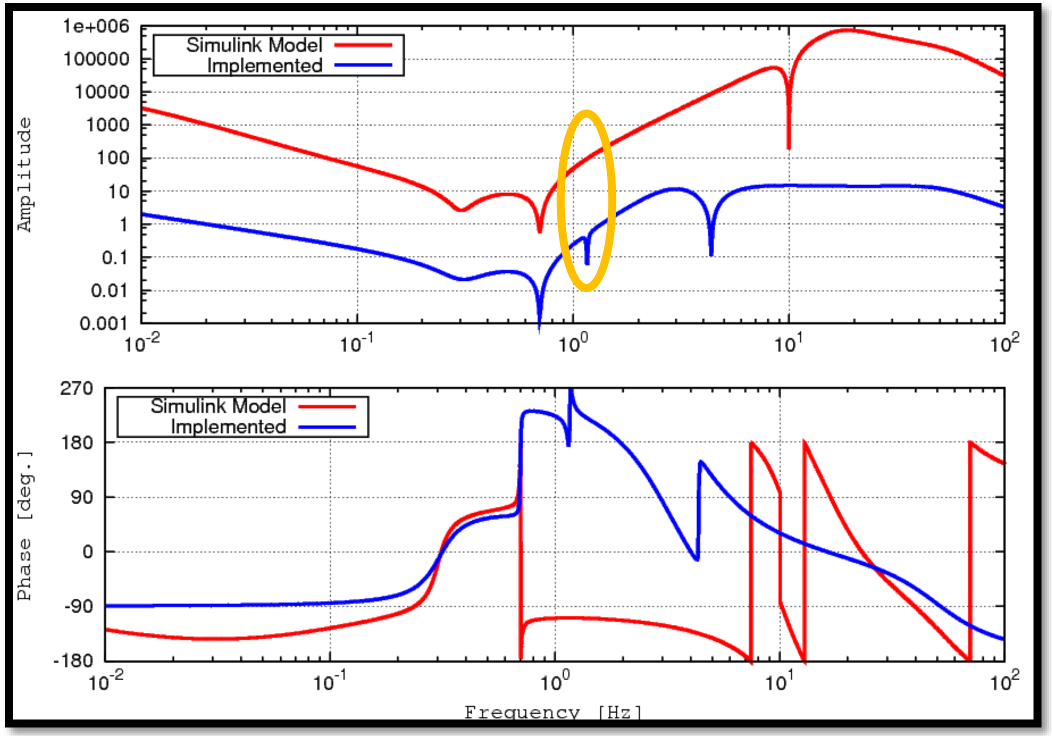
wire violin mode

❖ Implementation to BS SAS prototype exp.

In tuning servo filters

Change cut-off frequency / Add notch filter(, if necessary) at frequency easy to oscillate





❖ Implementation to BS SAS prototype exp.

Main flow

1. Make a model and do simulation on Simulink, Mathematica (and FEM)

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2. Assemble suspension system with Frequency response test

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⇩

4. implement the servo filters to the actual system

⇩

5. Test SAS performances

❖ Implementation to BS SAS prototype exp.

In testing SAS performances

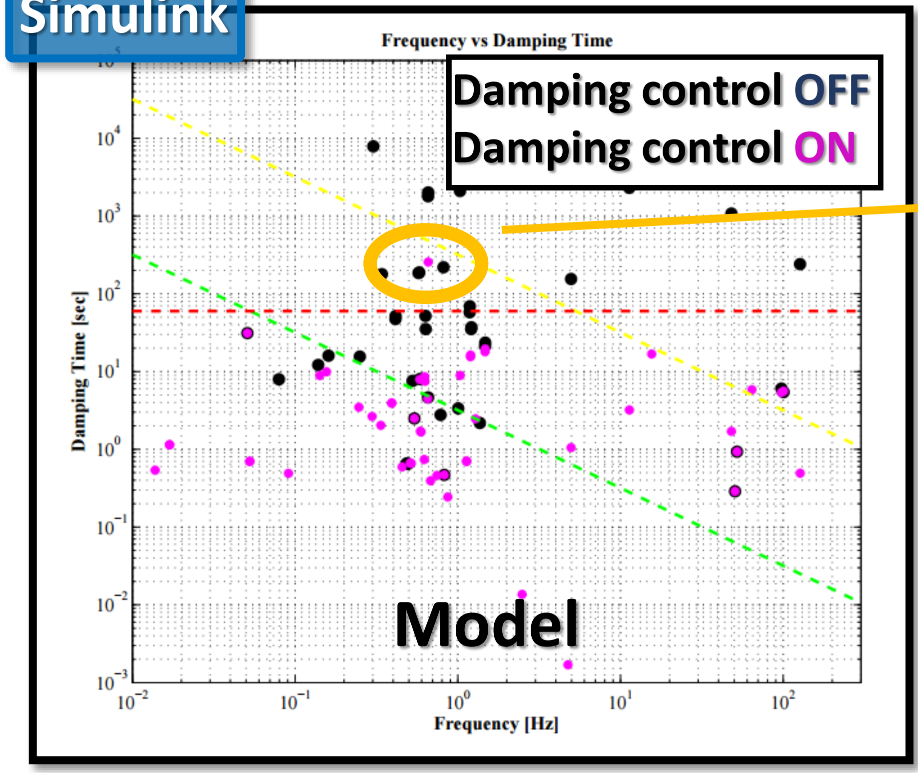
- Mechanical response test
- Damping control performance test → **For Calming the SAS down**
- Long term stability test

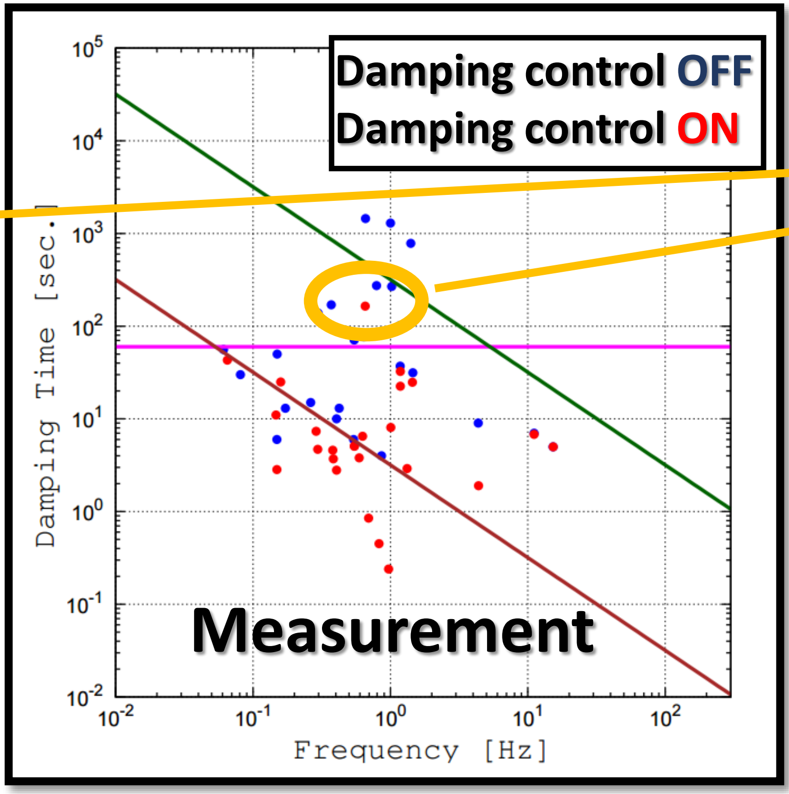
❖ Implementation to BS SAS prototype exp.

In testing SAS performances

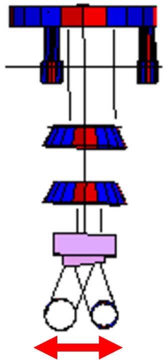
Damping control performance test for Calming the SAS down

Simulink





SUMCON



Lock acquisition failure doesn't contribute to this mode.

Summary

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

→ Using both of them Is useful !

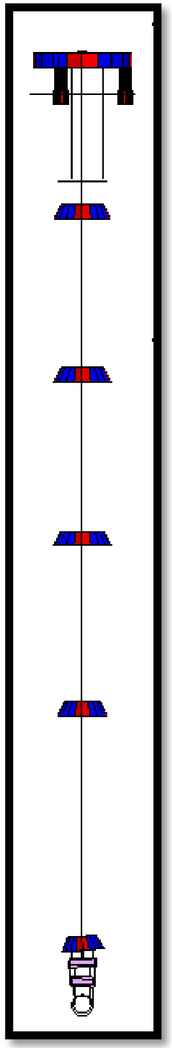
❖ We implemented those tools into actual SAS, for the first time;
- at low frequency → Rigid body model could explain actual system
- control digital system for the prototype worked well.

Next step

❖ build SAS for iKAGRA using those tools.

❖ Construct current bKAGRA TM SAS model.

You can use the modeling tools : SUMCON and Simulink !



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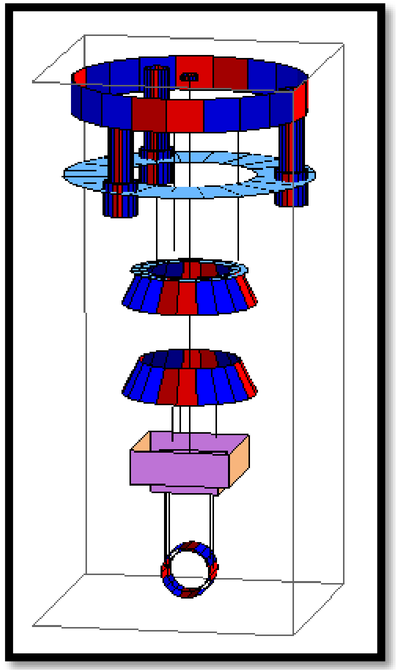
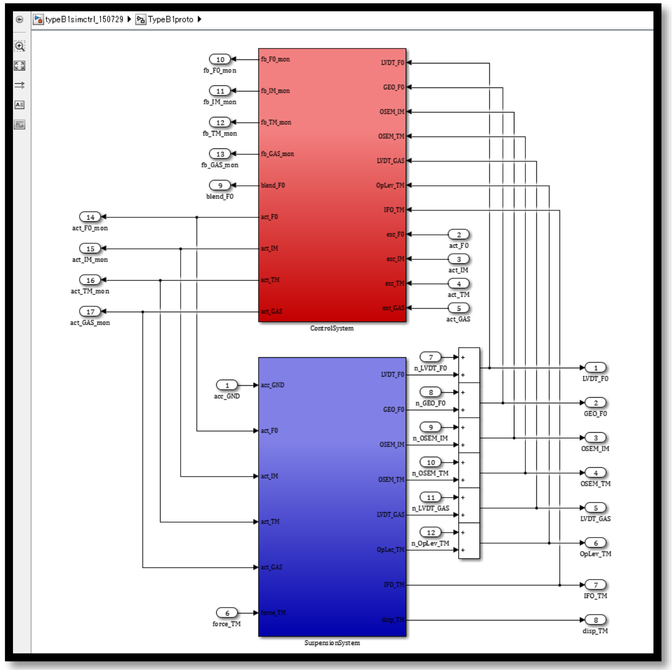




NOTE : we don't have any manuals, though.

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 (Suspension Model Constructor)

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

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

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

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

4. Construct Linearized Eq of motion

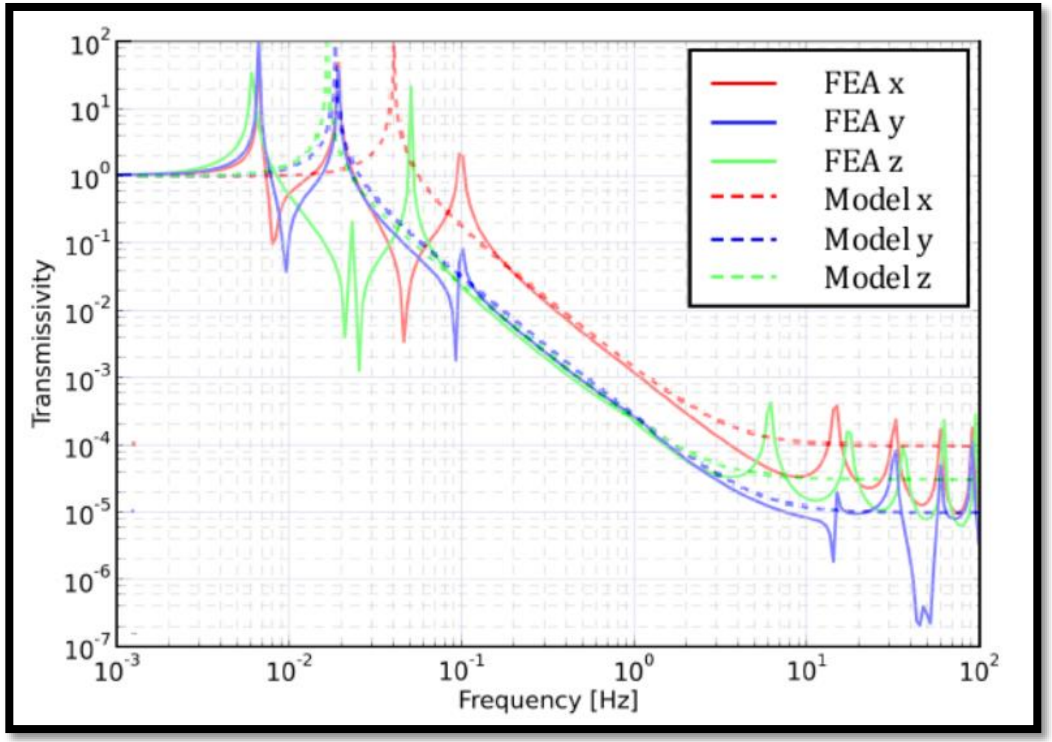
$$K\ddot{x} + C\dot{x} + K(x - x_e) = f$$

f : external force

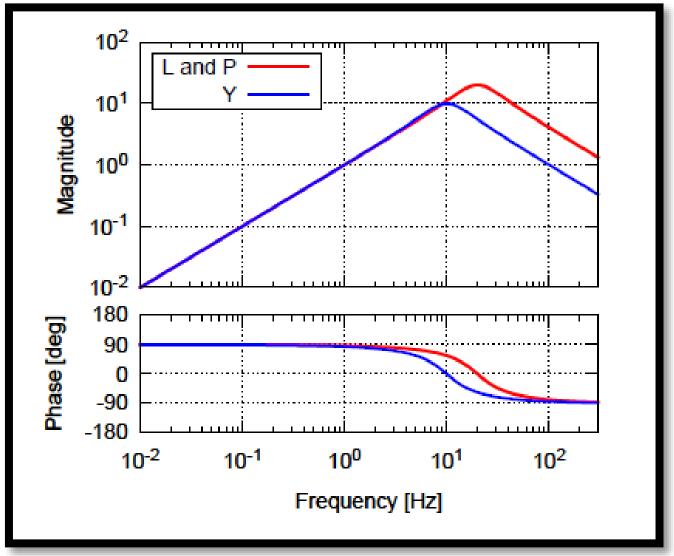
Assuming the vibration is small so that we can linearize the system

❖ Modeling tools : Mechanical model

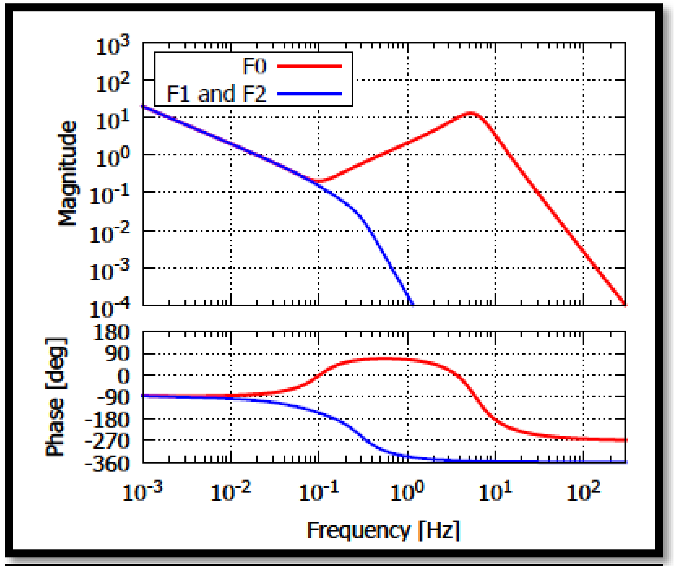
Heat links



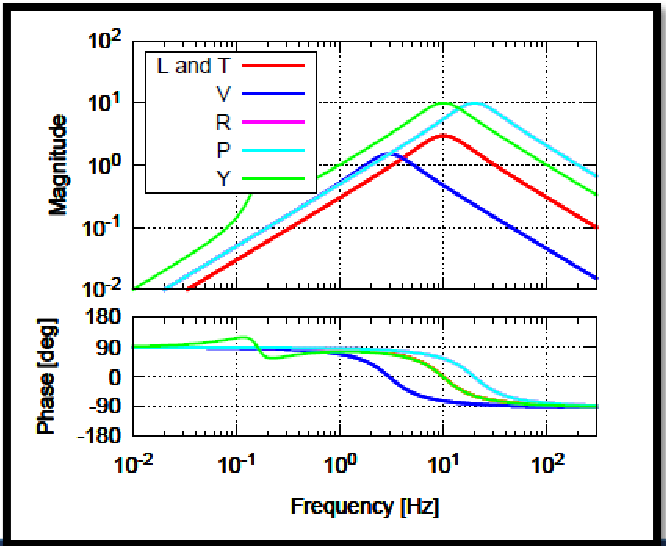
❖ Modeling tools : actual servo filters for damping



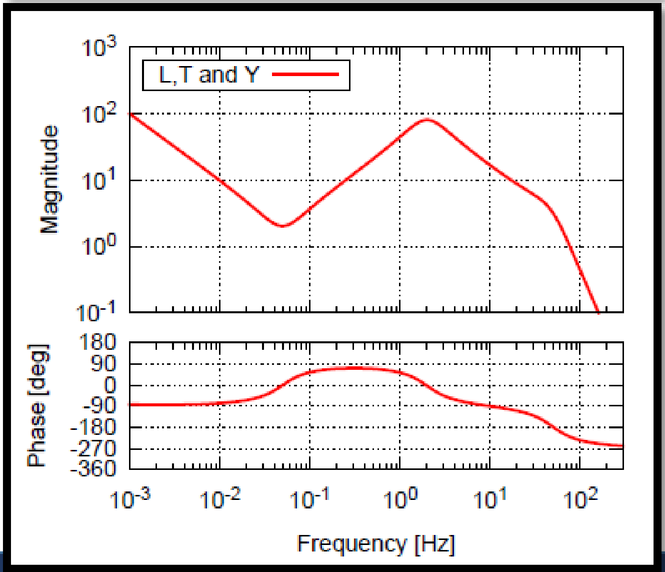
Servo filter For TM OSEM



Servo filter For GAS filter

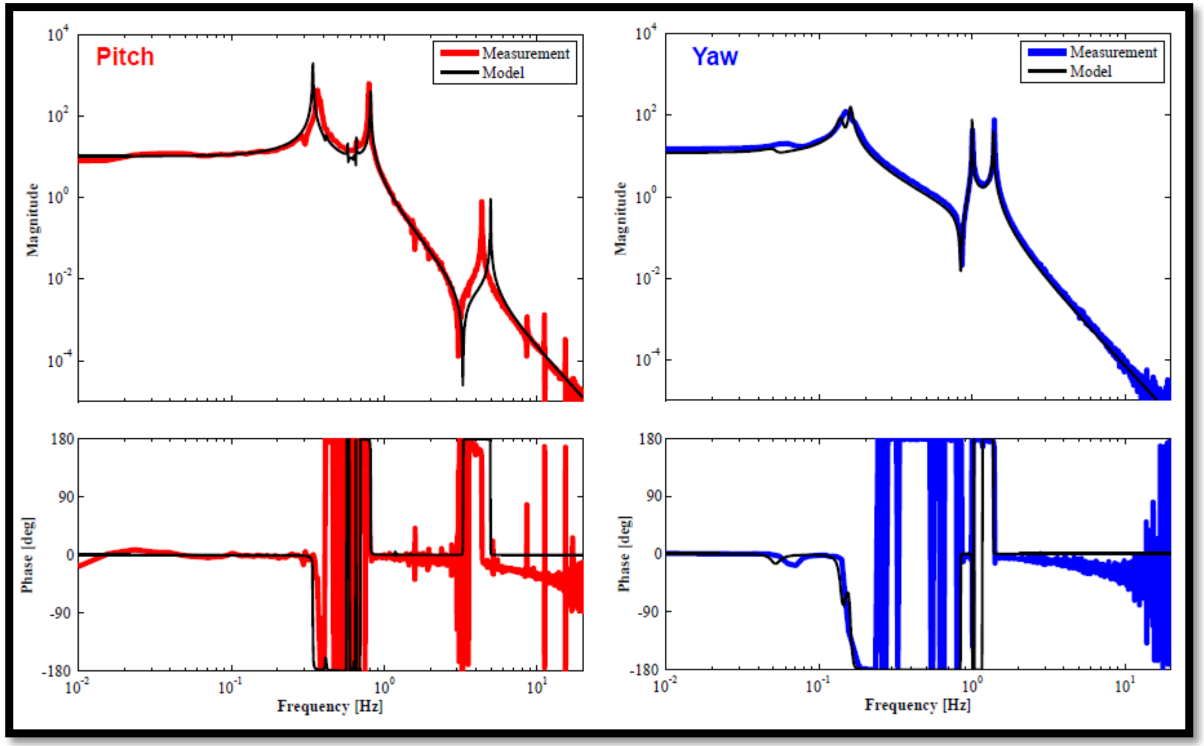


Servo filter For IM OSEM

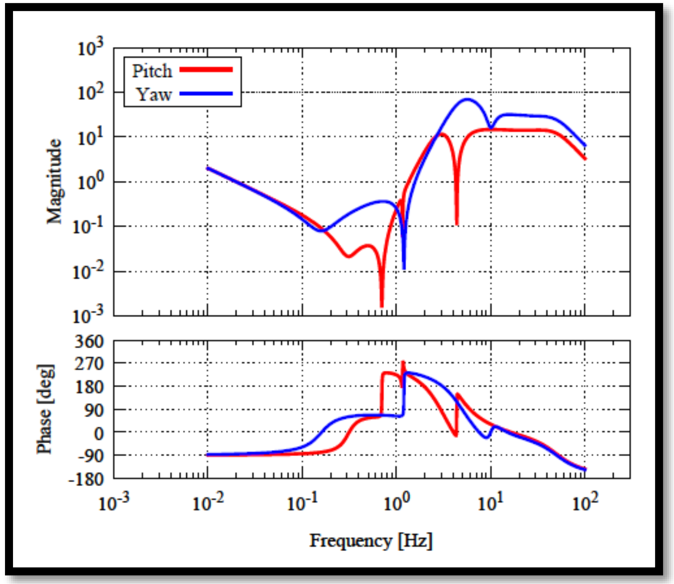


Servo filter For IP

❖ Modeling tools : actual servo filters for damping



Transfer function from TM act. to Oplev

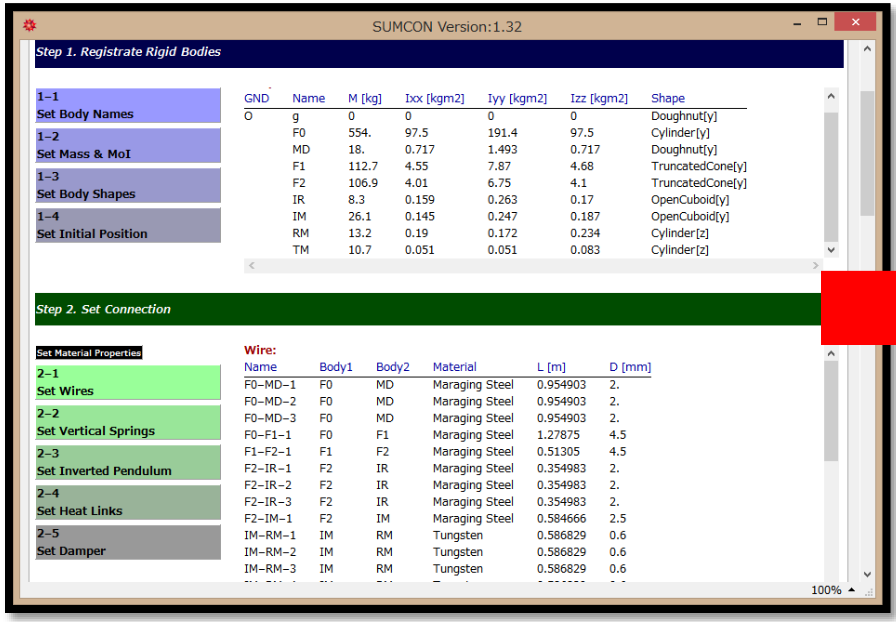


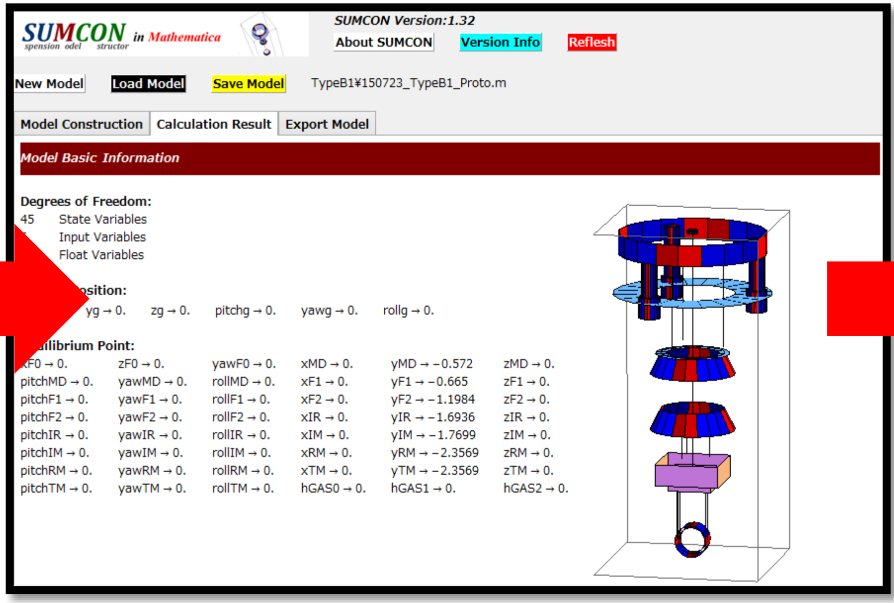
Servo filter for Oplev (in front of TM)

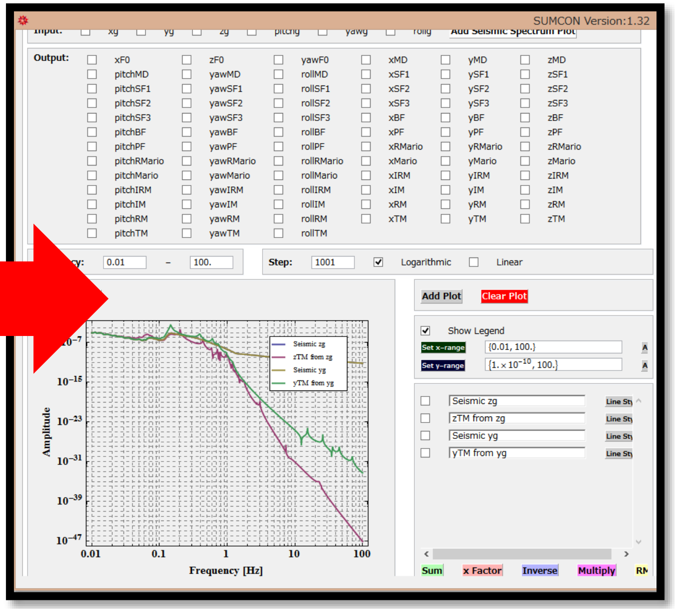
❖ Modeling tools : Mechanical model

SUMCON in Mathematica
spension odel structor

For instance,

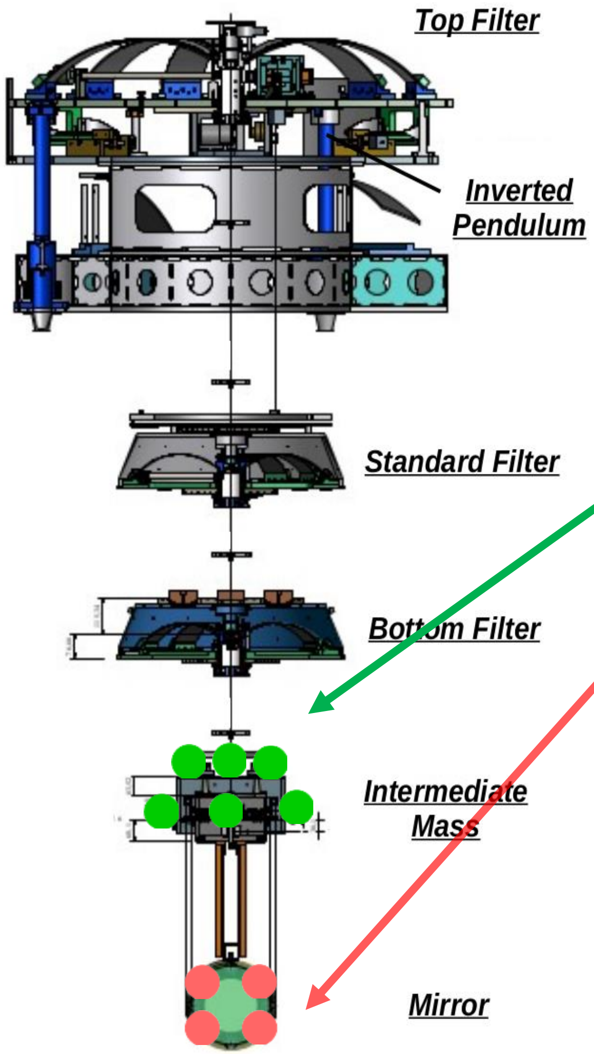


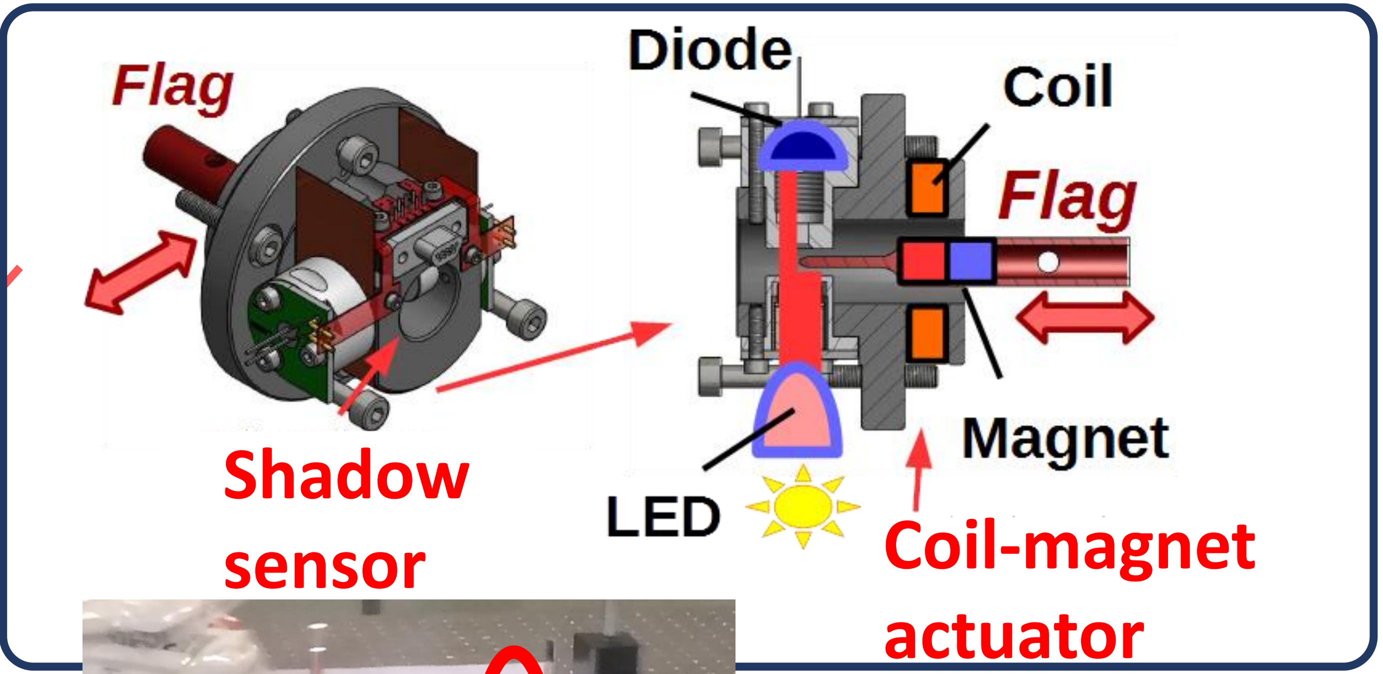


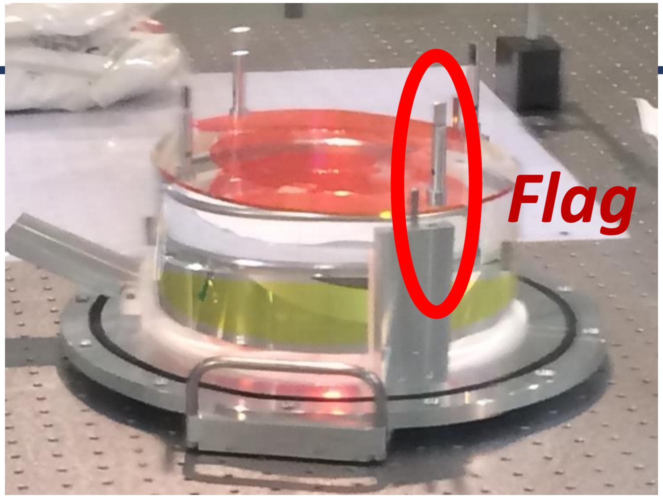


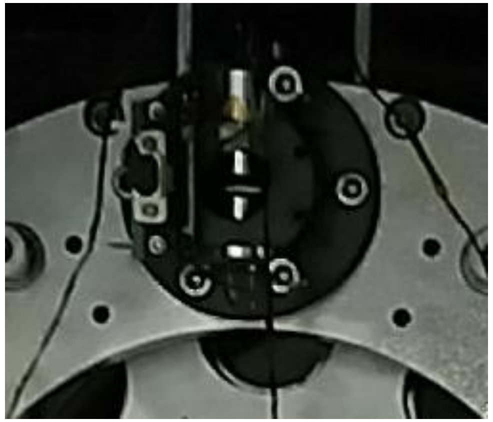
❖ BS SAS proto : OSEM

Shadow sensor & Coil-magnet actuator unit









Type B の防振比のsimulation