Commissioning and performance of the Signal Recycling suspensions of KAGRA

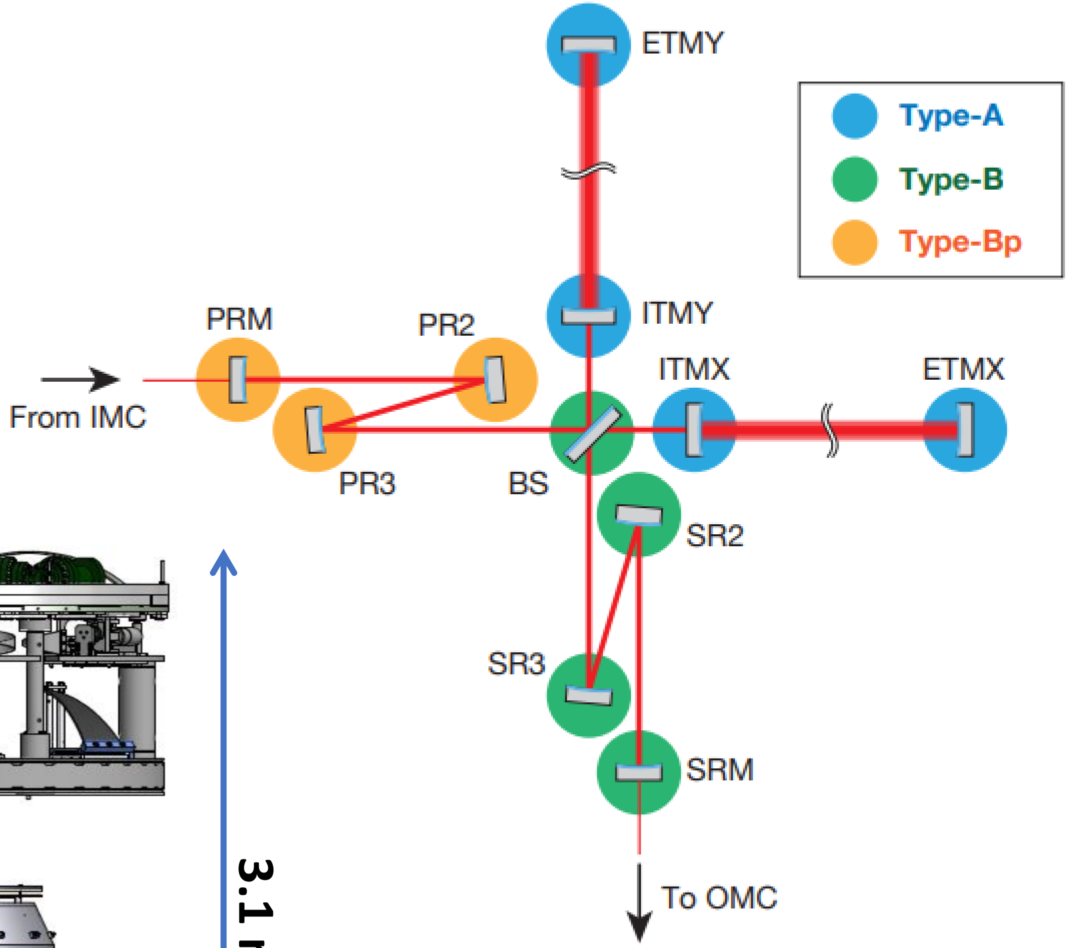
Enzo Tapia S.

On behalf of KAGRA collaboration.

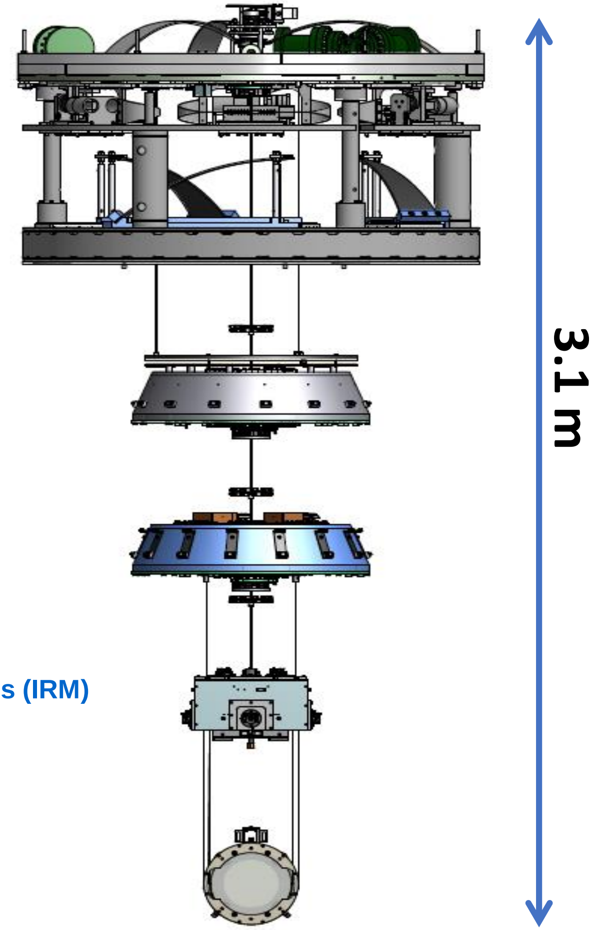
Index

Type B suspensions

BS, SR2, SR3 and SRM



By K. Okutomi. Ref 4.

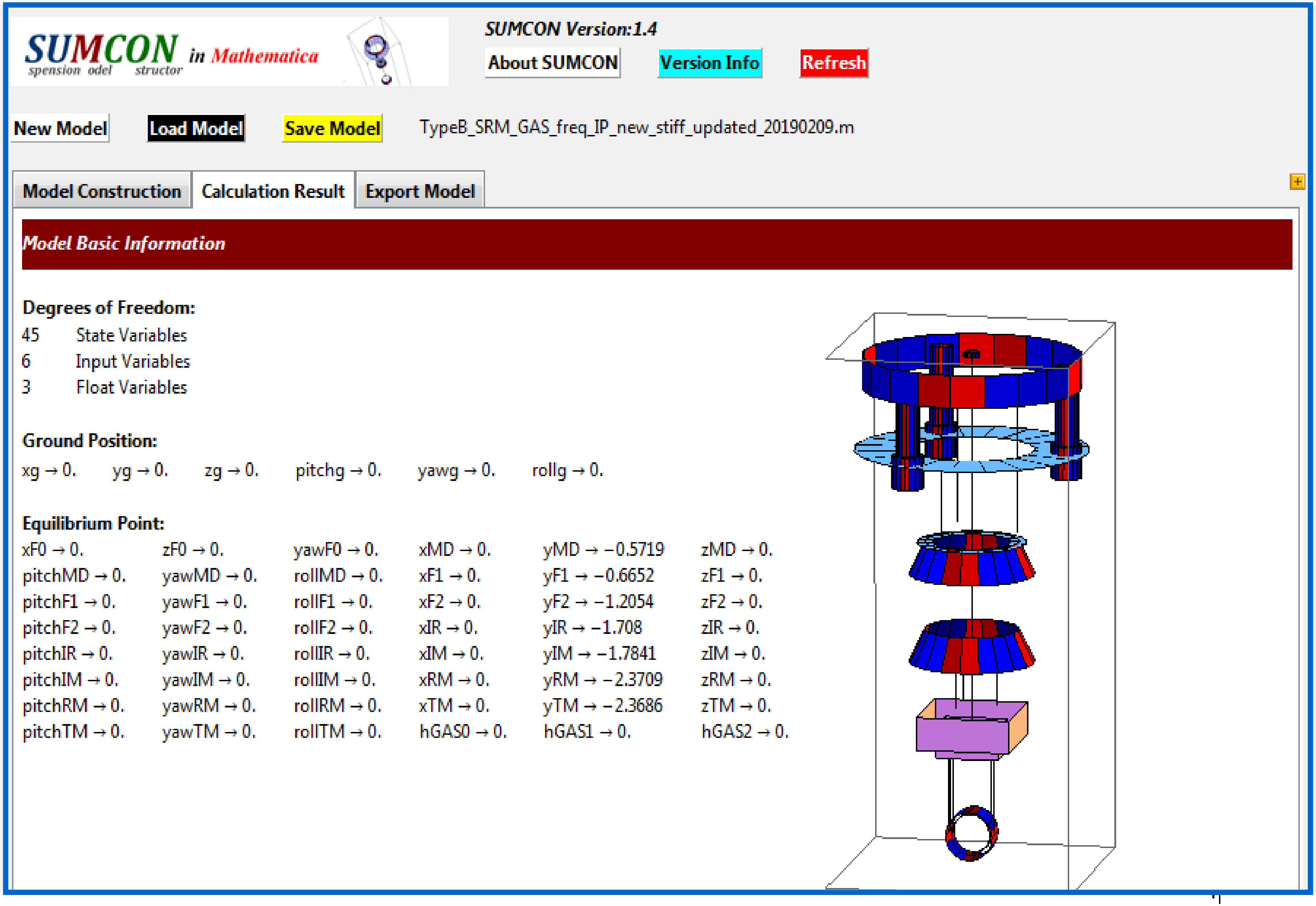


Pre-Isolator
- **Top Filter (TF)**
- **Filter0 (F0)**
- **Inverted Pendulum (IP)**

GAS Filter Chain
- **Magnetic Damper (MD)**
- **Standard Filter (SF)**
- **Bottom Filter (BF)**

Payload
- **Intermediate Recoil Mass (IRM)**
- **Intermediate Mass (IM)**
- **Recoil Mass (RM)**
- **Optics (SR)**

Type B model in SUMCON



SUMCON Version:1.4

TypeB_SRM_GAS_freq_IP_new_stiff_updated_20190209.m

Model Basic Information

Degrees of Freedom:

```
45    State Variables
6     Input Variables
3     Float Variables
```

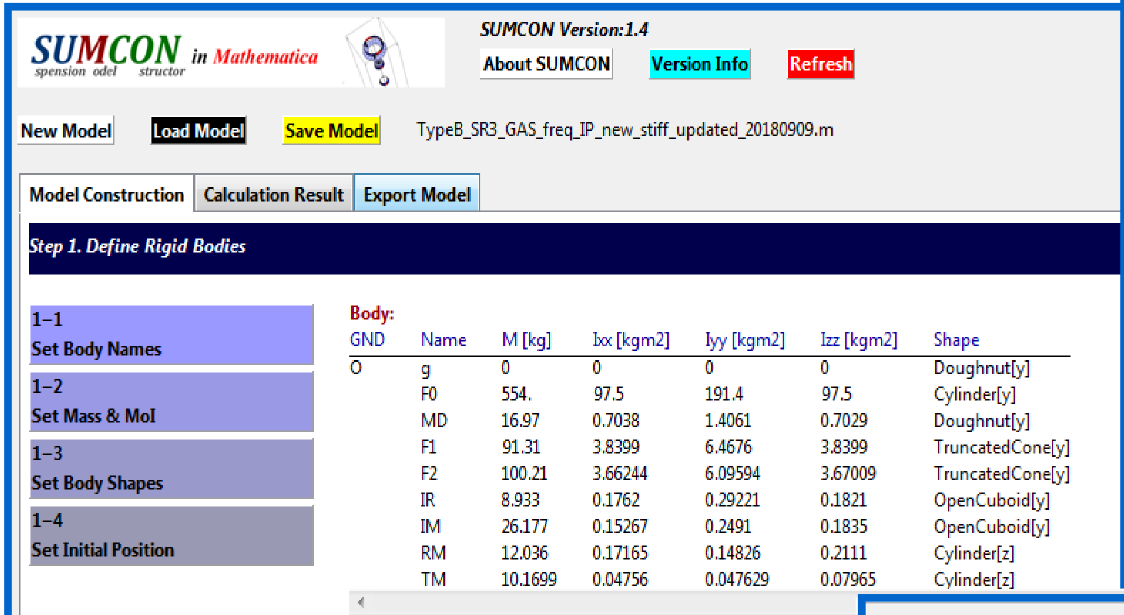
Ground Position:

```
xg → 0.    yg → 0.    zg → 0.    pitchg → 0.    yawg → 0.    rollg → 0.
```

Equilibrium Point:

```
xF0 → 0.        zF0 → 0.        yawF0 → 0.      xMD → 0.        yMD → −0.5719     zMD → 0.
pitchMD → 0.    yawMD → 0.      rollMD → 0.     xF1 → 0.        yF1 → −0.6652     zF1 → 0.
pitchF1 → 0.    yawF1 → 0.      rollF1 → 0.     xF2 → 0.        yF2 → −1.2054     zF2 → 0.
pitchF2 → 0.    yawF2 → 0.      rollF2 → 0.     xIR → 0.        yIR → −1.708      zIR → 0.
pitchIR → 0.    yawIR → 0.      rollIR → 0.     xIM → 0.        yIM → −1.7841     zIM → 0.
pitchIM → 0.    yawIM → 0.      rollIM → 0.     xRM → 0.        yRM → −2.3709     zRM → 0.
pitchRM → 0.    yawRM → 0.      rollRM → 0.     xTM → 0.        yTM → −2.3686     zTM → 0.
pitchTM → 0.    yawTM → 0.      rollTM → 0.     hGAS0 → 0.      hGAS1 → 0.        hGAS2 → 0.
```

Type B model in SUMCON



SUMCON Version:1.4

TypeB_SR3_GAS_freq_IP_new_stiff_updated_20180909.m

Step 1. Define Rigid Bodies

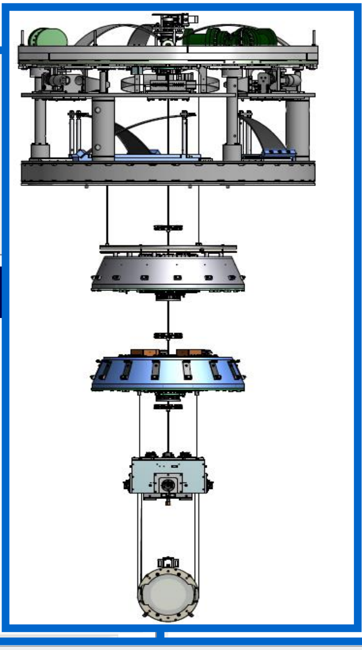
Body:

GND	Name	M [kg]	Ixx [kgm2]	Iyy [kgm2]	Izz [kgm2]	Shape
O	g	0	0	0	0	Doughnut[y]
	F0	554.	97.5	191.4	97.5	Cylinder[y]
	MD	16.97	0.7038	1.4061	0.7029	Doughnut[y]
	F1	91.31	3.8399	6.4676	3.8399	TruncatedCone[y]
	F2	100.21	3.66244	6.09594	3.67009	TruncatedCone[y]
	IR	8.933	0.1762	0.29221	0.1821	OpenCuboid[y]
	IM	26.177	0.15267	0.2491	0.1835	OpenCuboid[y]
	RM	12.036	0.17165	0.14826	0.2111	Cylinder[z]
	TM	10.1699	0.04756	0.047629	0.07965	Cylinder[z]

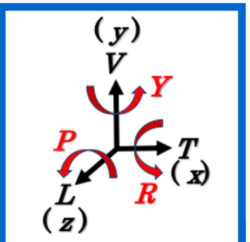
Step 2. Define Connections

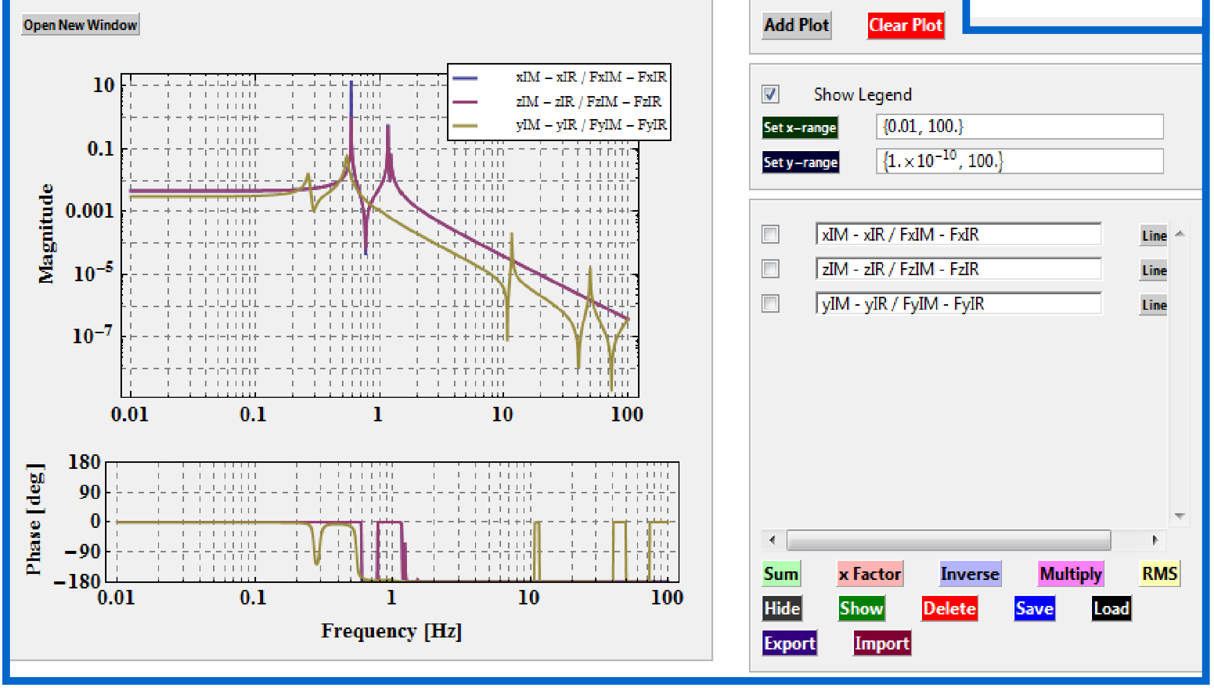
Wire:

Name	Body1	Body2	Material	L [m]
F0–MD–1	F0	MD	Maraging Steel	0.954811
F0–MD–2	F0	MD	Maraging Steel	0.954811
F0–MD–3	F0	MD	Maraging Steel	0.954811
F0–F1–1	F0	F1	Maraging Steel	1.27762
F1–F2–1	F1	F2	Maraging Steel	0.512716



With help of a 3D model (Autodesk Inventor in this case), is posible to get the mass, and moments of inertia of each element of one suspension.





☑ Show Legend

Set x–range {0.01, 100.}

Set y–range {$1.\times10^{-10}$, 100.}

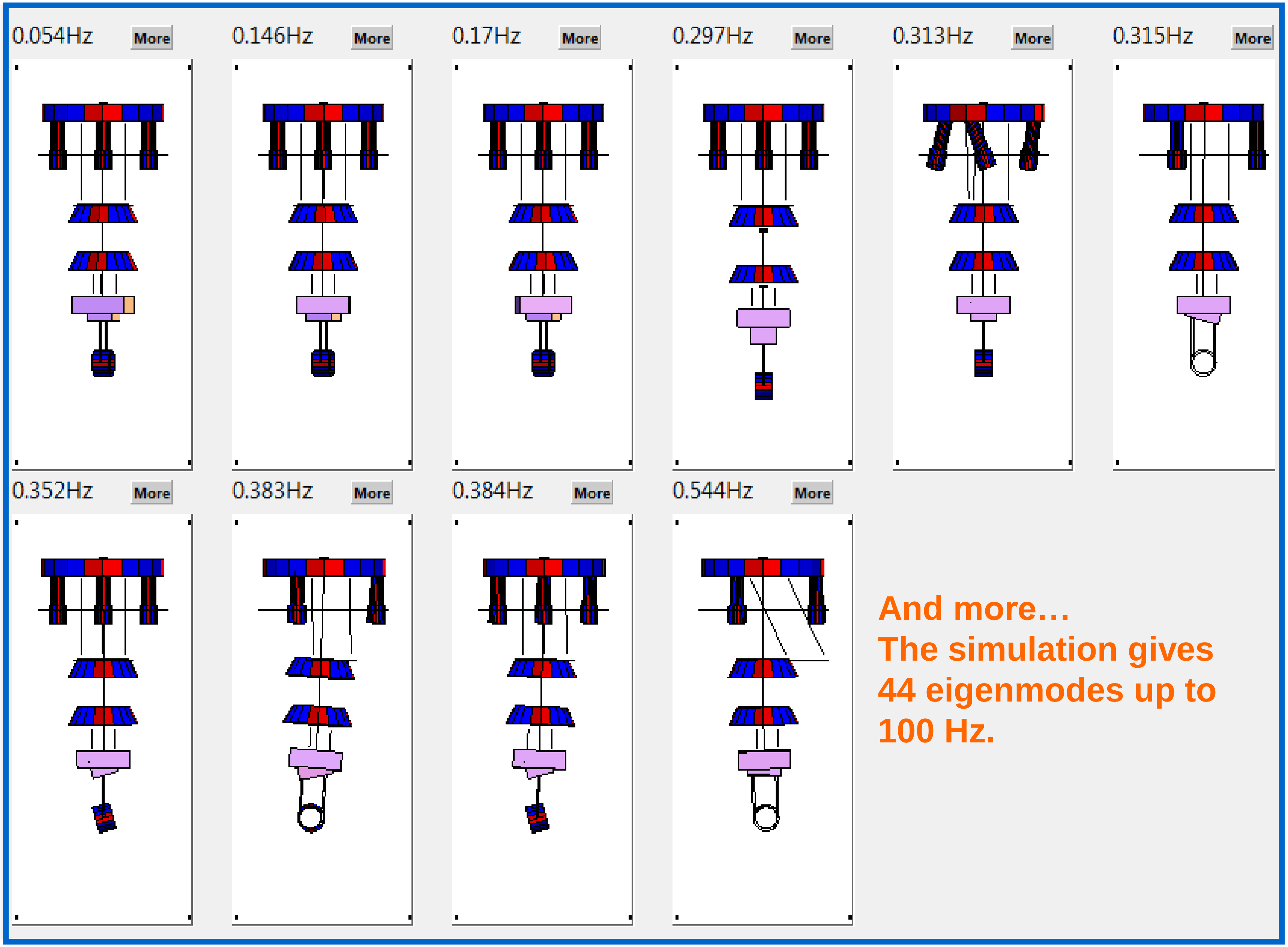
☐ xIM - xIR / FxIM - FxIR

☐ zIM - zIR / FzIM - FzIR

☐ yIM - yIR / FyIM - FyIR

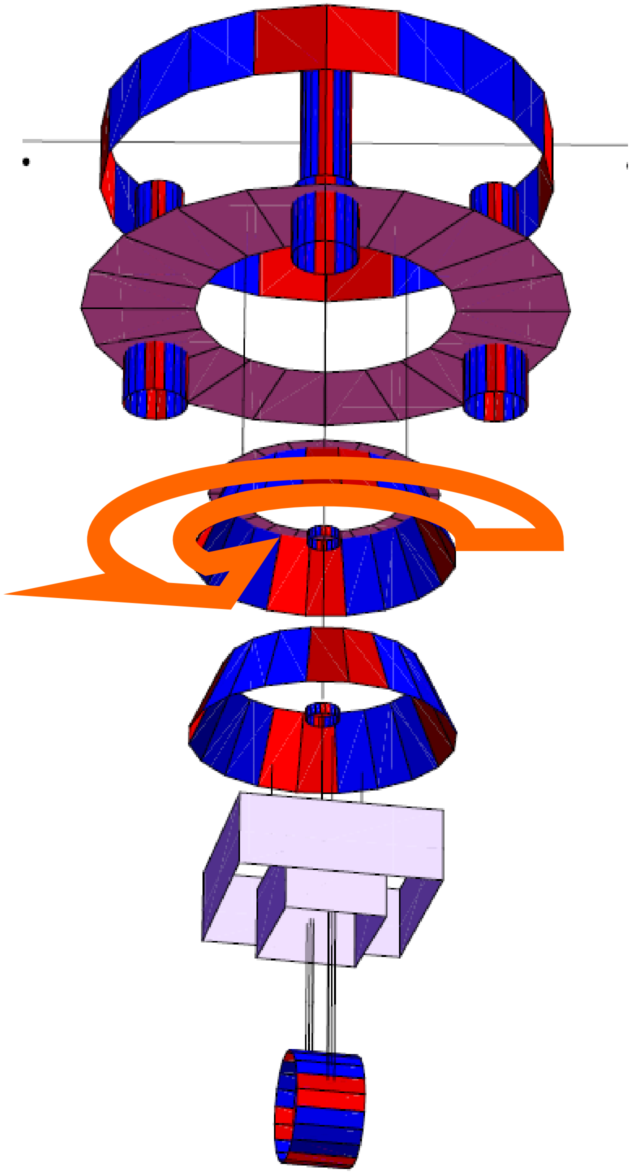
SUMCON allows you to get the response of the system (in terms of transfer functions) for a given force in one degree of freedom or from ground motion.

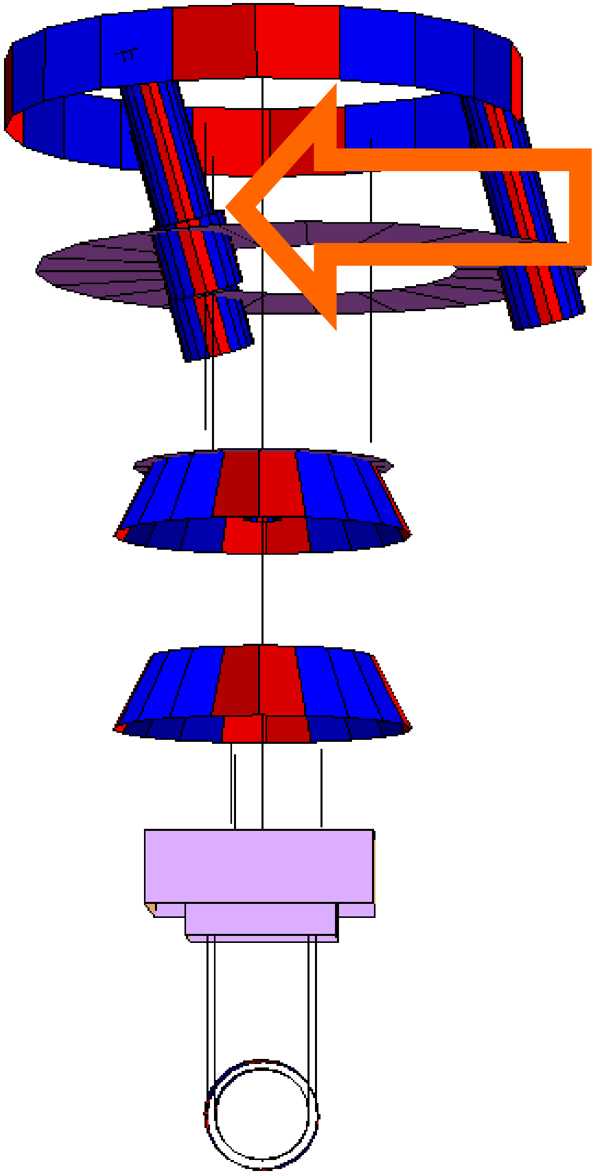
Type B eigenmode list

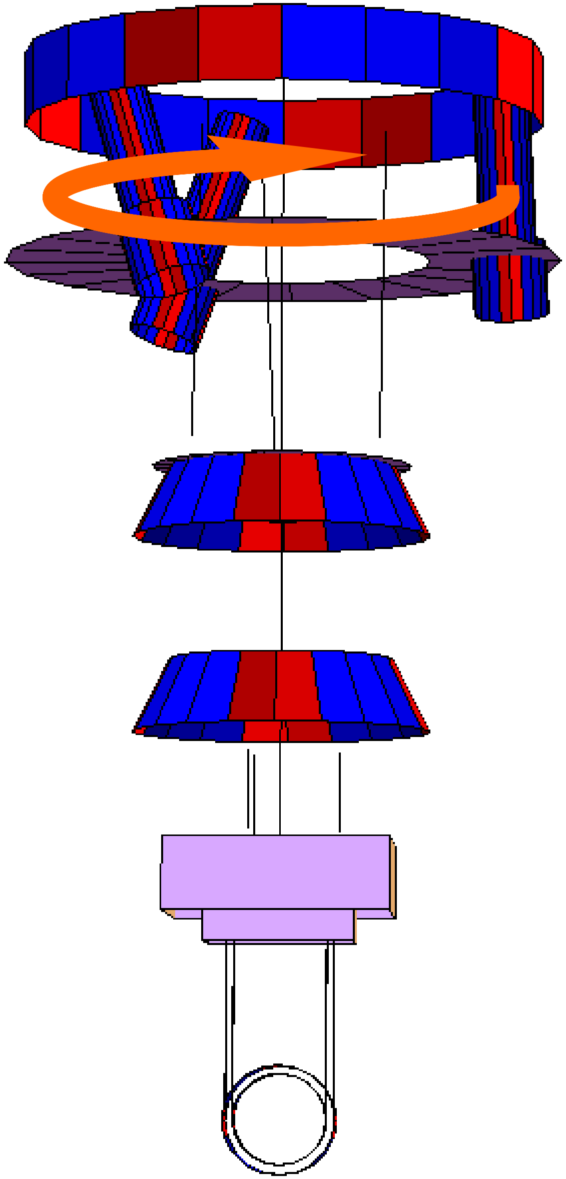


**And more…
The simulation gives 44 eigenmodes up to 100 Hz.**

Type B eigenmodes (Individually)

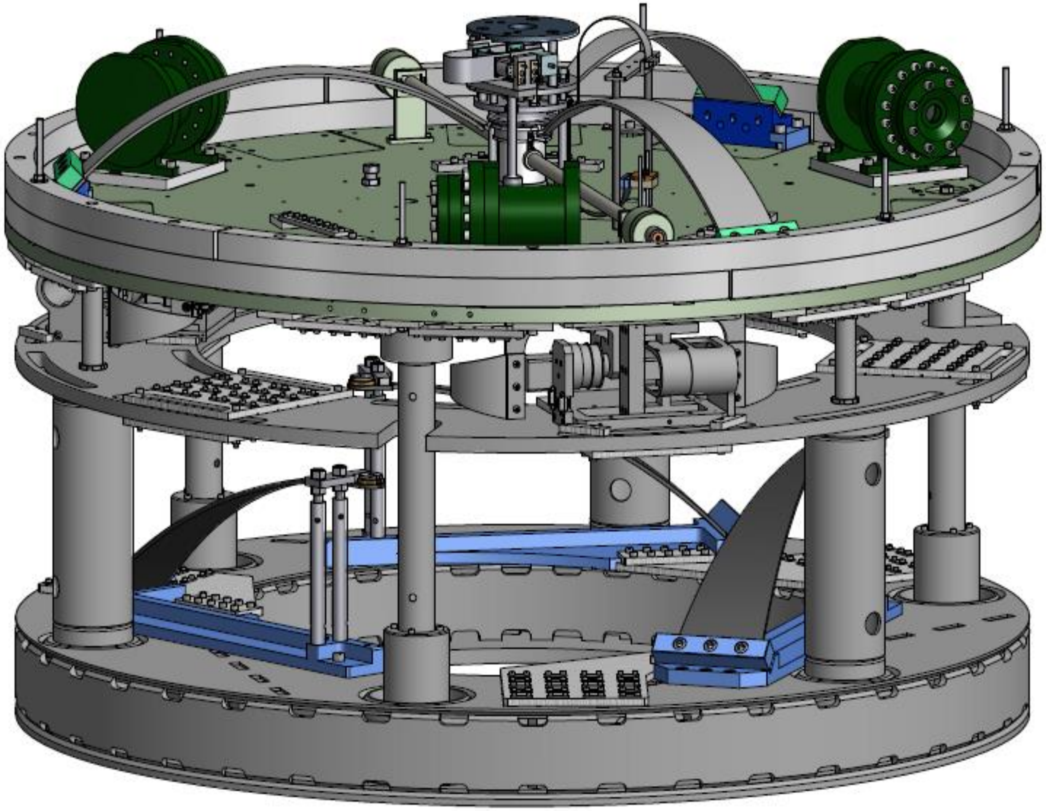

#1 Wire torsion
(0.054 Hz)


#2, 3 IP Translation
(0.063 Hz)

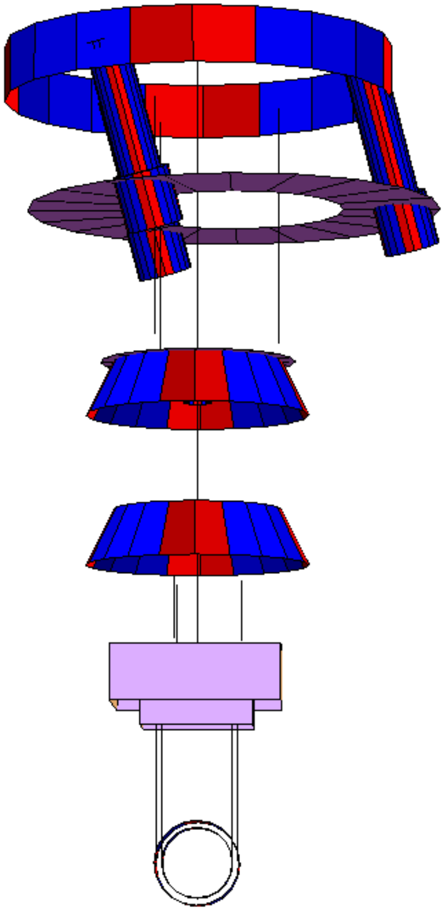

#7 IP Rotation
(0.31 Hz)

Cross-coupling on the IP stage

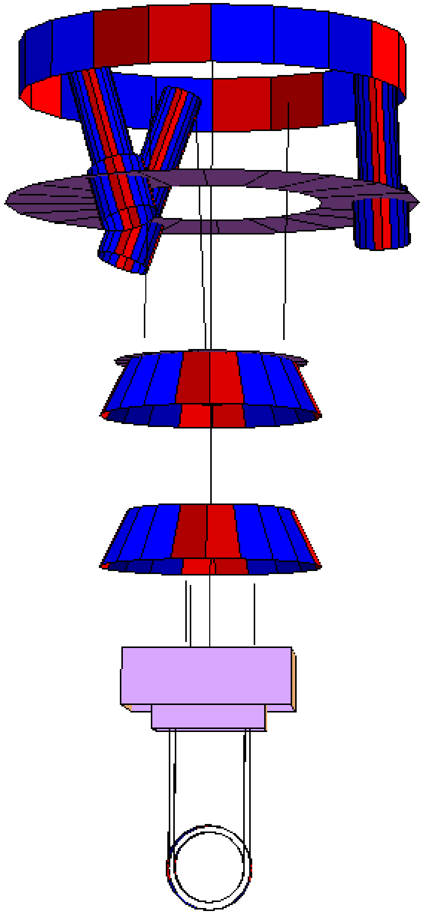
Unlike the ideal system, the suspensions exhibit cross-coupling in their stages. It is necessary to decouple the DoFs.



#2, 3 IP Translation (0.063 Hz)



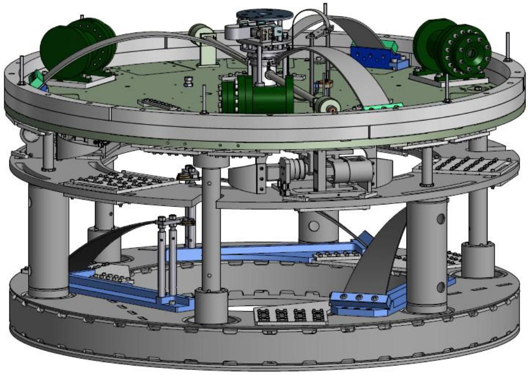
#7 IP Rotation (0.31 Hz)

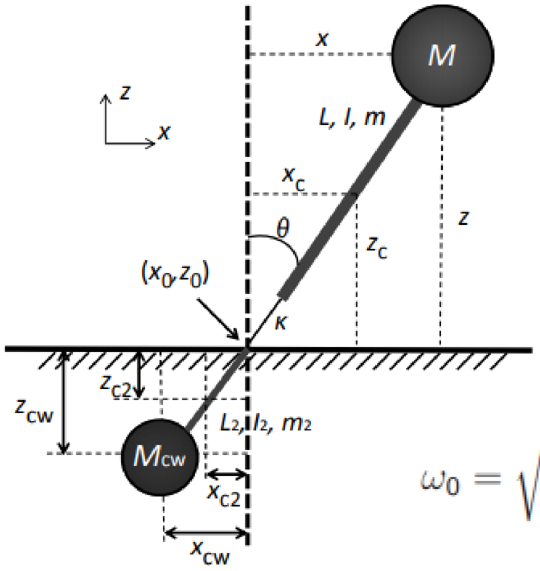


IP frequency tuning

But first...

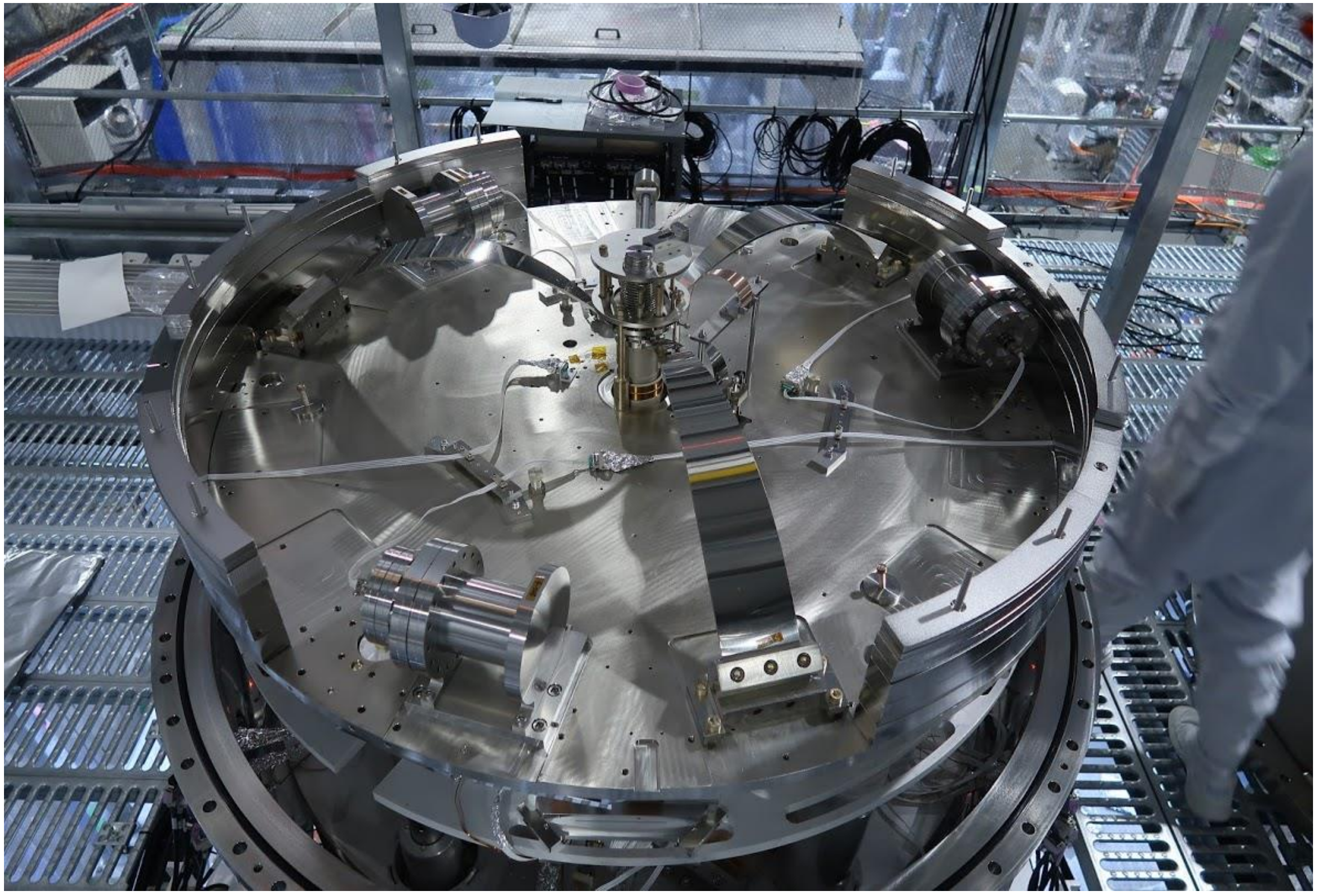
Add mass on the IP table to get a lower resonant frequency.



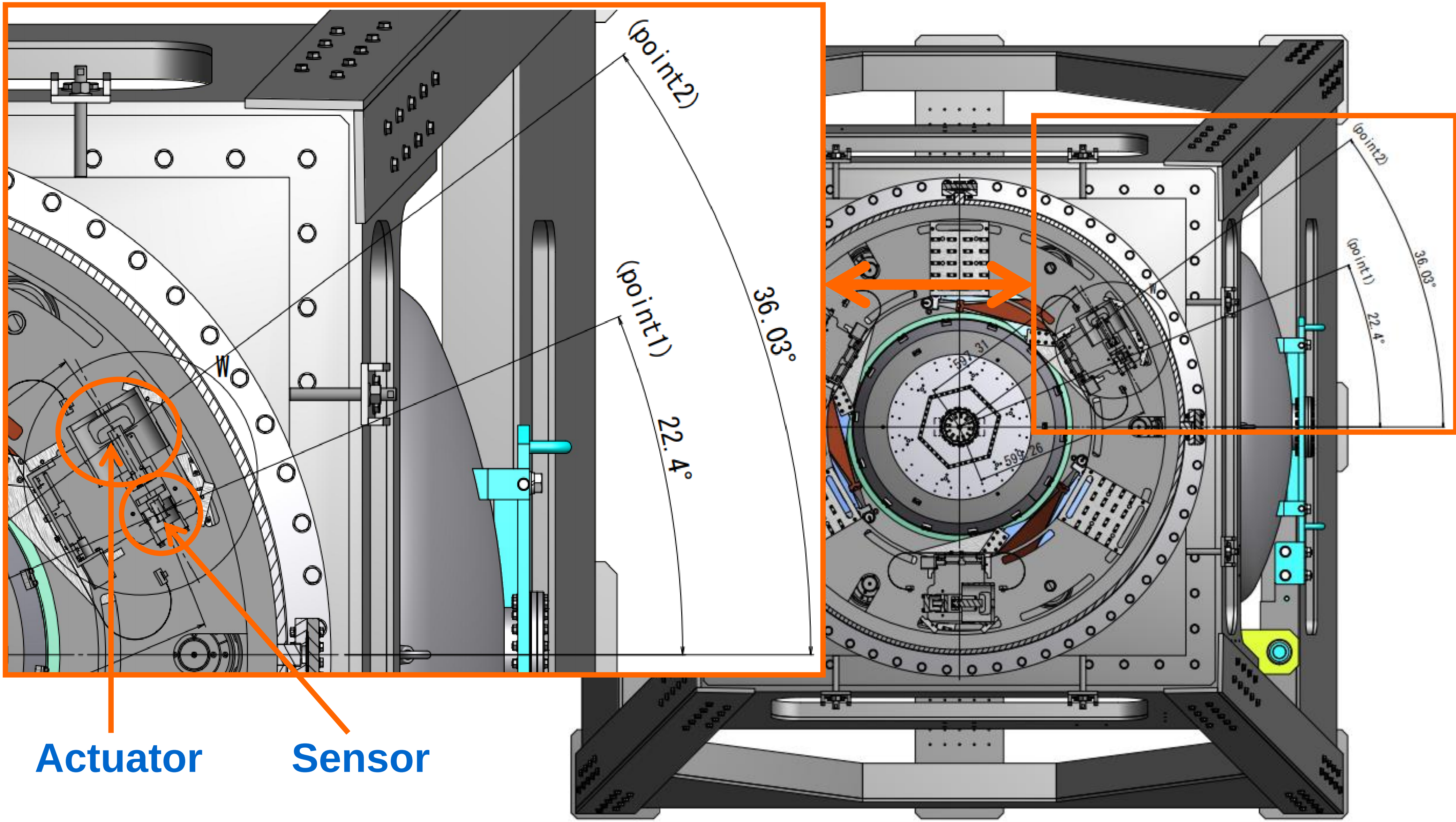


$$\omega_0 = \sqrt{\frac{k}{M} - \frac{g}{L}}$$

By M. Blom. Ref 5.

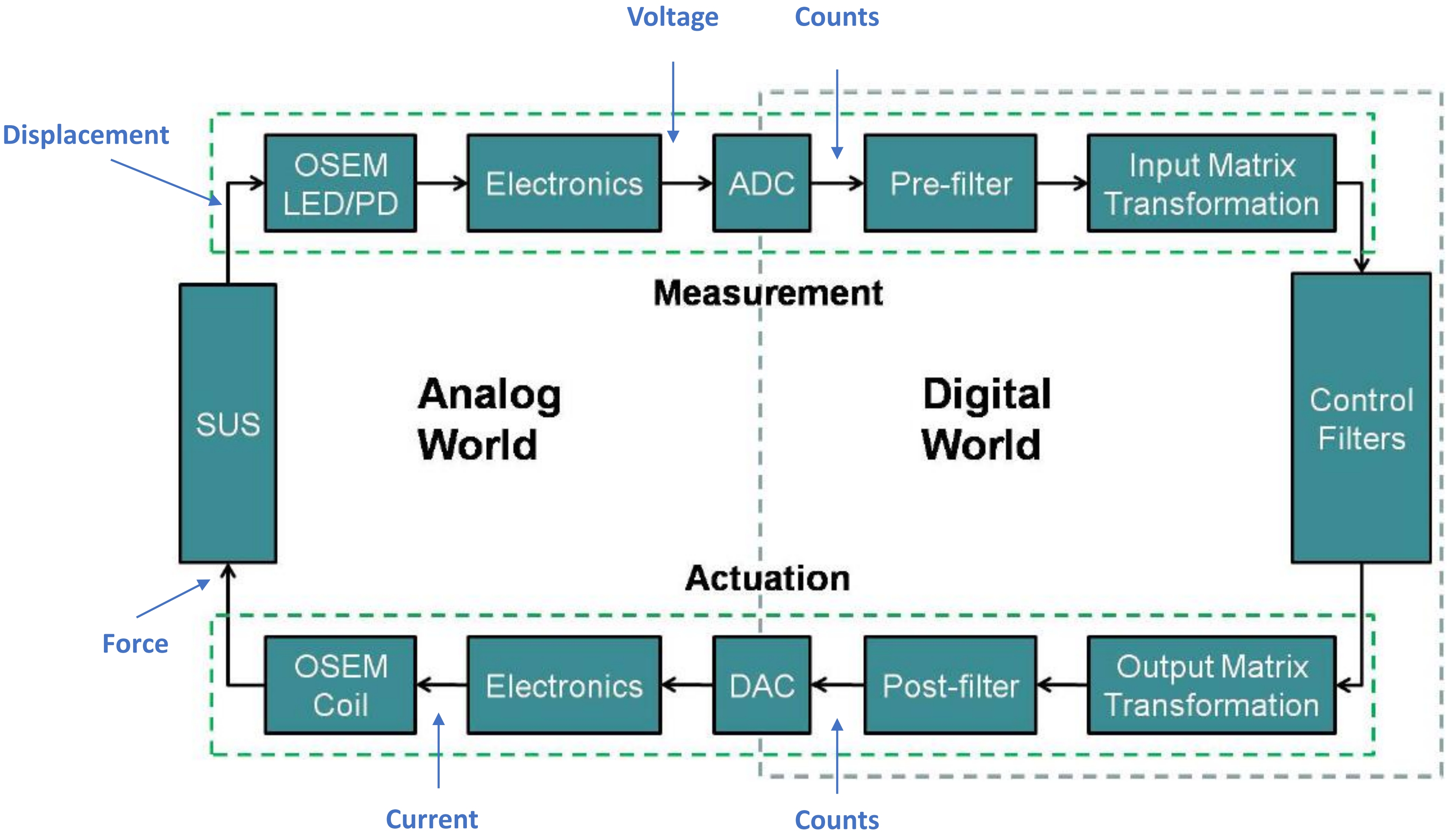


IP sensor/actuator diagonalization



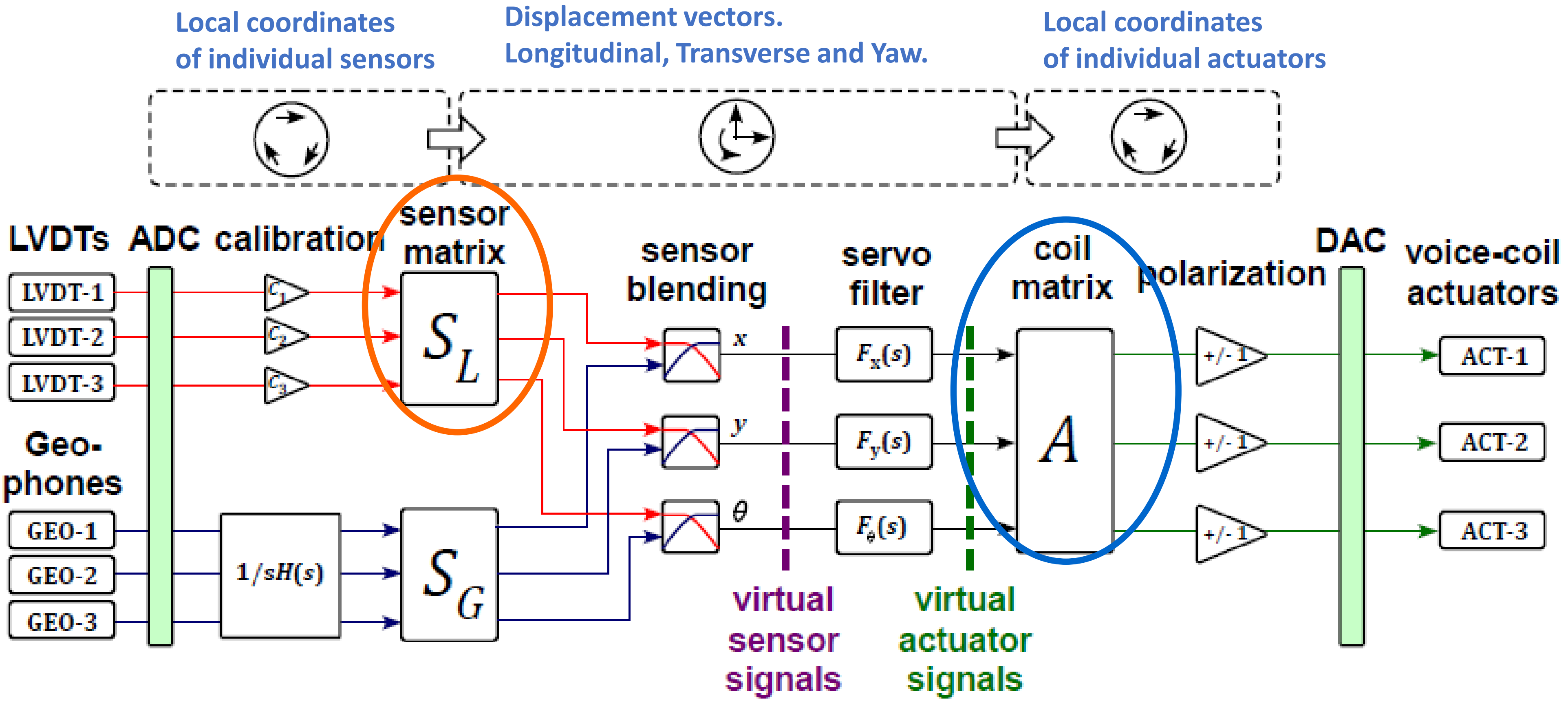
**Cross section view of a Type B system (from the top).
Sensors and actuators of the IP at different positions.**

Analog-Digital diagram



By B. Shapiro. Ref 1.

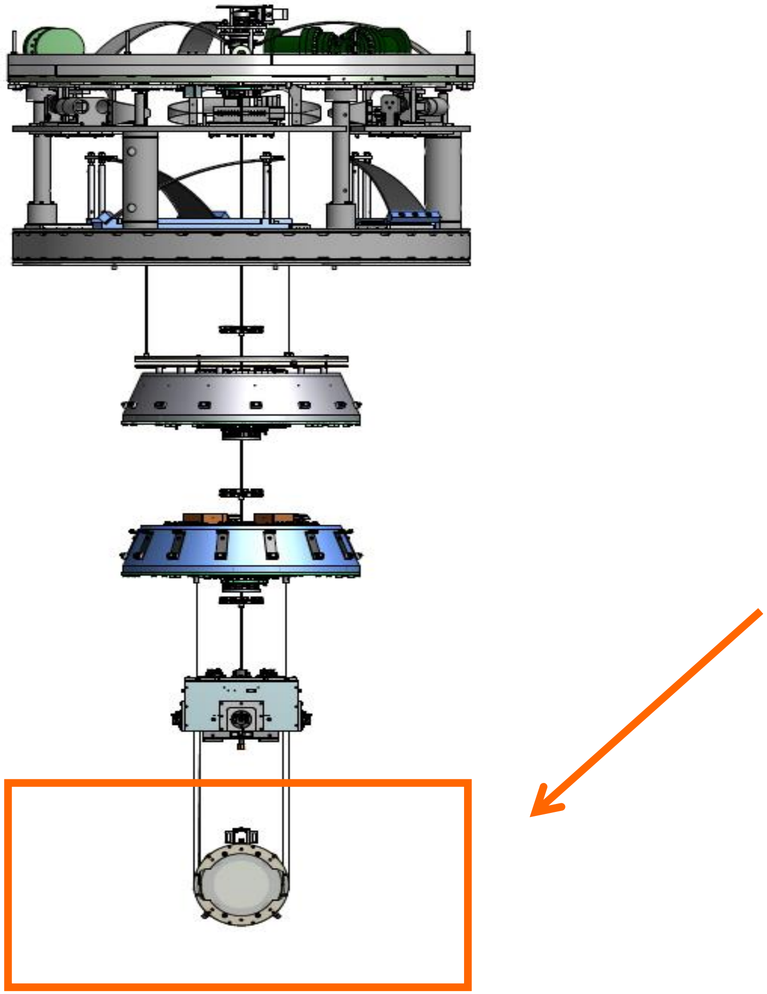
IP sensor/actuator diagonalization



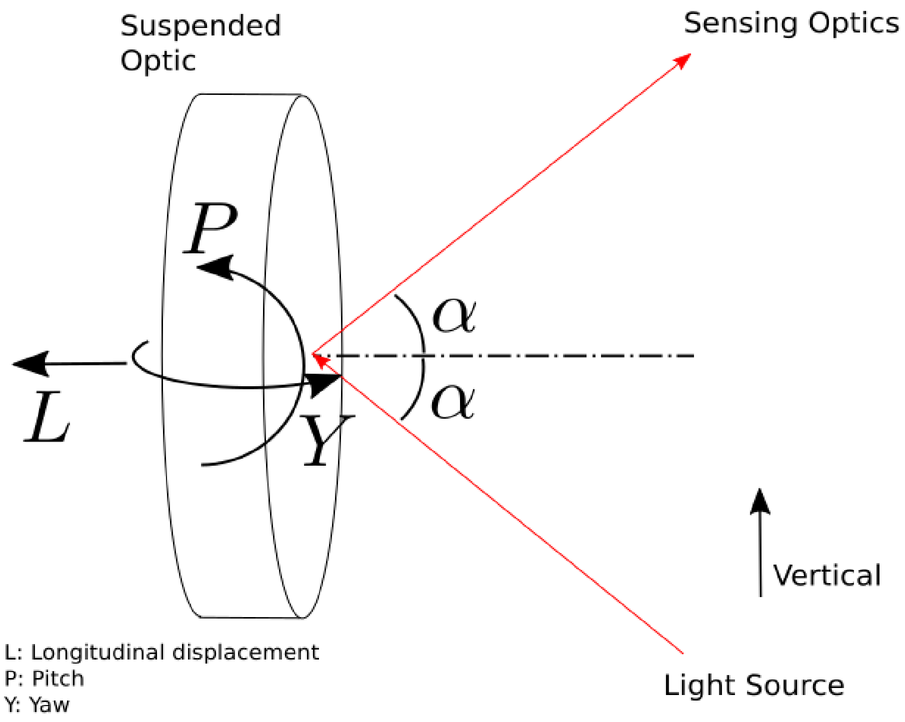
By T. Sekiguchi. Ref 2.

Measure the motion of the IP stage when injecting a signal at a single frequency at each coil, using the sensing matrix.
Get the TF coefficients for each DoF and compute the TF coefficients matrix.
Use the inverse of this matrix as the new coil matrix.

Mirror Displacement Sensing (Optical Lever)



Motion of the suspended mirror



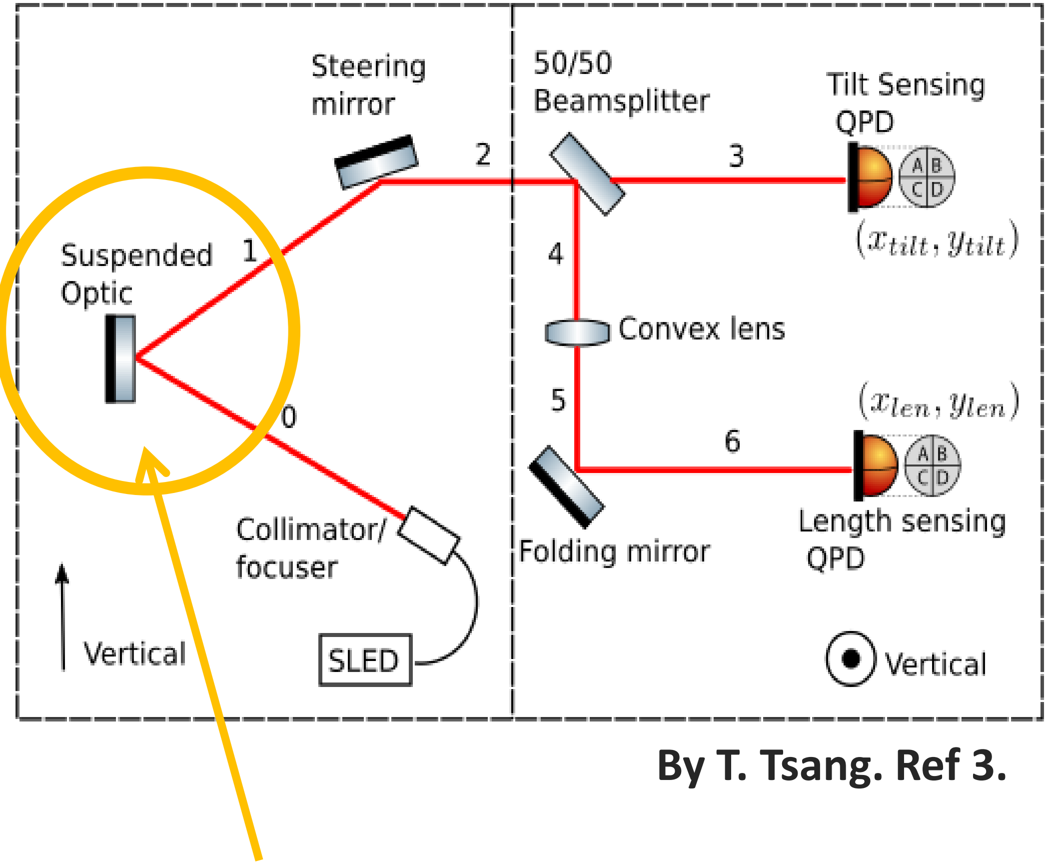
L: Longitudinal displacement
P: Pitch
Y: Yaw

By T. Tsang. Ref 3.

A Type B suspension with its security structure assembled

Mirror Displacement Sensing (Optical Lever)

QPD: Quadrant photodiode



By T. Tsang. Ref 3.

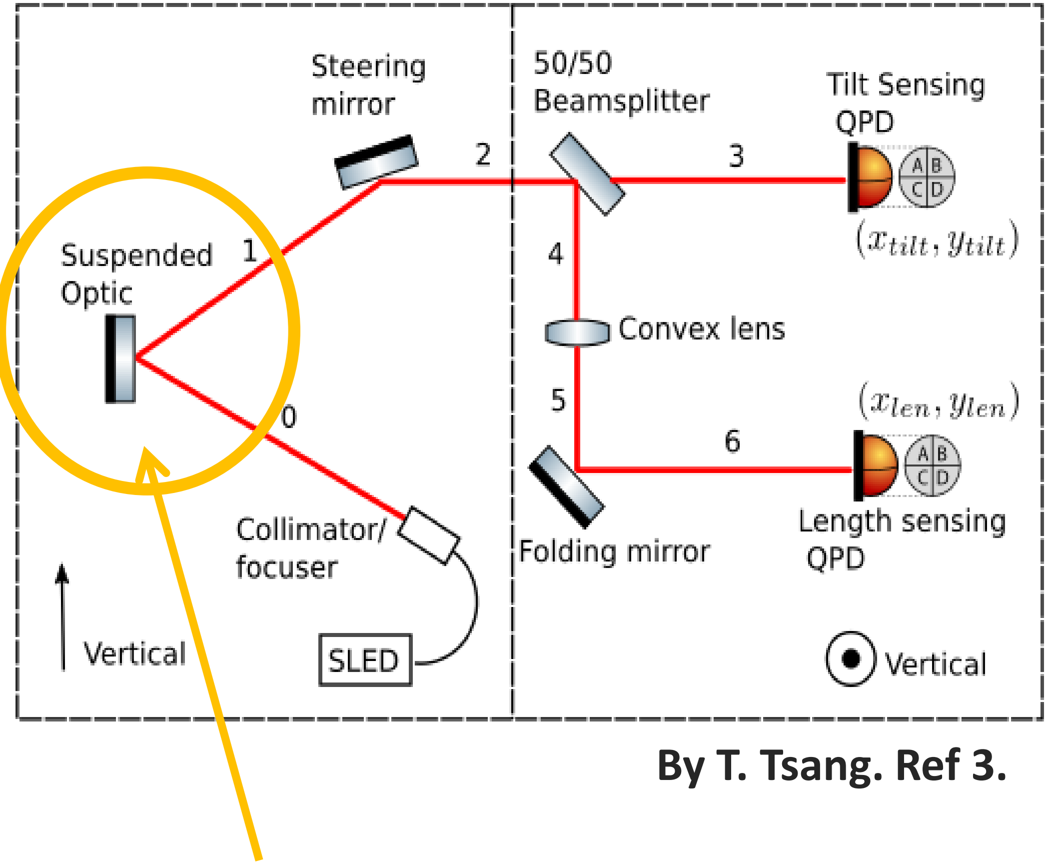
SRM, SR2 or SR3

In the ideal case, an actual motion in Pitch or Yaw, produces a variation in the readout of the Tilt QPD. Then this beam spot displacement can be decompose into Pitch and Yaw motion.

And an actual longitudinal motion, produces a variation in the readout of the Length QPD. Then from this beam spot displacement is possible to calculate the Longitudinal motion.

Mirror Displacement Sensing (Optical Lever)

QPD: Quadrant photodiode



By T. Tsang. Ref 3.

SRM, SR2 or SR3

Tilt (Pitch and Yaw) sensing QPD:

$$\begin{pmatrix} X_b \\ \theta_b \end{pmatrix} = \begin{pmatrix} 1 & r \\ 0 & 1 \end{pmatrix} \begin{pmatrix} X_a \\ \theta_a \end{pmatrix} \qquad r = 1 + 2 + 3$$

Length sensing QPD:

$$\begin{pmatrix} X_b \\ \theta_b \end{pmatrix} = \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{-1}{f} & 1 \end{pmatrix} \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} \begin{pmatrix} X_a \\ \theta_a \end{pmatrix}$$

$$= \begin{pmatrix} 1 - \frac{d}{f} & d + l\left(1 - \frac{d}{f}\right) \\ \frac{-1}{f} & 1 - \frac{l}{f} \end{pmatrix} \begin{pmatrix} X_a \\ \theta_a \end{pmatrix}.$$

$$l = 1 + 2 + 4 \qquad d = 5 + 6$$

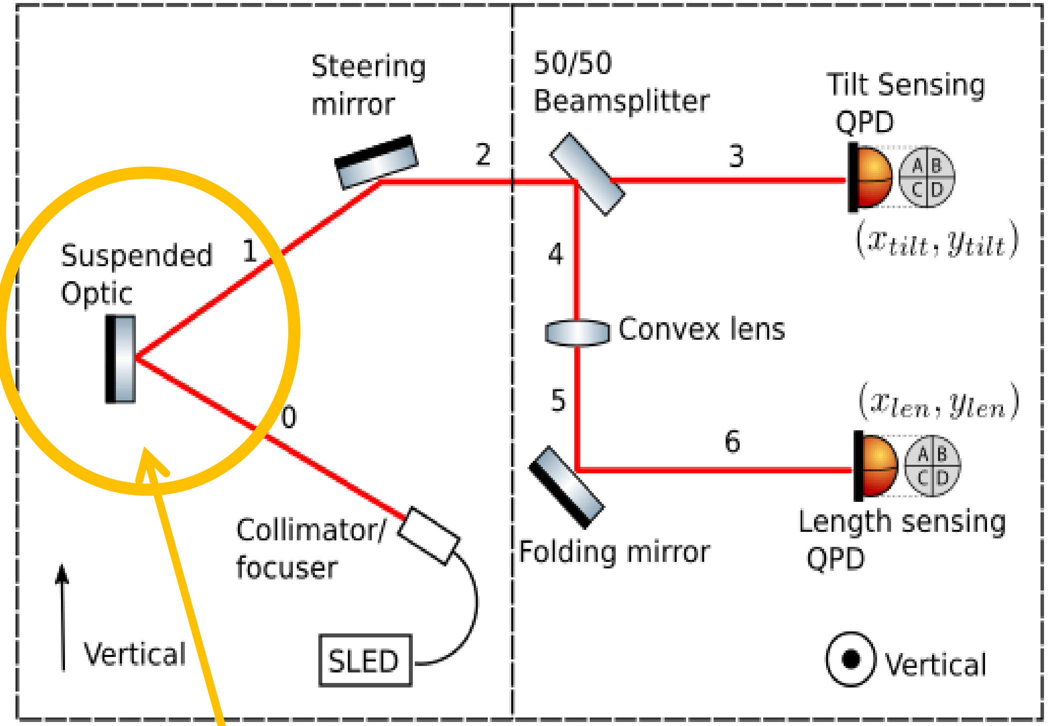
Choosing $d = \frac{lf}{l-f}$ **(Image plane) We get:**

$$X_b = \left[1 - \frac{\left(\frac{lf}{l-f}\right)}{f} \right] X_a = \left(\frac{-f}{l-f} \right) X_a$$

In this way the length sensing QPD is only sensitive to longitudinal displacement. See reference 3 (by T. Tsang).

Mirror Displacement Sensing (Optical Lever)

QPD: Quadrant photodiode



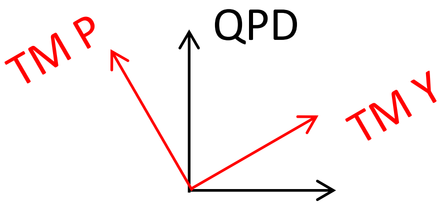
By T. Tsang. Ref 3.

SRM, SR2 or SR3

But in reality Longitudinal, Pitch and Yaw are all cross-coupled. So a diagonalization to decouple these three motions is required.

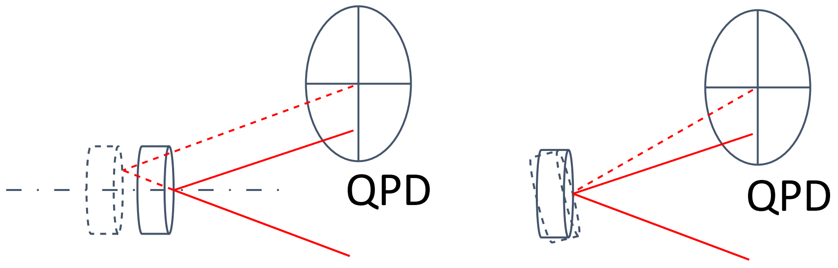
Cross-coupling origins

1. Pitch to Yaw or Yaw to Pitch:



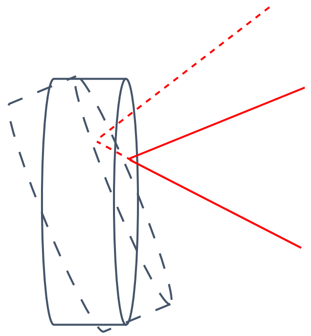
Due to misaligment.
(Ex: Tilt in steering mirror)

2. Longitudinal to Tilt:



Due to non-zero angle of incidence.
(Pitch and Yaw)

3. Tilt to Longitudinal:



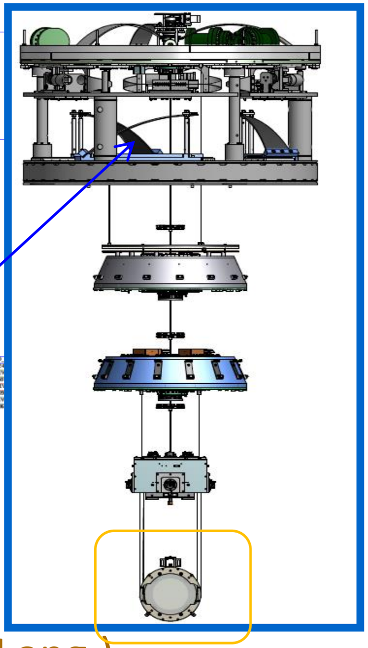
Due to off-centered beam.

4. Others:

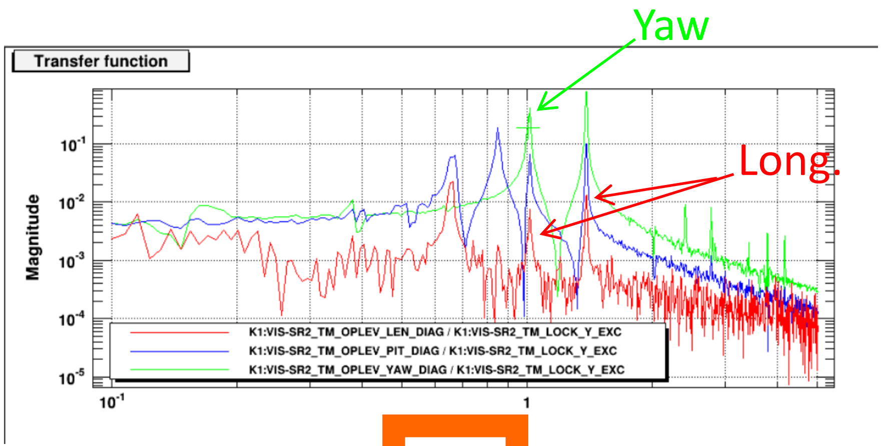
E.g. Misplacement of Length sensing QPD, etc

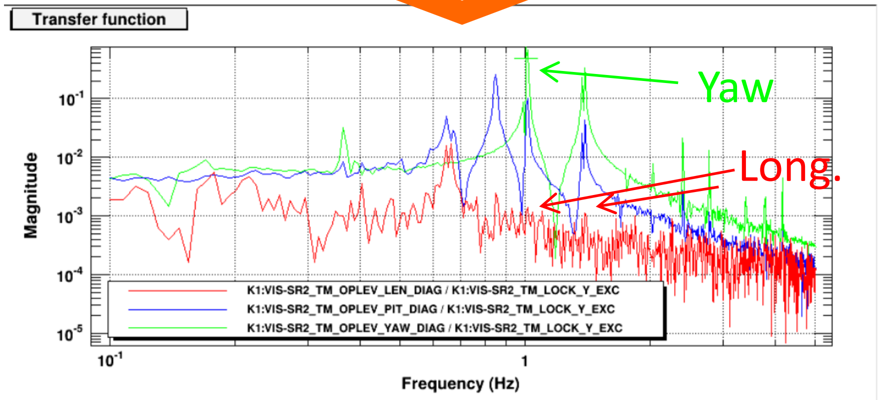
See reference 3 (by T. Tsang).

Diagonalization

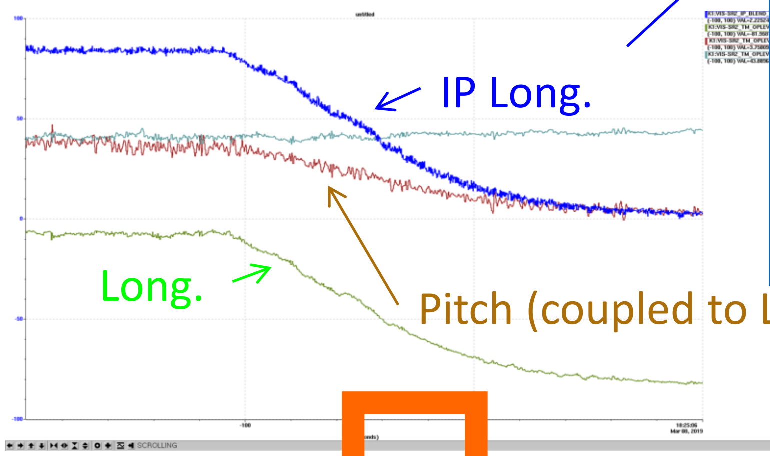


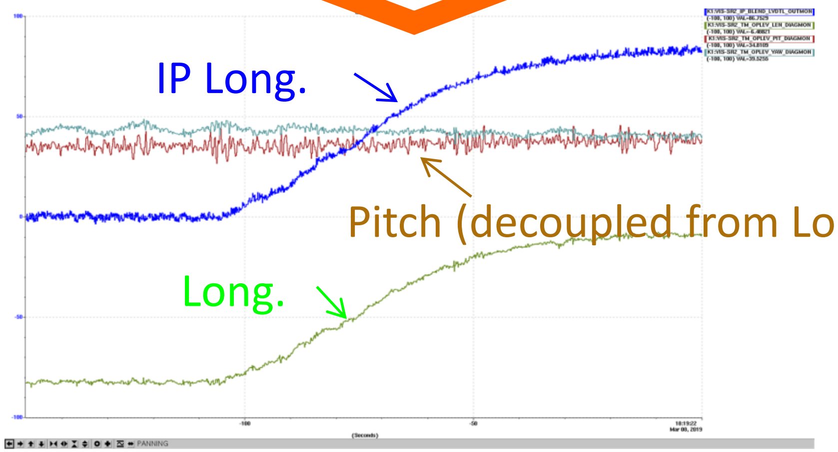
Yaw to Longitudinal coupling:





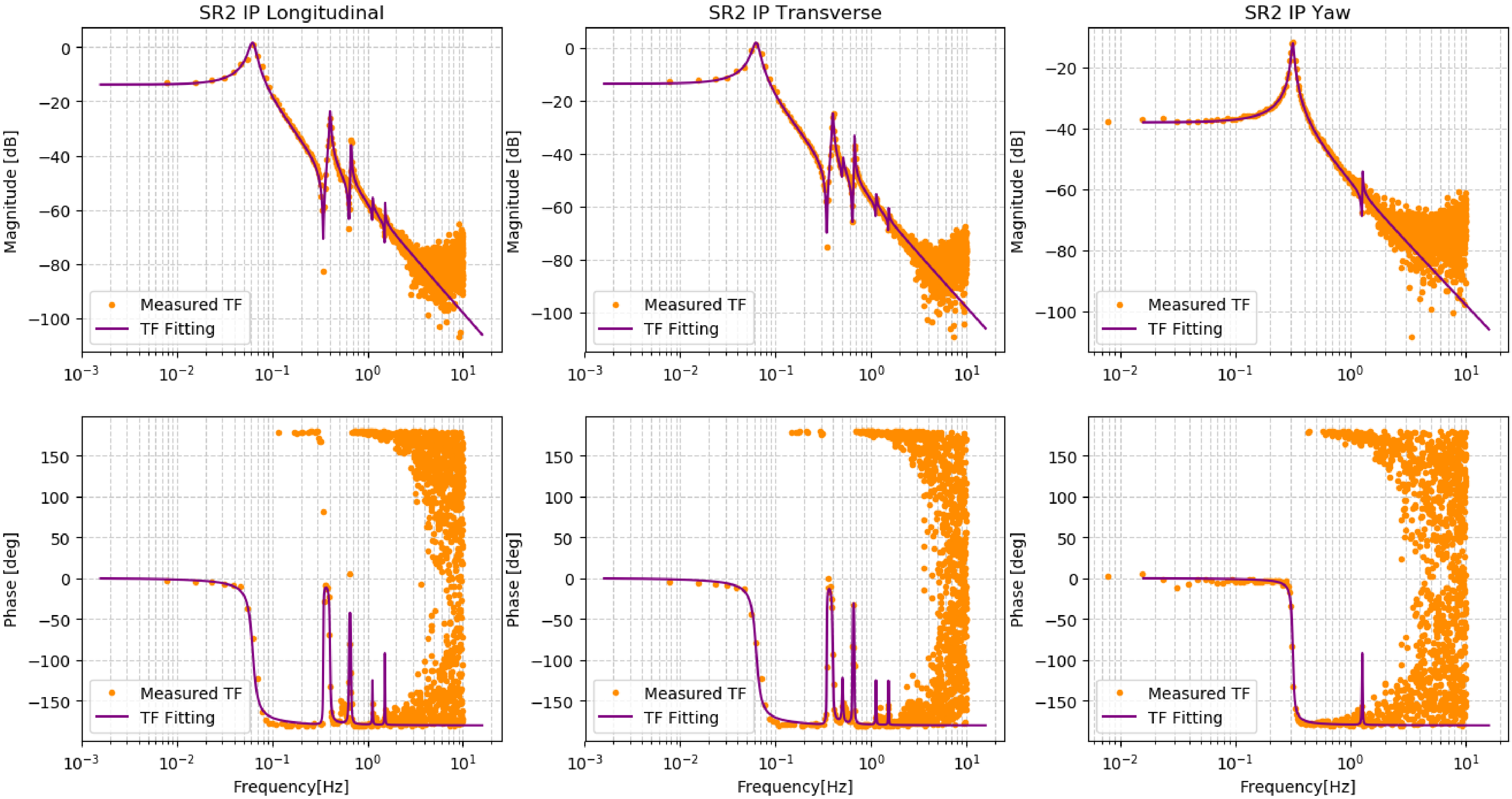
Longitudinal Pitch coupling:





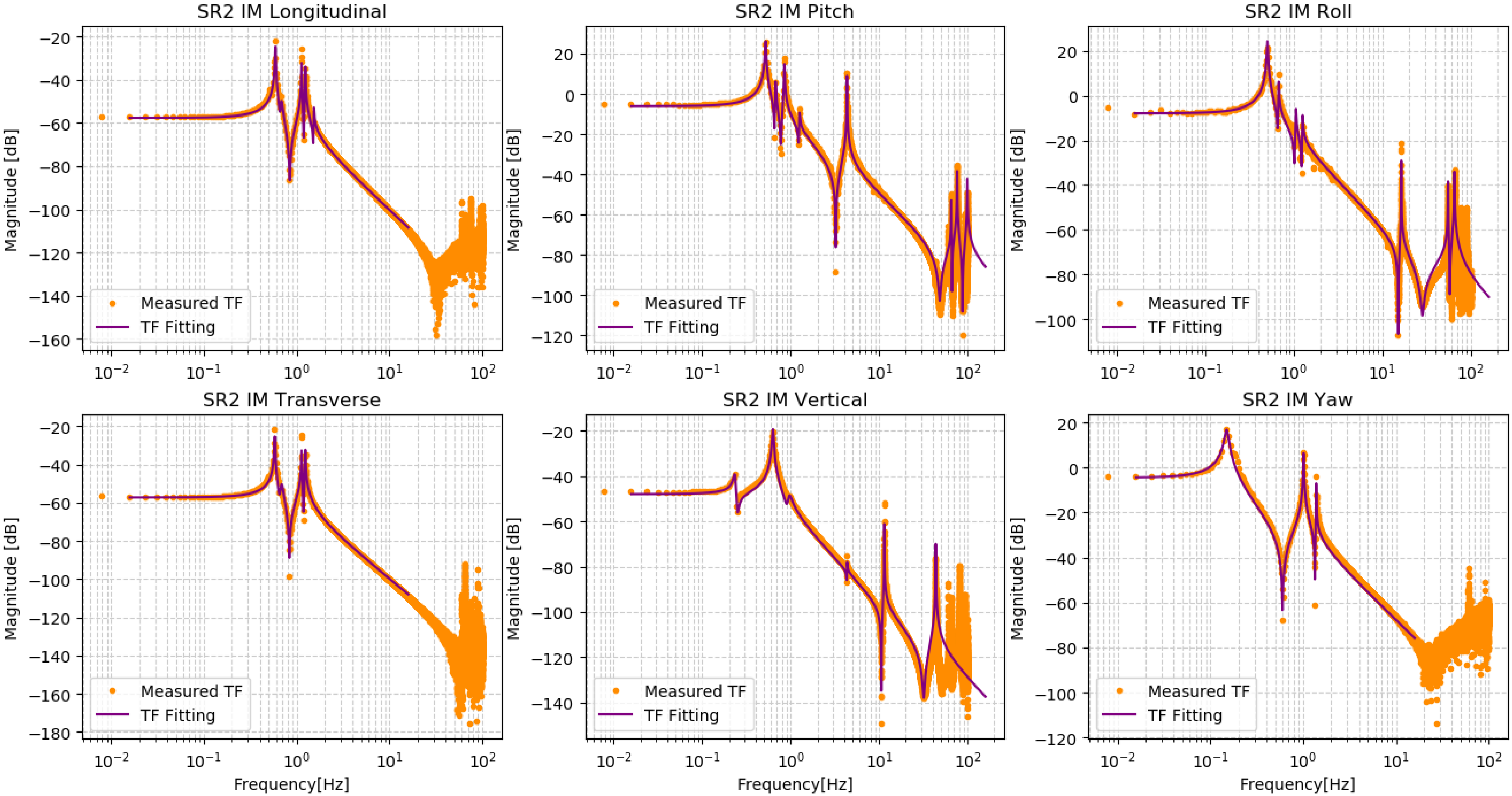
By T. Tsang. Ref 3.

Transfer functions of the system



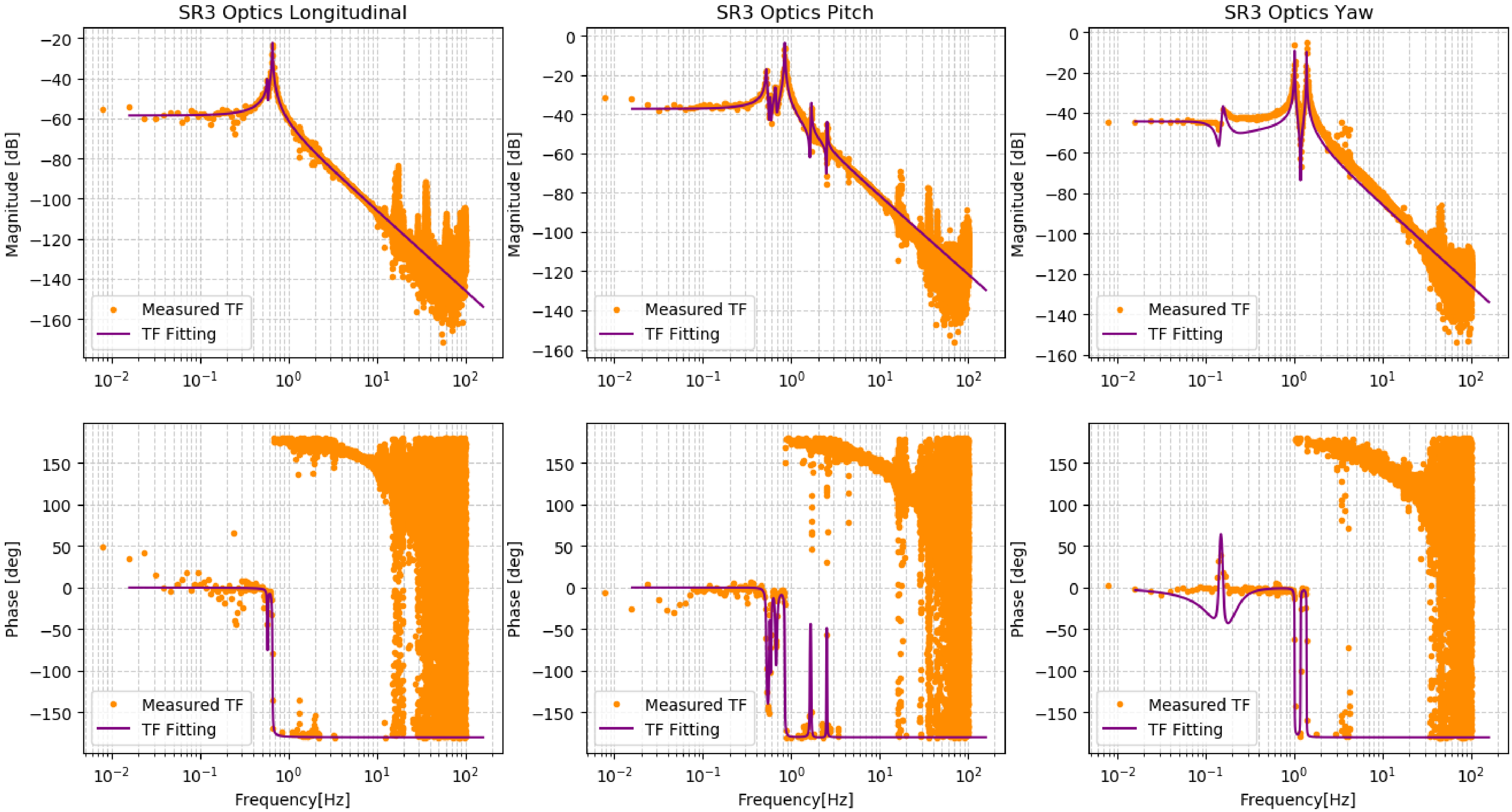
IP stage ZPK (zero, pole and gain) fitting to help with the design of active filters.

Transfer functions of the system



IM stage ZPK (zero, pole and gain) fitting to help with the design of active filters.

Transfer functions of the system



Mirror stage ZPK (zero, pole and gain) fitting to help with the design of active filters.

Sensing is ready

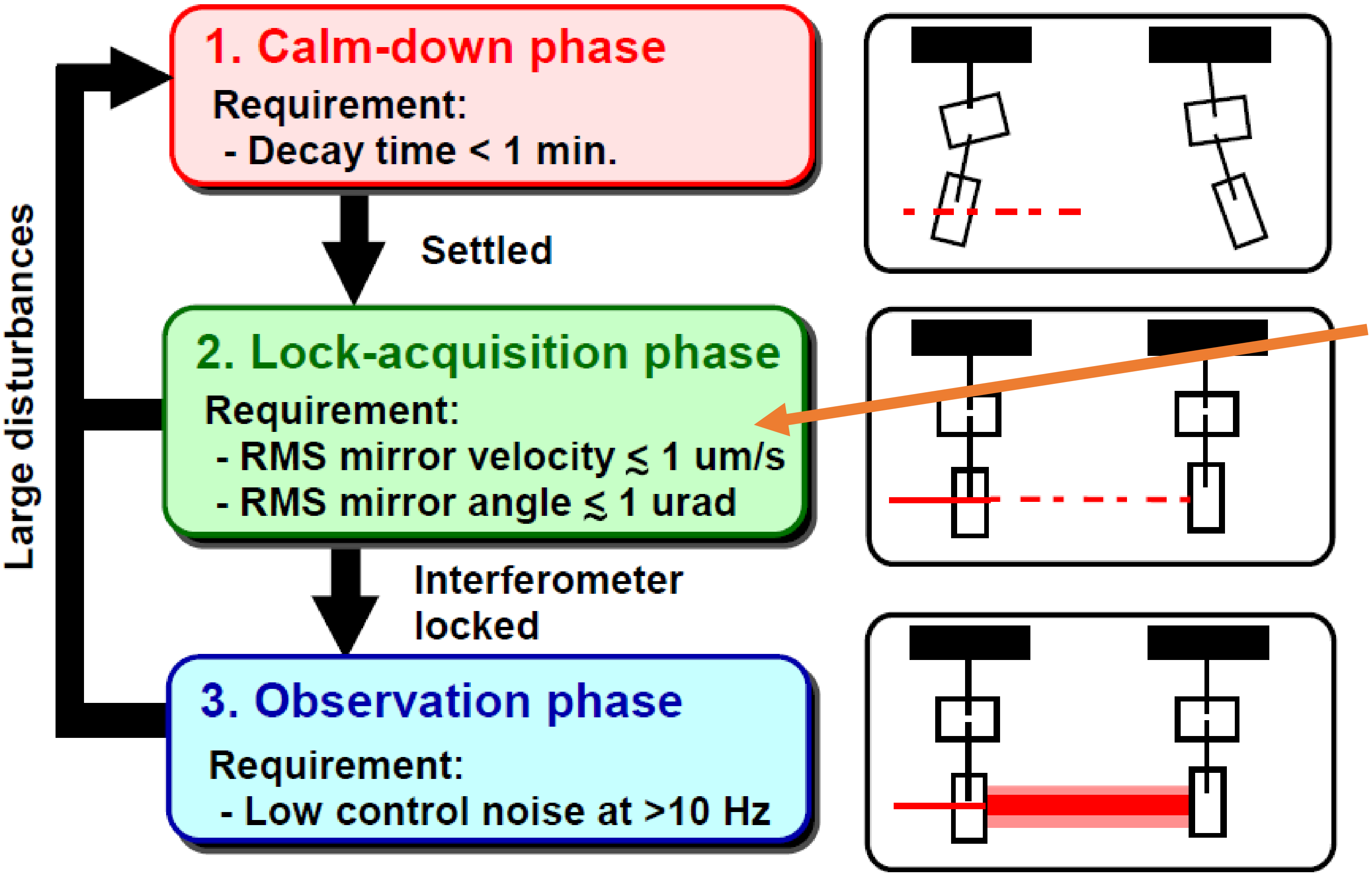
Now is possible to measure all the different degrees of freedom (15), that we can actuate.

Studying the transfer function shapes of the system, is possible to know wether is healthy or not. The system must not touch or rub any surroundng security structure.

Commissioning: How to make these systems work as designed and integrate them to all other subsystems in order to run the interferometer.

Performance: I the system meeting the requirements to run the interferometer and to have its expected sensitivity?

Requirements



1. Calm-down phase

Requirement:
- Decay time < 1 min.

2. Lock-acquisition phase

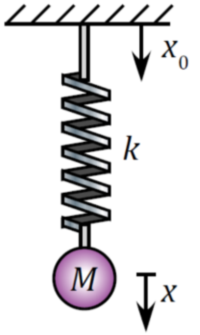
Requirement:
- RMS mirror velocity ≲ 1 um/s
- RMS mirror angle ≲ 1 urad

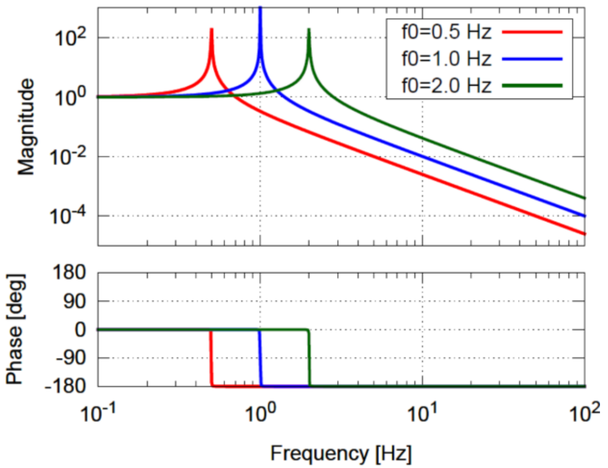
3. Observation phase

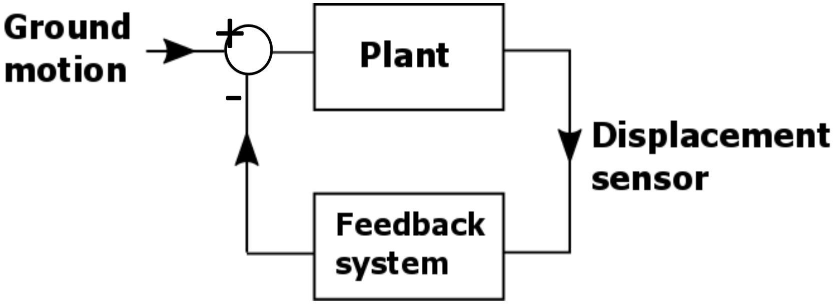
Requirement:
- Low control noise at >10 Hz

Requirement updated:
0.5 μm/s.

Local Control Required





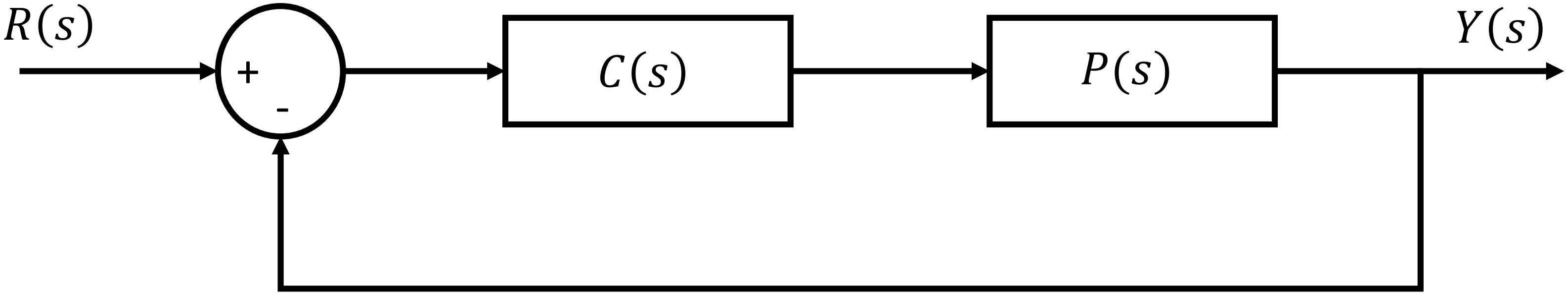


EoM $M\ddot{x} = -k(x - x_0)$

Laplace transformation

Reference or Setpoint

Output Actual displacement

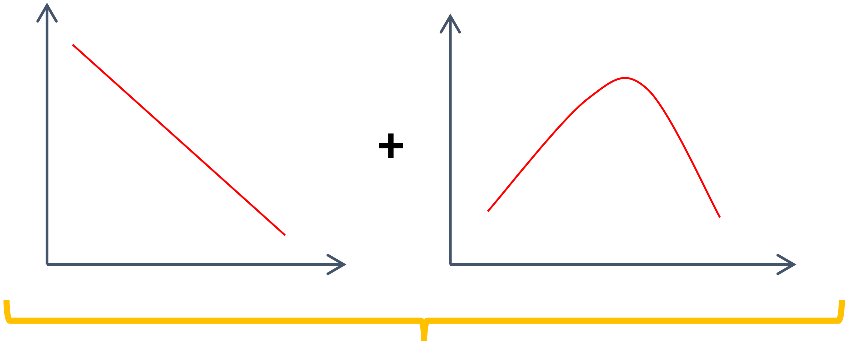


Transfer function $$\frac{Y(s)}{R(s)} = \frac{C(s)P(s)}{1 + C(s)P(s)}$$

It can be written in terms of Poles and Zeros. It is used to study the stability of the closed loop system.

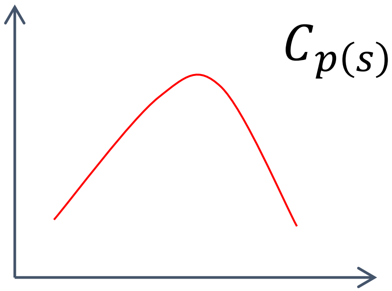
Local Control Required

Position control + Damping control

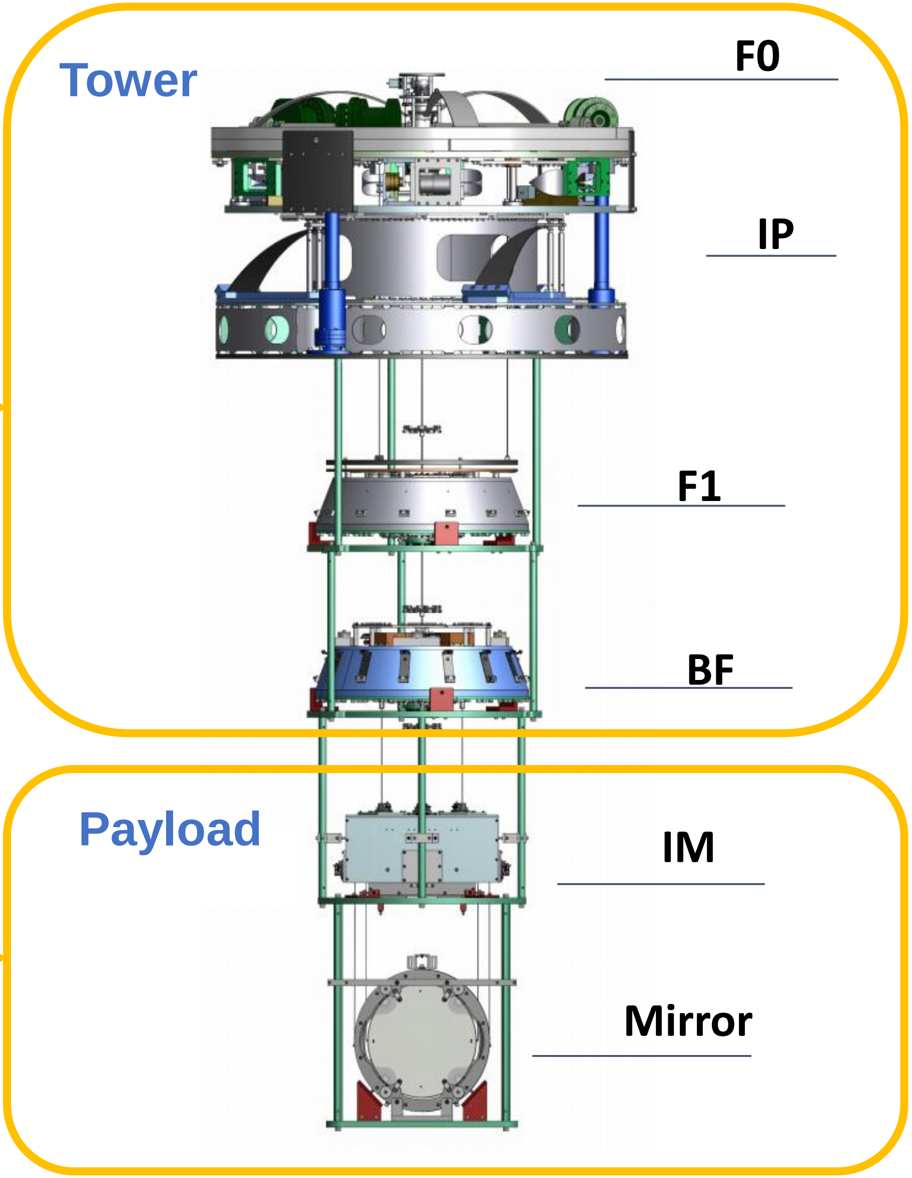


$C_{t(s)}$

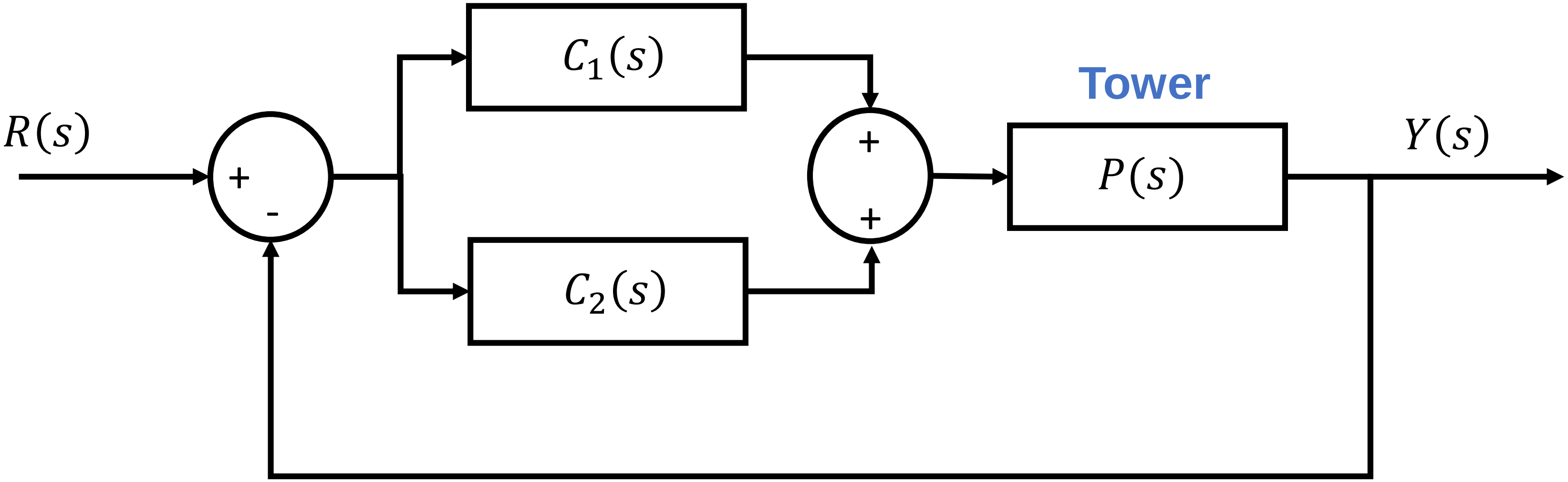
Damping control

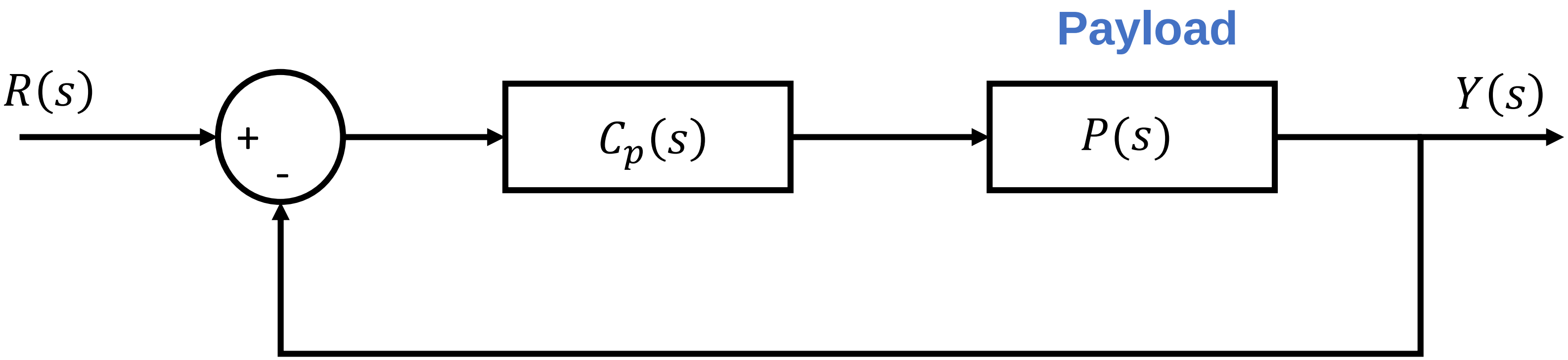


$C_{p(s)}$



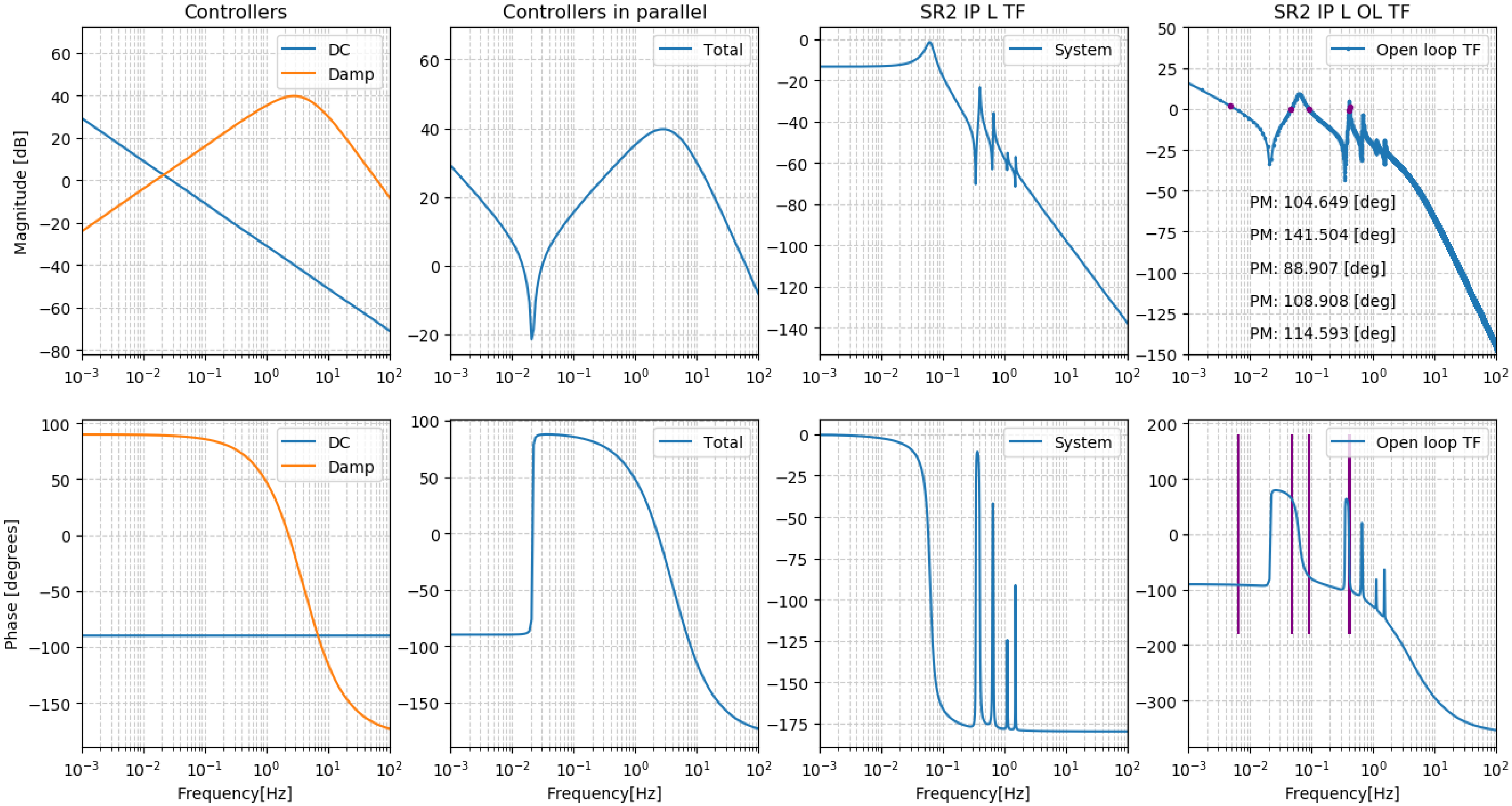
Damping of the modes stage by stage





Check of control loop stability

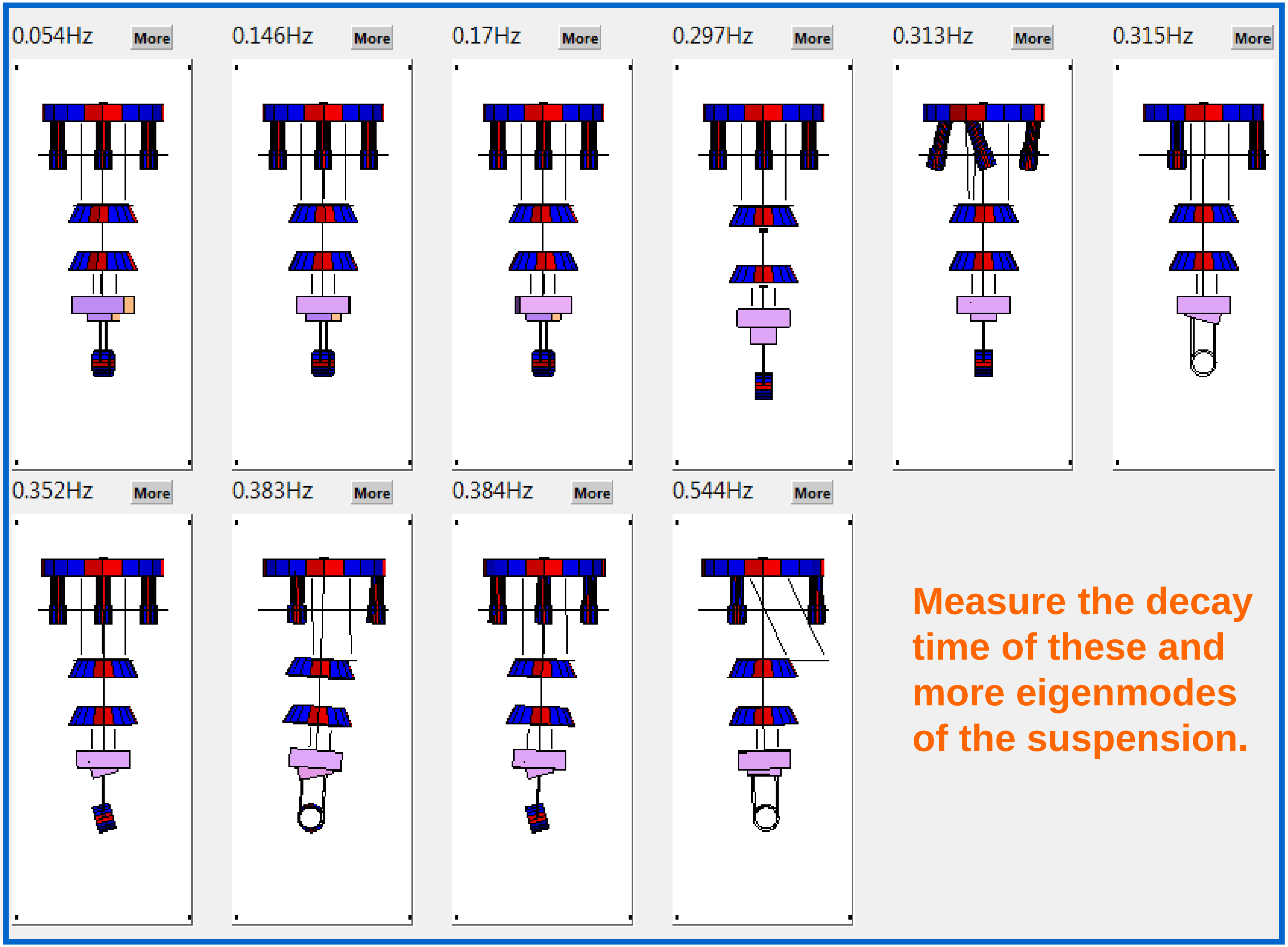
$C_{1(s)}$ **and** $C_{2(s)}$ $C_{t(s)}$ $P(s)$ $C_{t(s)}P(s)$



Example: SR2 IP Longitudinal.

Open loop TF

Decay time of the eigenmodes



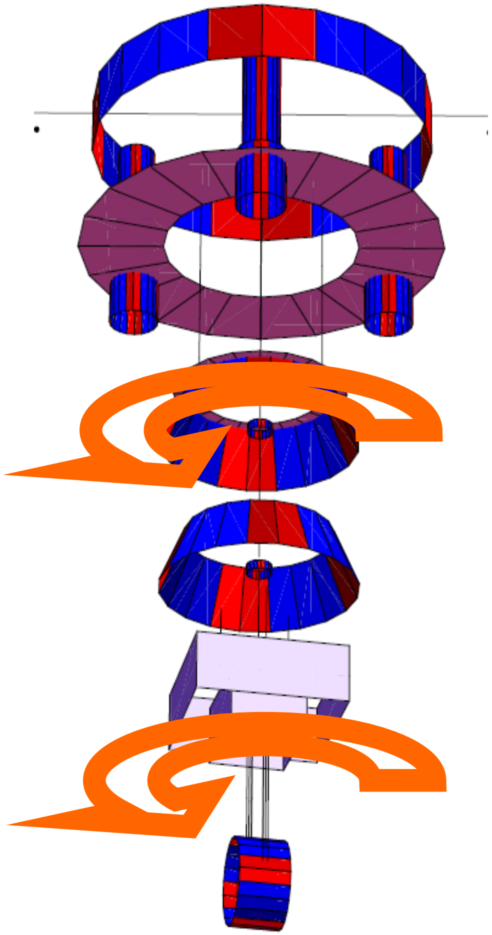
Measure the decay time of these and more eigenmodes of the suspension.

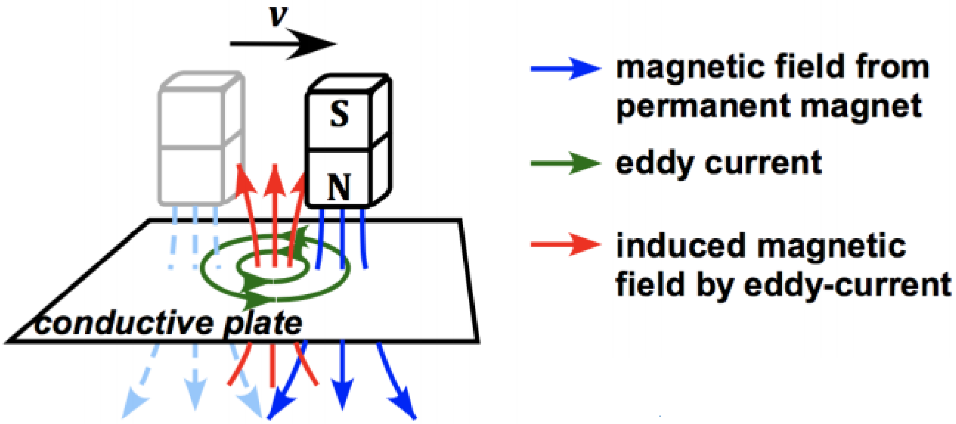
Damping of the torsion mode (#1)

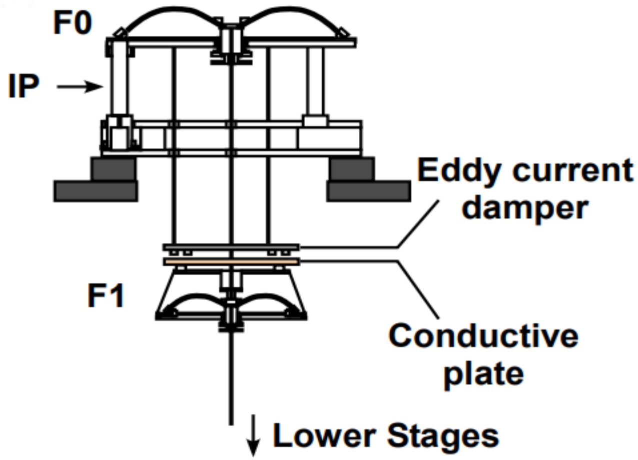
High quality factor means long decay time.

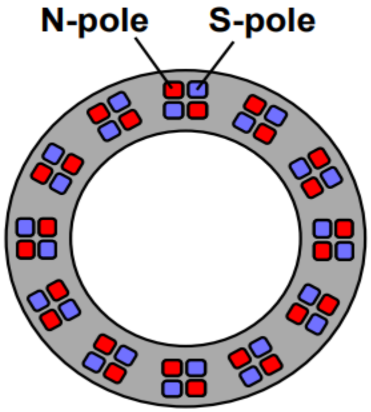
Torsion mode is passively damped by the eddy current damper.

#1 Wire torsion (0.054 Hz)



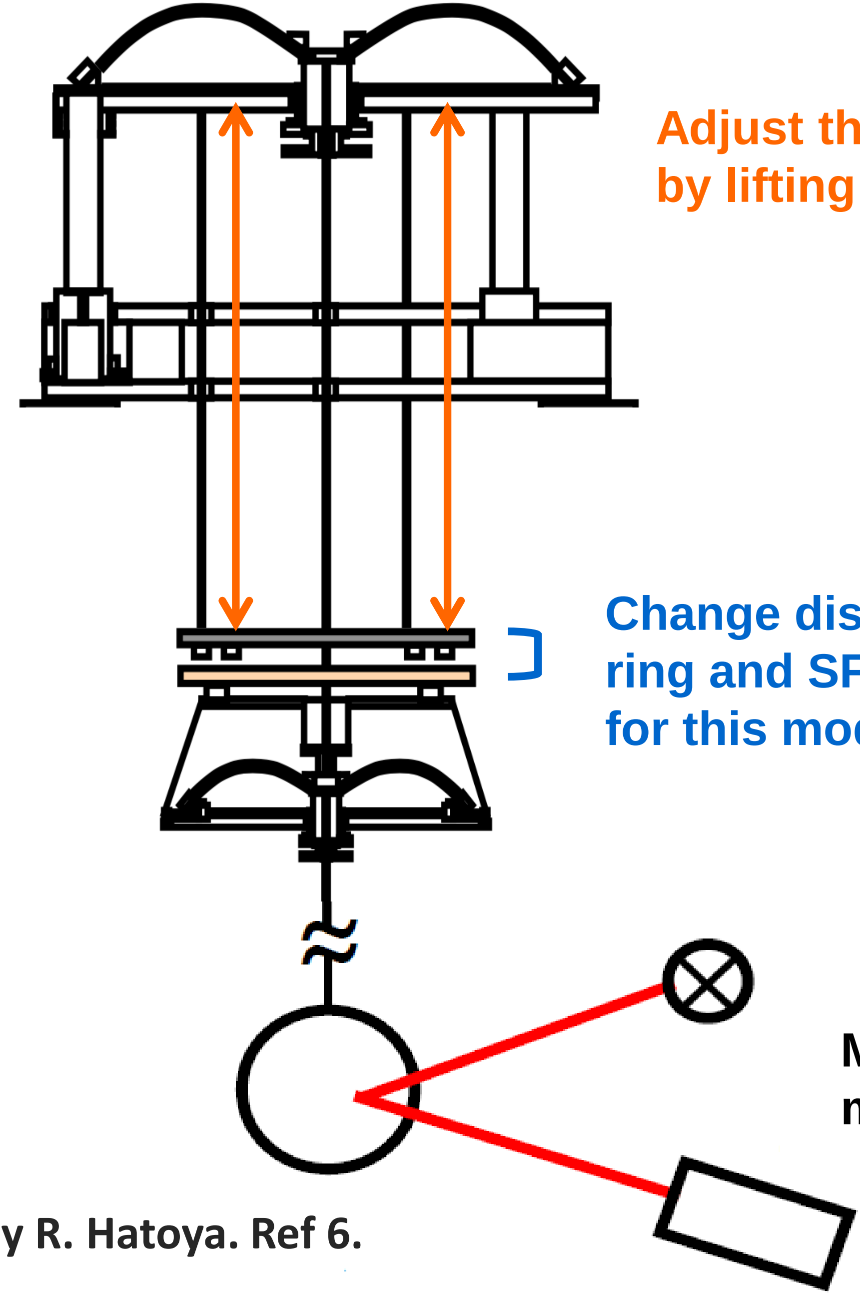






By R. Hatoya. Ref 6.

Damping of the torsion mode (#1)



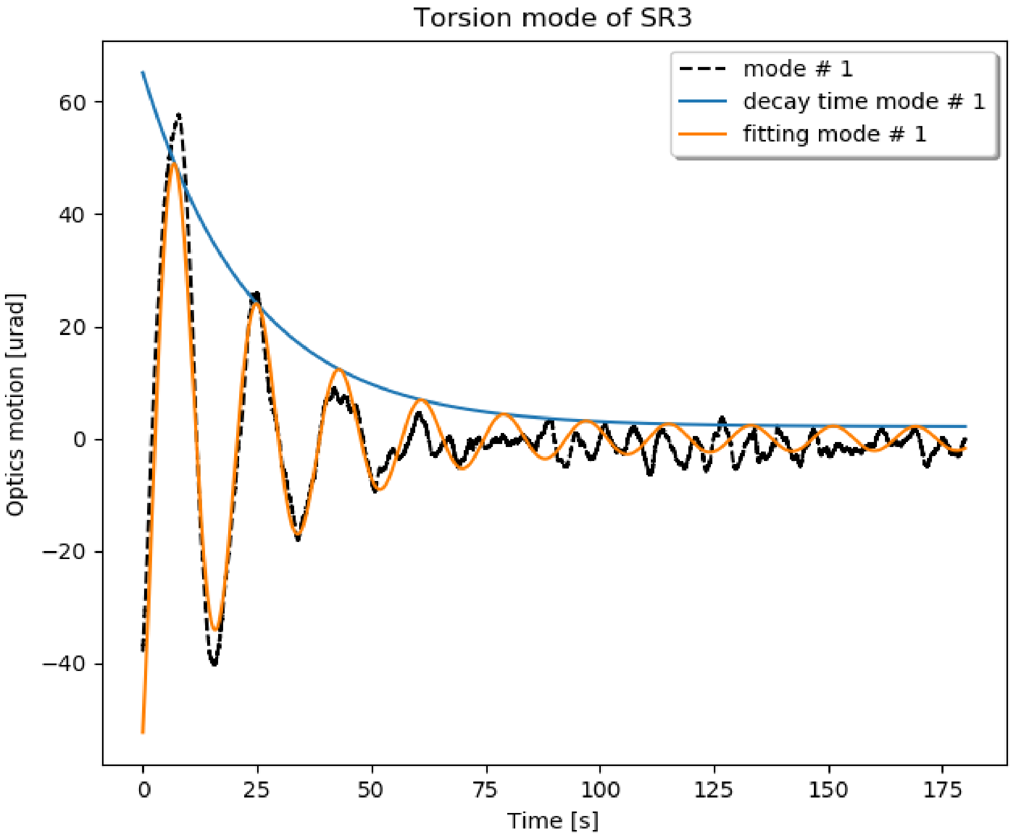
Adjust the height of the MD by lifting the rods.

Change distance between MD ring and SF to tune the damping for this mode.

Measure motion of the mirror with the optical lever.

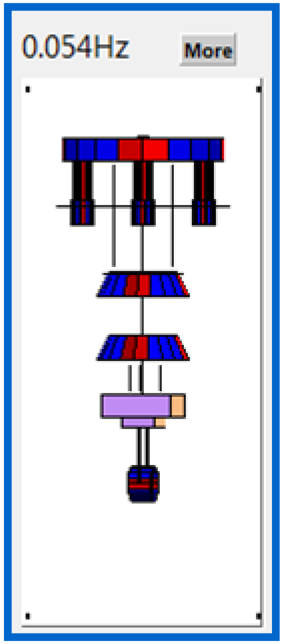
By R. Hatoya. Ref 6.

Damping of the Torsion mode (SR3)



Decay time <60[s]

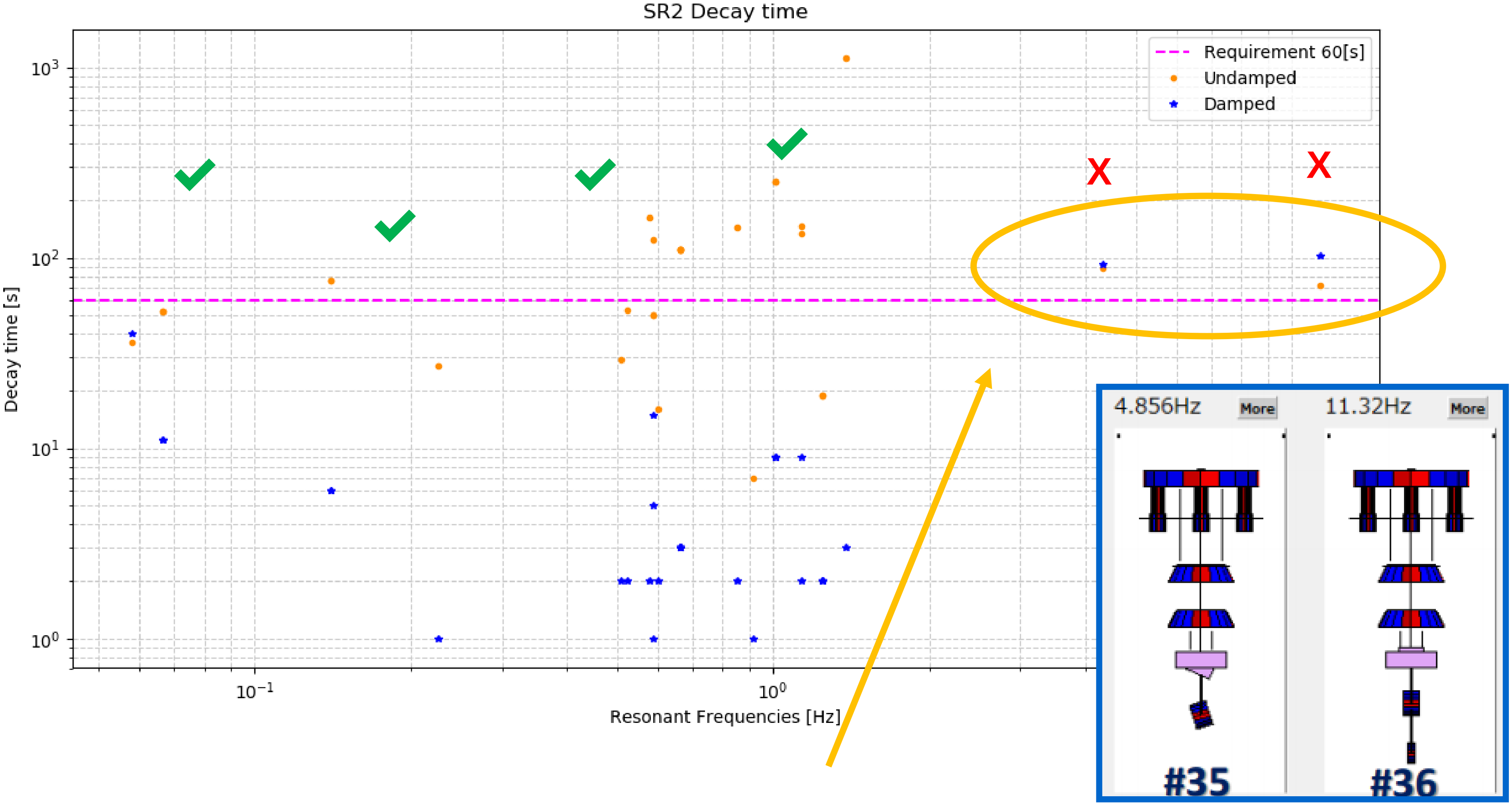
Freq. Measured:
0.055 [Hz]



Then, the rest of the decay times of the eigenmodes are also measured with the corresponding sensor.

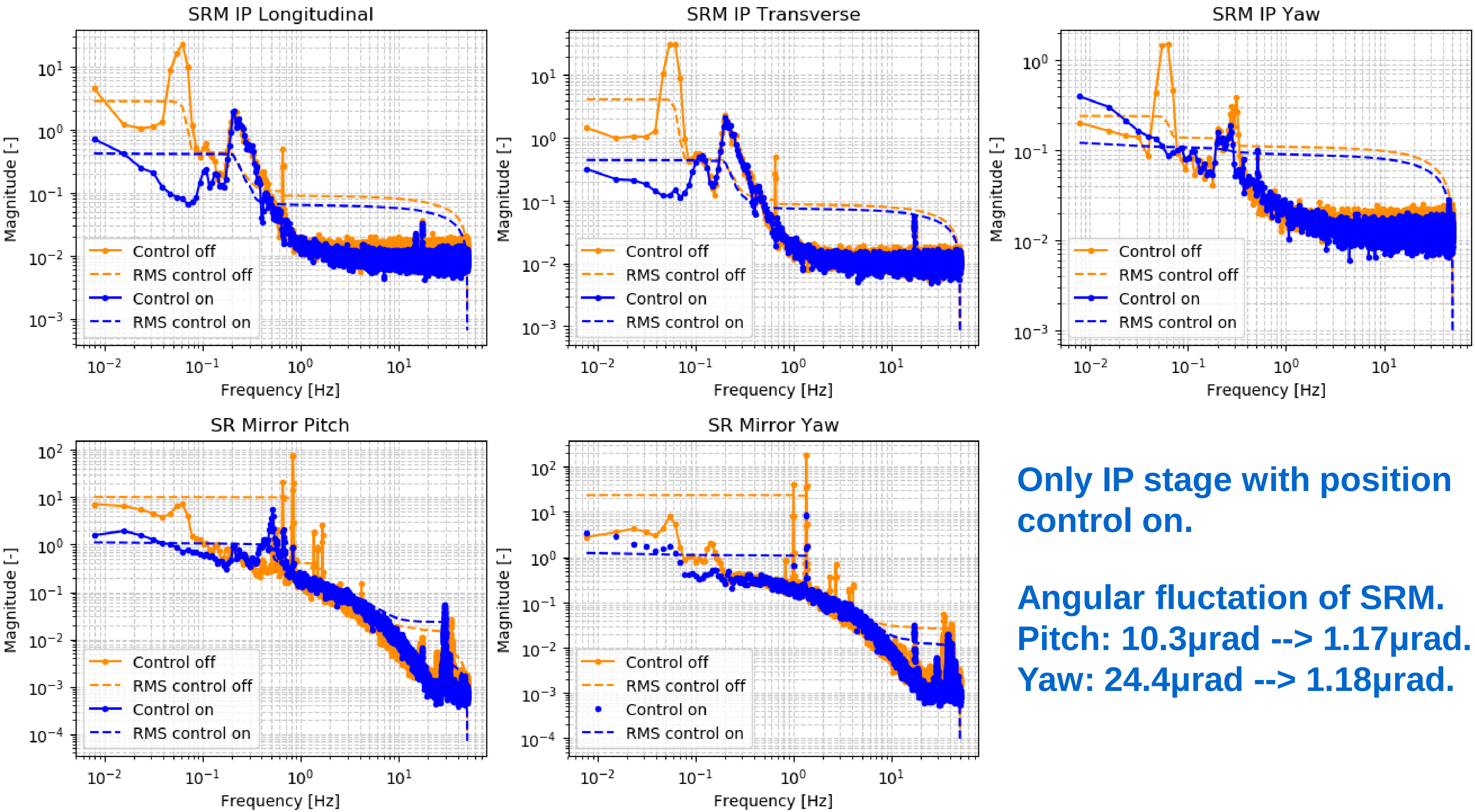
Note: There are some eigenmodes, shown at the simulation tool that can not be measured, since there are no sensors for this, but those modes are les important for the purposes of the interferometer.

Decay time summary



Two of the eigenmodes (up to ~10 Hz) have still a long decay time. This means we need to identify these modes by looking at its frequency and we need to modify and improve the controllers of the control loop.

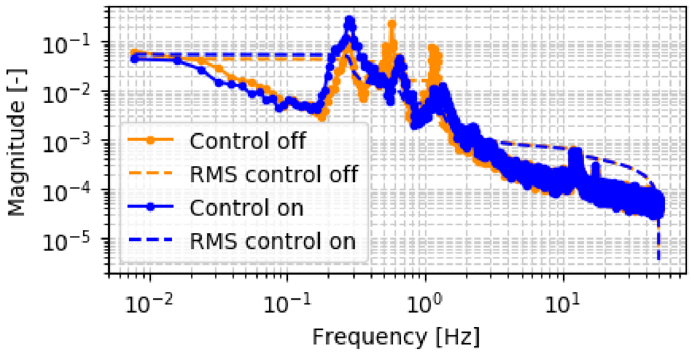
Damping of the modes stage by stage

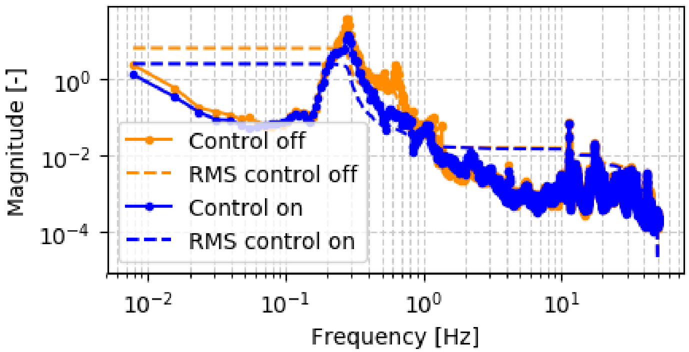


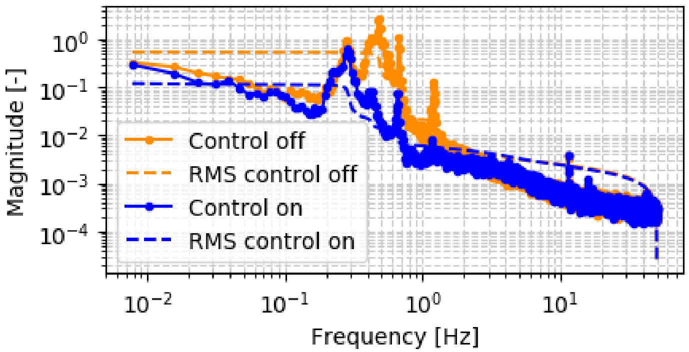
Only IP stage with position control on.

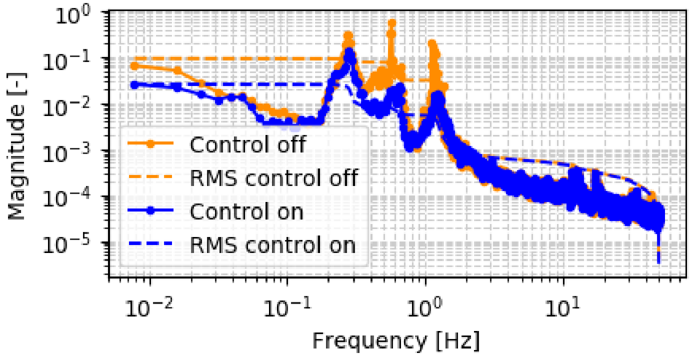
Angular fluctation of SRM.
Pitch: 10.3μrad --> 1.17μrad.
Yaw: 24.4μrad --> 1.18μrad.

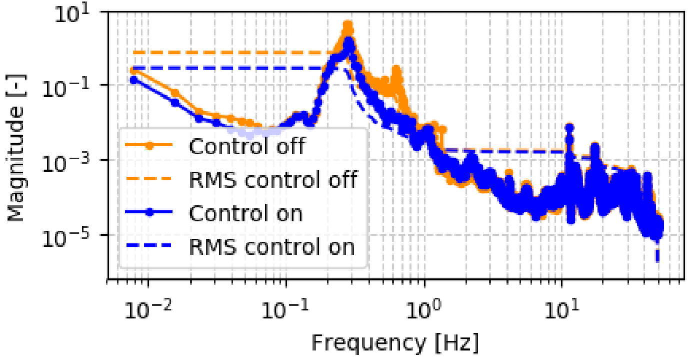
Damping of the modes stage by stage

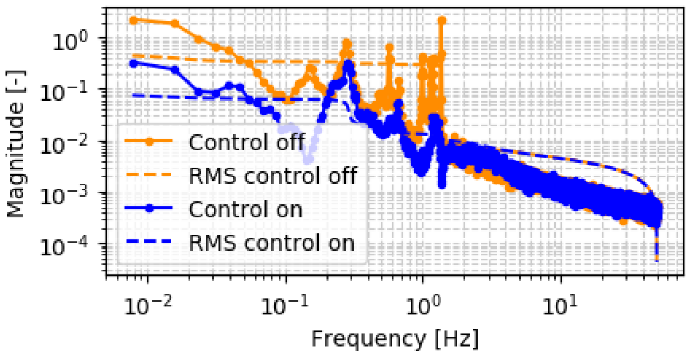

SRM IM Longitudinal

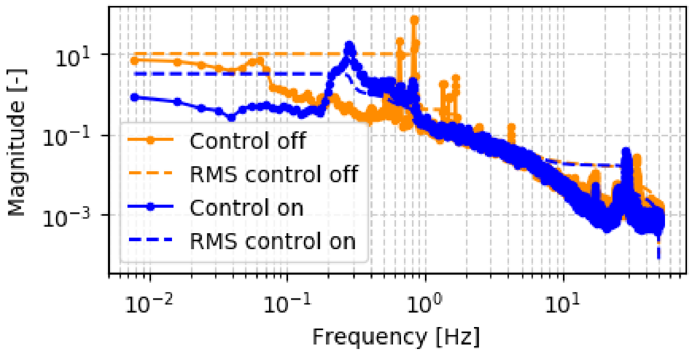

SRM IM Pitch

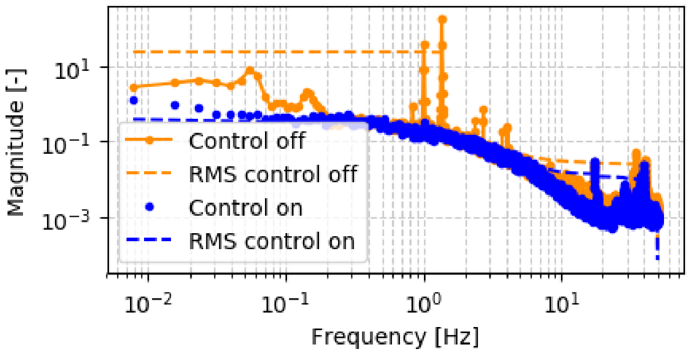

SRM IM Roll


SRM IM Transverse


SRM IM Vertical


SRM IM Yaw

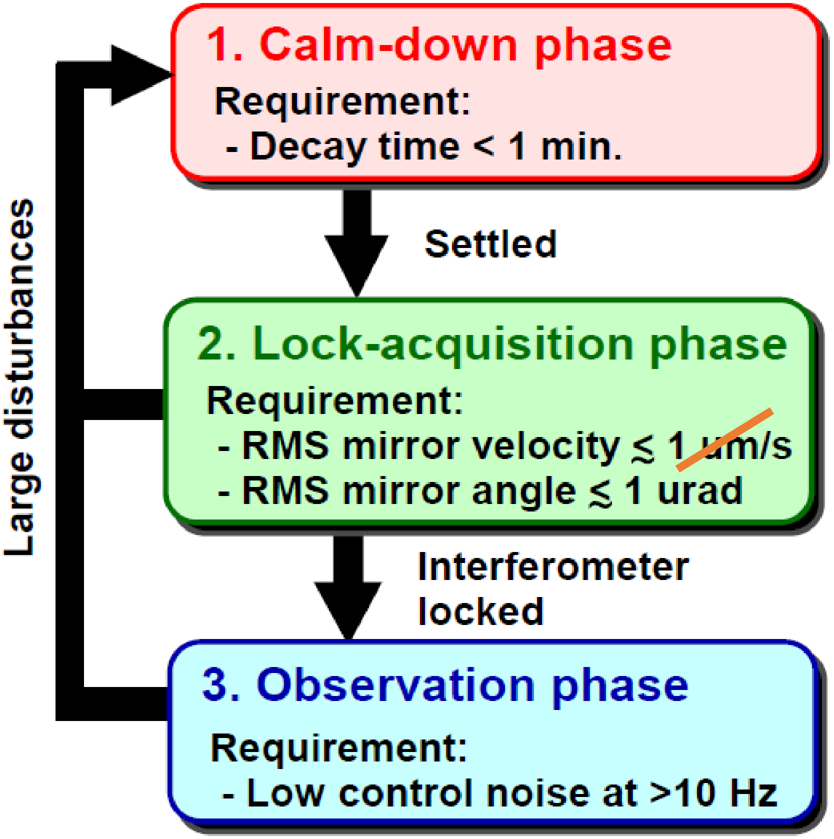

SR Mirror Pitch


SR Mirror Yaw

IP and IM stage with controls on.

Angular fluctation of SRM.
Pitch: 10.3μrad --> 3.3μrad.
Yaw: 24.4μrad --> 0.4μrad.

Meeting the requirements



0.5 μm/s.

IP controlled:

Angular fluctation of SRM.
Pitch: 10.3μrad --> 1.17μrad.
Yaw: 24.4μrad --> 1.18μrad.

IP and IM controlled:

Angular fluctation of SRM.
Pitch: 10.3μrad --> 3.3μrad. X
Yaw: 24.4μrad --> 0.4μrad. ✓

At this point we had to work on the tuning of the controls again in order to meet the requirements.

If we don’t meet the requirements, we need to go back and redesign damping filtersin order to integrate the SR suspensions and run the interferometer.

Ongoing Work

Characterization

- IM stage diagonalization.
- Include signal from Geophones.

Controls

- Implement IP stage inertial damping (geophone).
- Coupling cancellation filters for payload.

References

(1) Electronics setup and testing for Advanced LIGO suspensions. LIGO document. B. Shapiro.

(2) Low frequency vibration isolation system for Large Scale Gravitational wave Detectors, PhD Thesis. T. Sekiguchi.

(3) Optic displacement sensing. KAGRA document. T. Tsang.

(4) Development of 13.5 m Vibration Isolation System for the Main Mirrors in KAGRA. PhD Thesis. K. Okutomi.

(5)Seismic attenuation for Advanced Virgo. Vibration isolation for the external injection bench, PhD Thesis. M. Blom.

(6) Study and improvement of torsion damping for the signal recycling mirrors of KAGRA. Summer student project. R. Hatoya.

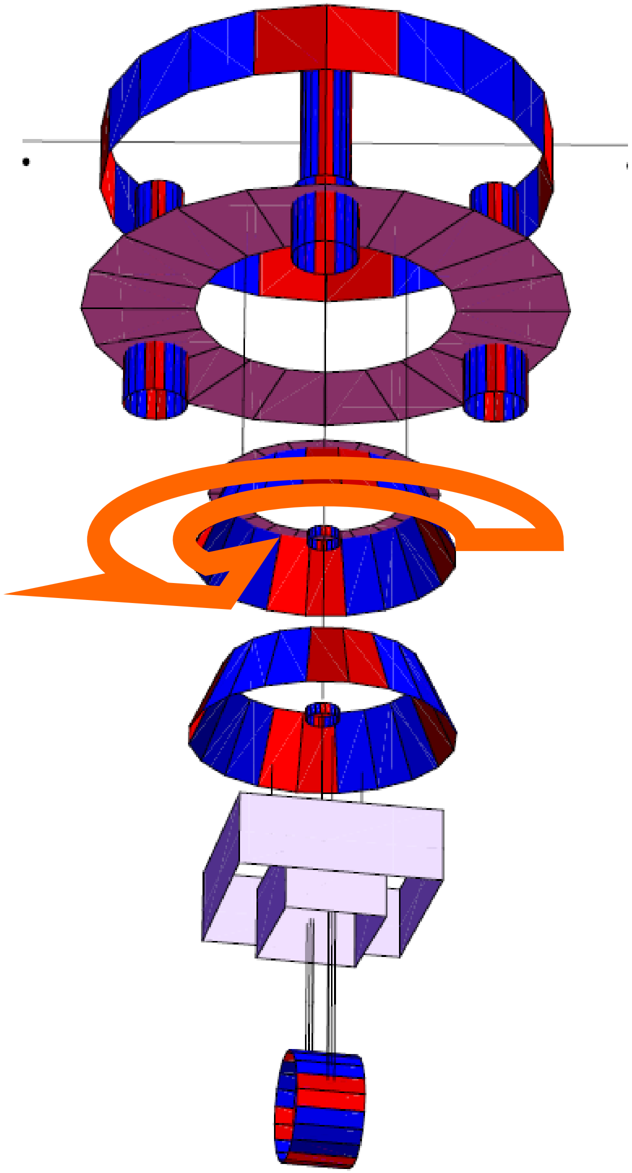
(7) SUMCON User Manual. KAGRA Document. Y. Fujii.

Thank you!

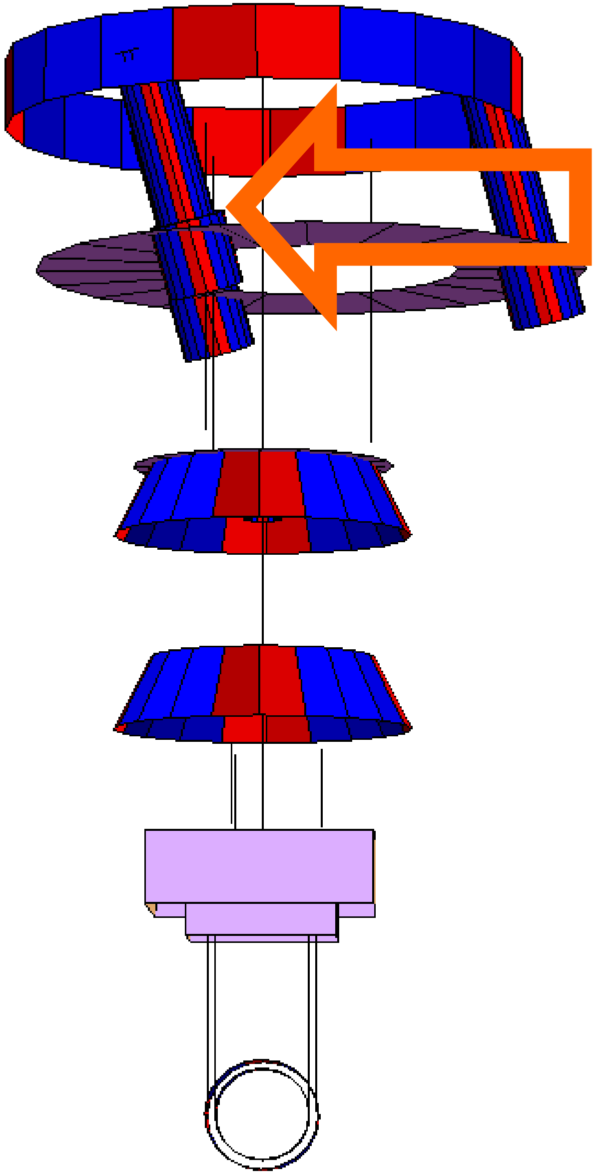
Extras

Type B eigenmodes

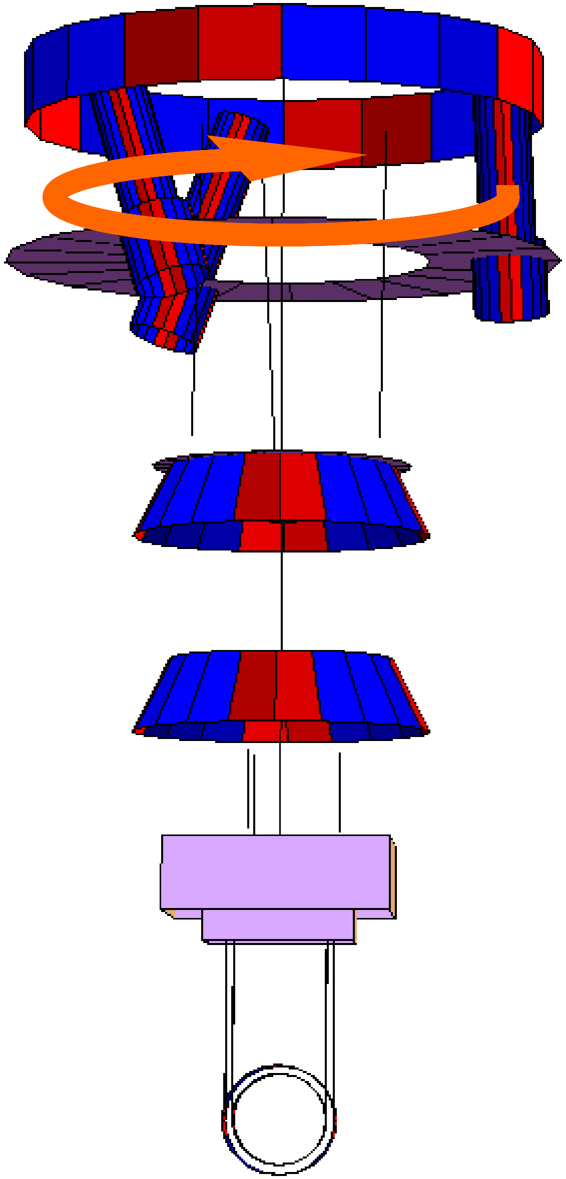
#1 Wire torsion
(0.054 Hz)



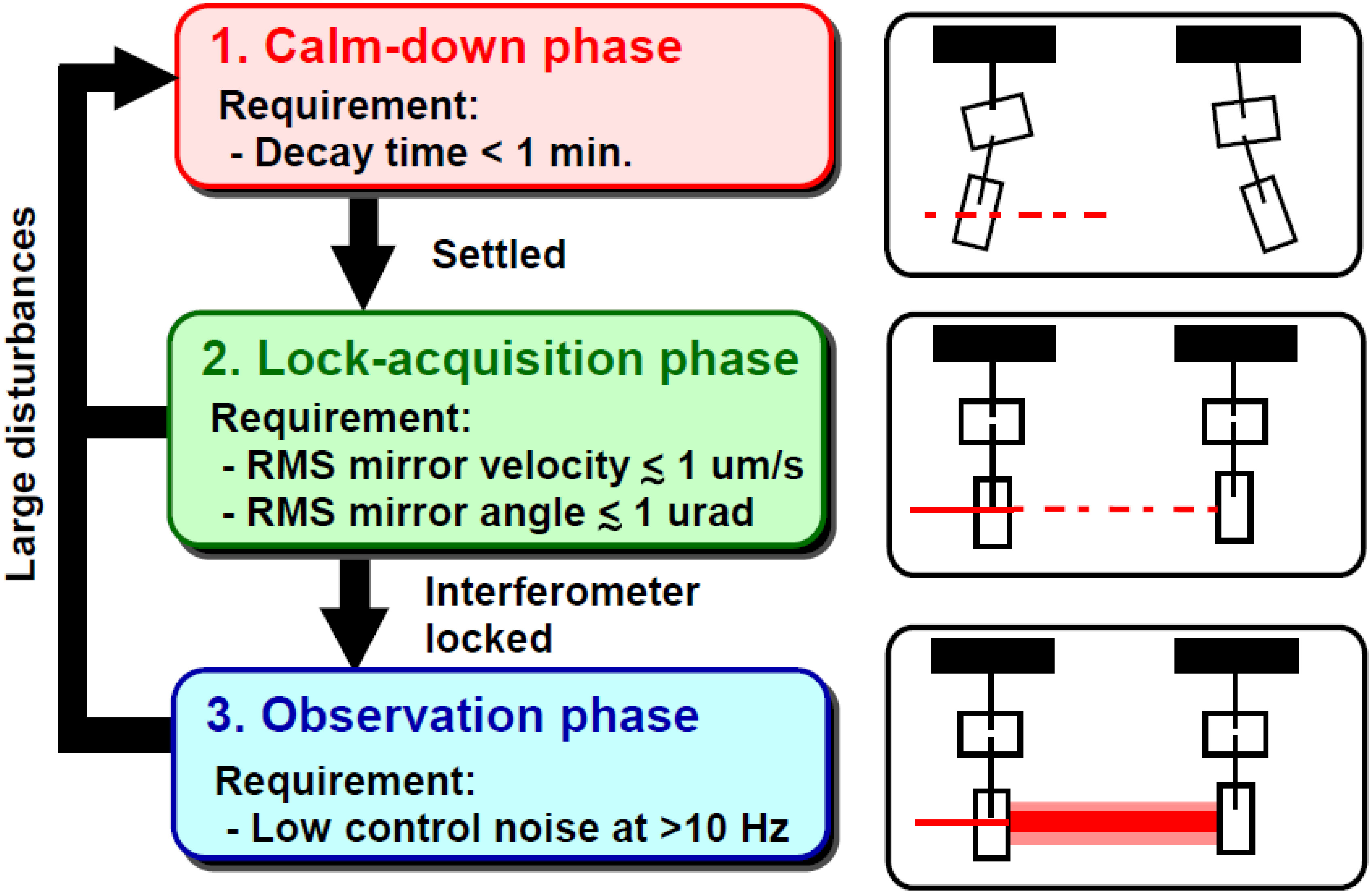
#2, 3 IP Translation
(0.063 Hz)



#7 IP Rotation
(0.31 Hz)



Requirements



1. Calm-down phase

Requirement:
- **Decay time < 1 min.**

Settled

2. Lock-acquisition phase

Requirement:
- **RMS mirror velocity $\lesssim$ 1 um/s**
- **RMS mirror angle $\lesssim$ 1 urad**

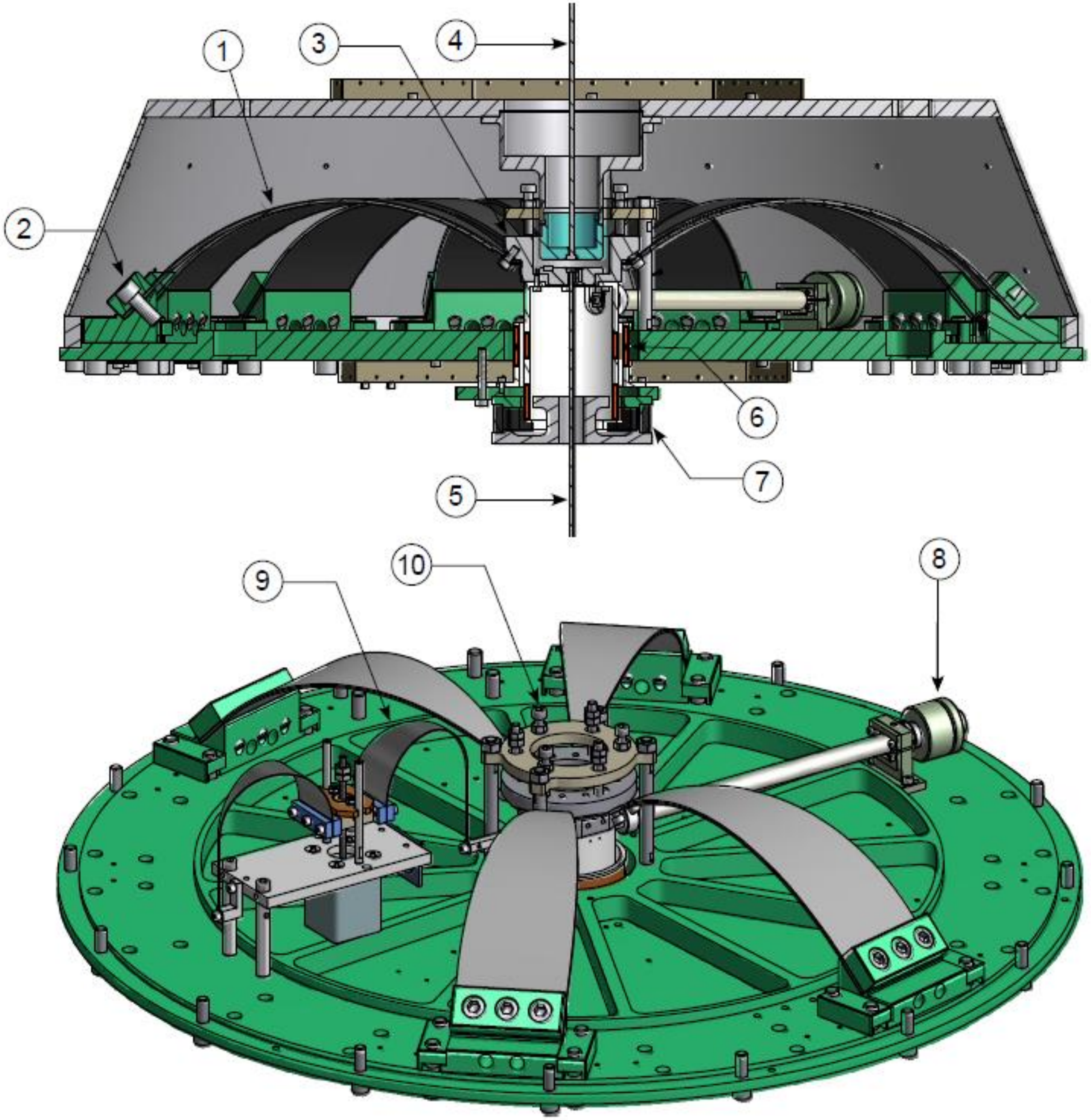
Interferometer locked

3. Observation phase

Requirement:
- **Low control noise at >10 Hz**

Large disturbances

GAS (Geometric Anti-Spring) filter



(1)Blades.

(2)Blade attachment to the base.

(3)Keystone.

(4)Upper rod supporting the weight to the GAS filter and the mass below it.

(5)Lower rod connected to the lower stage (It moves the Keystone).

(6)LVDT (it measures the displacement of the Keystone).

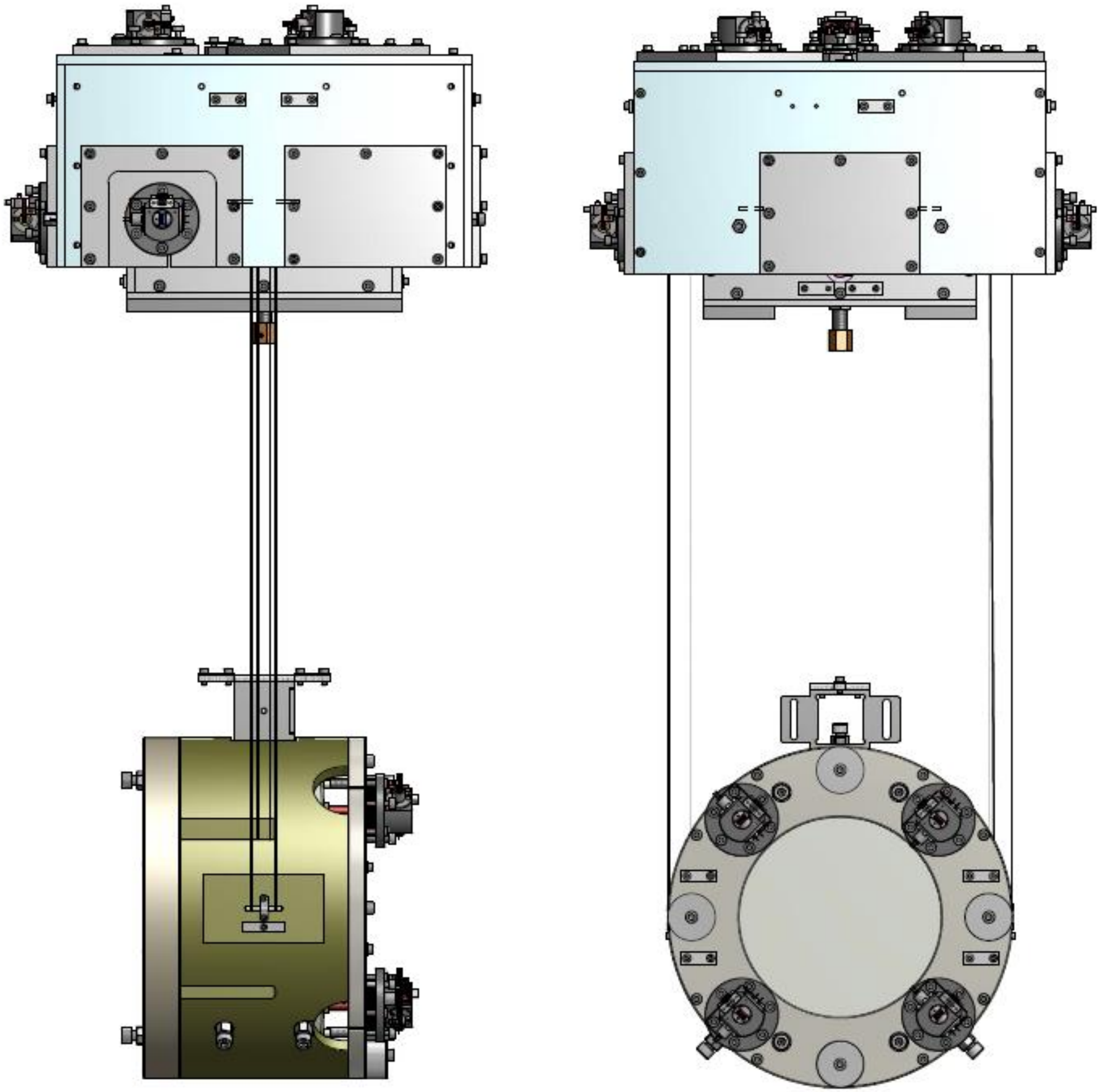
(7)Coil magnet actuator.

(8)Magic wand (to improve the saturation value of isolation)

(9)Fishing rod (to move the Keystone).

(10) Locking system screws.

IM OSEMs and TM coil actuators



6 OSEMs at the IM stage (sen

4 Coil actuators
at the optic stage.