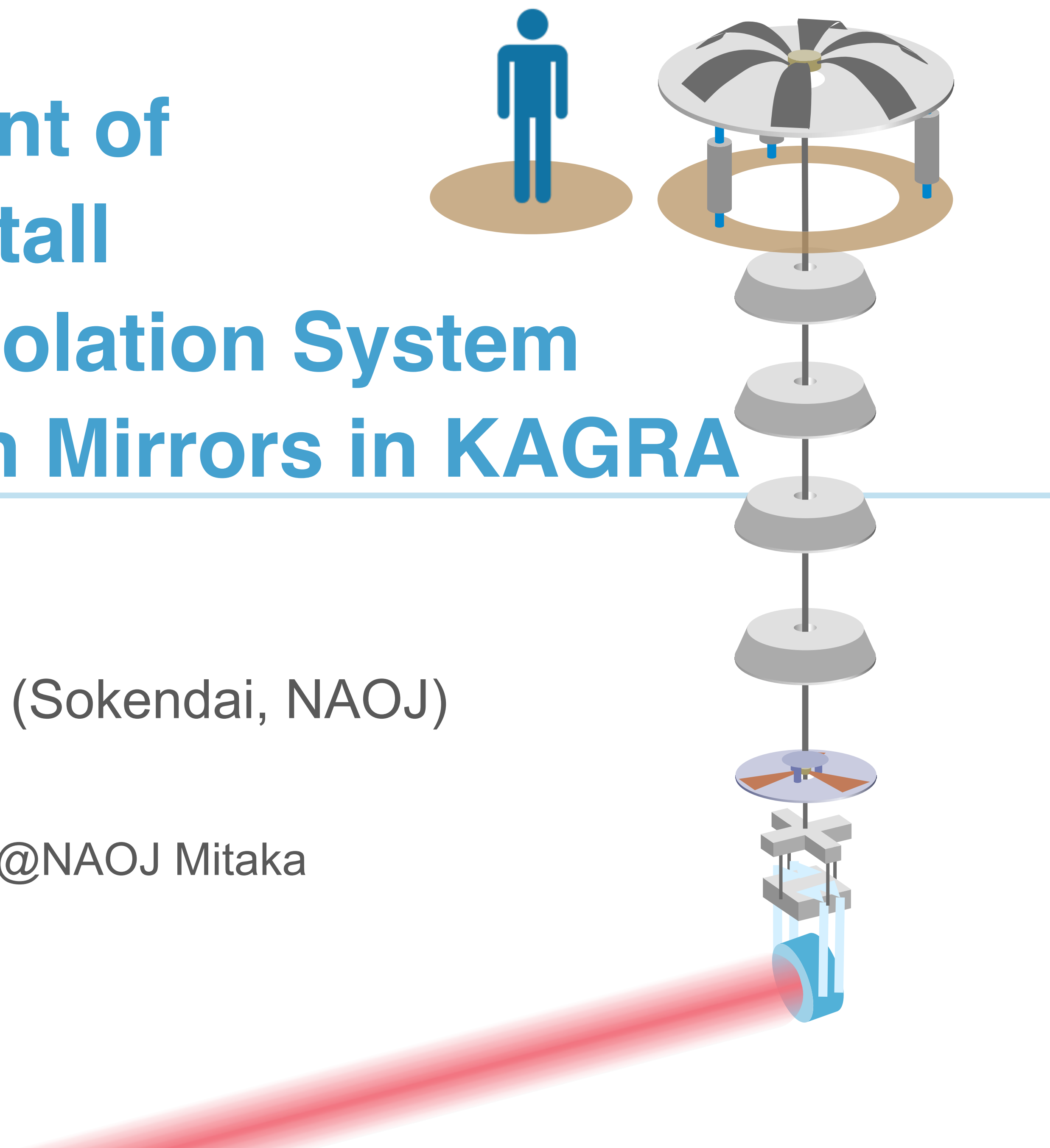
Development of 13.5-meter-tall Vibration Isolation System for the Main Mirrors in KAGRA

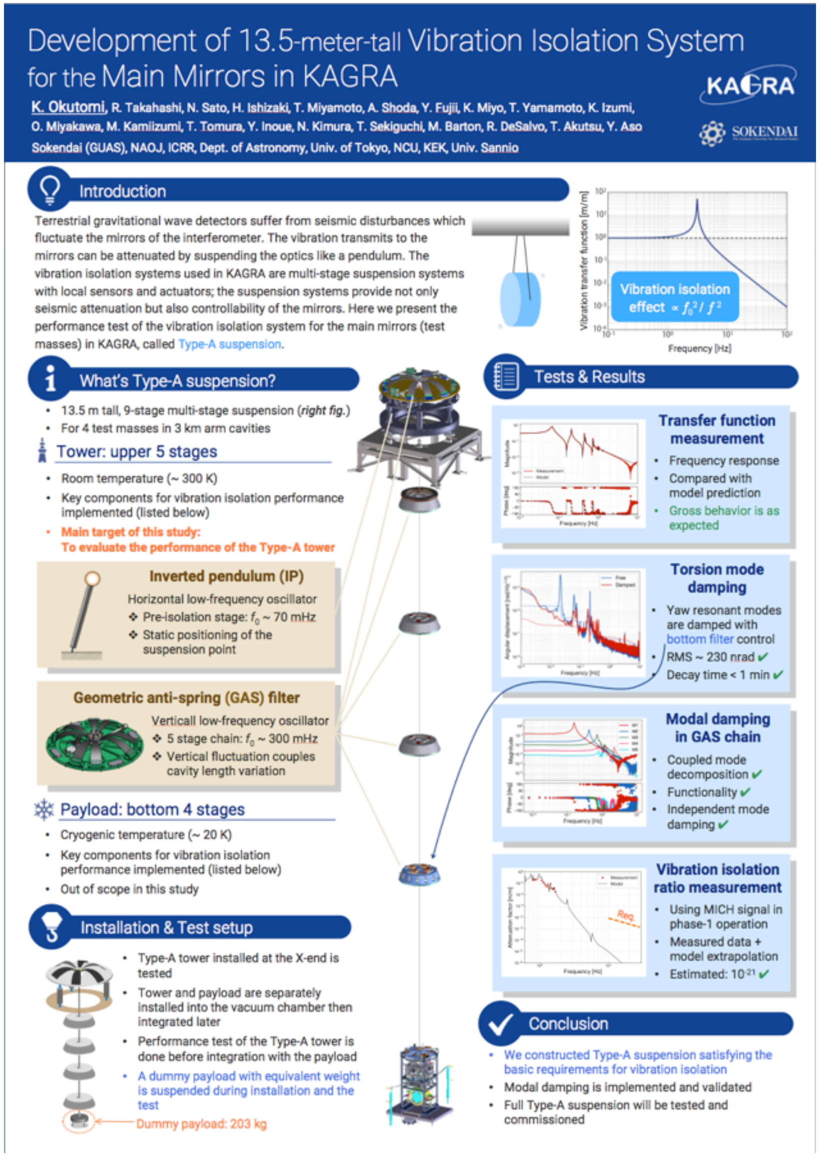


Koki Okutomi (Sokendai, NAOJ)

Dec 6, 2018

KAGRA F2F meeting @NAOJ Mitaka

Poster: Overview of My Work



- Details: Thesis coming soon!
- Stay tuned!
- Poster: SE09

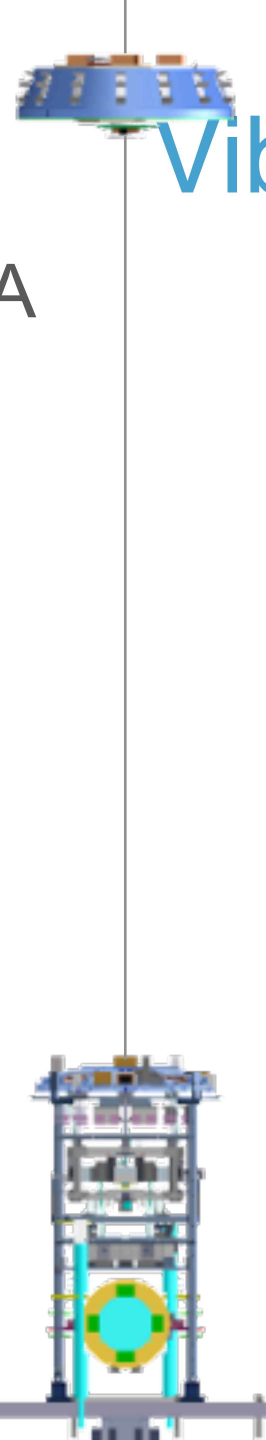
Contents

- Type-A suspension
- Modal damping for GAS vertical modes

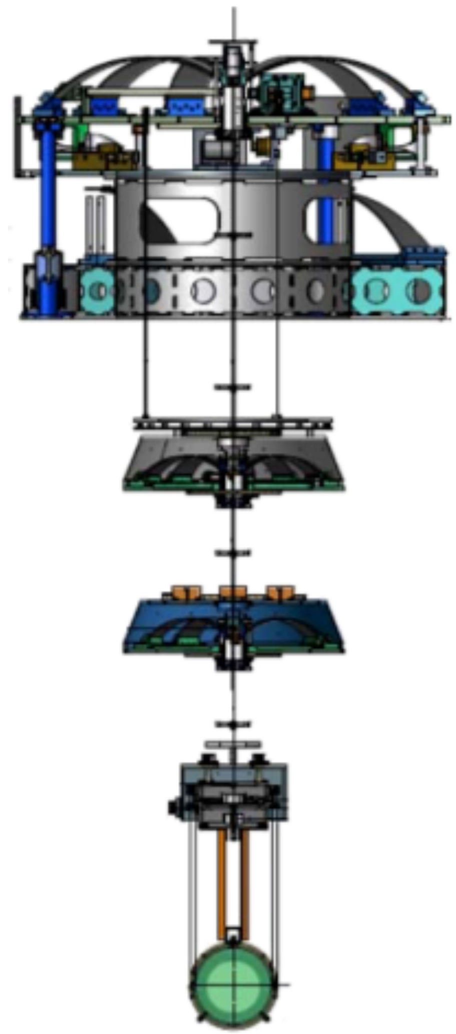
Type-A Suspension

Vibration Isolation Systems in KAGRA

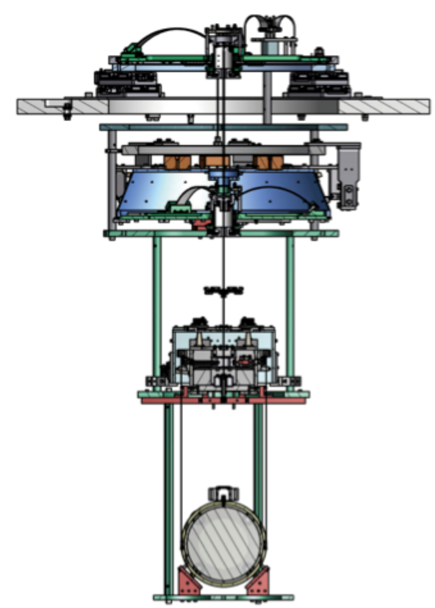
Type-A



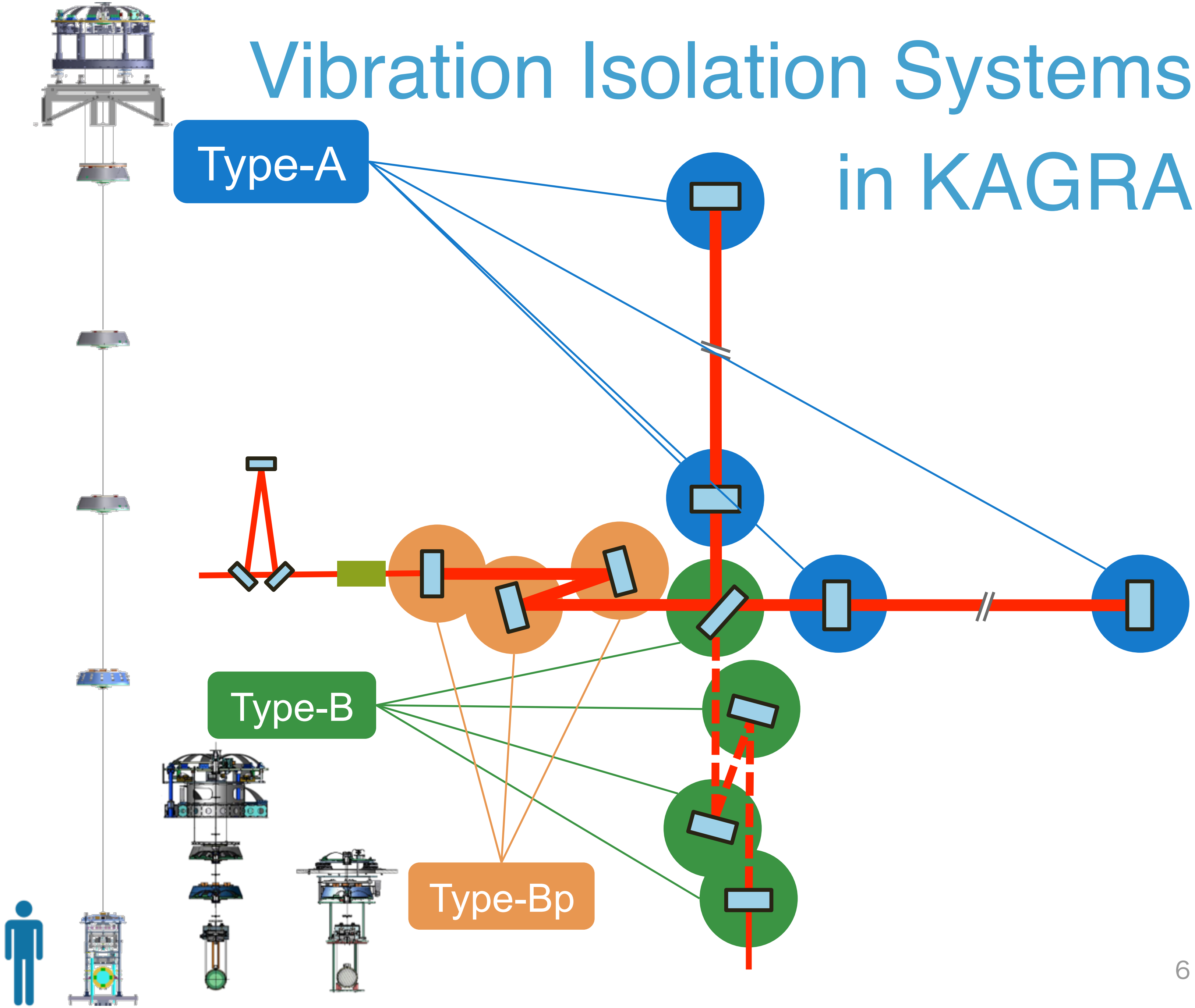
Type-B



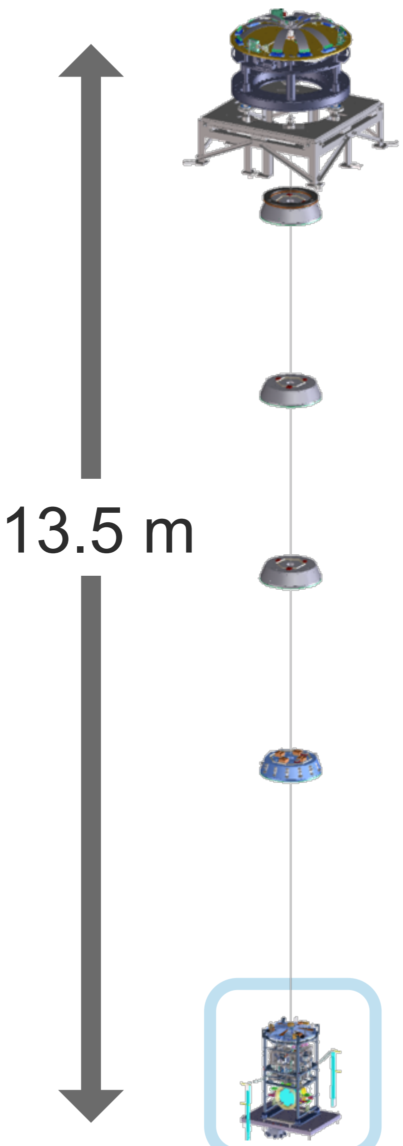
Type-Bp



Vibration Isolation Systems in KAGRA



Type-A Suspension

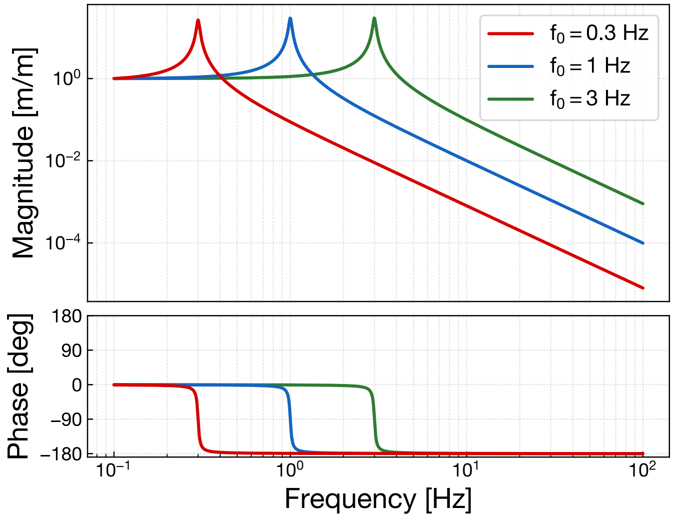


9-stage multiple pendulum

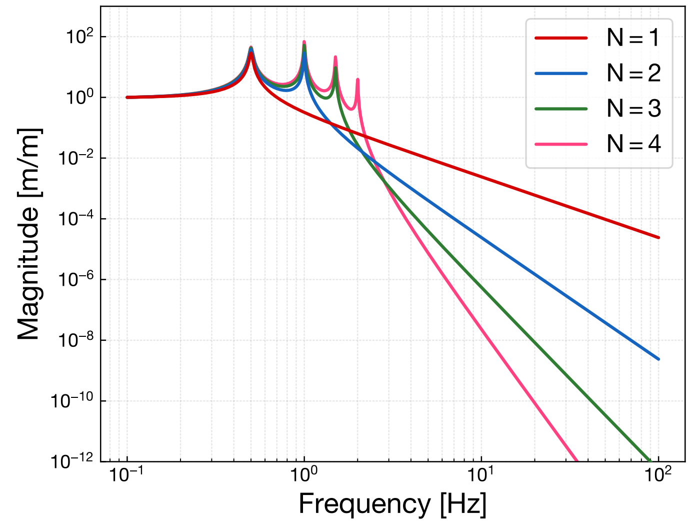
- Top 5 stages: Tower (~300 K)
- Bottom 4 stages： Payload (~20 K)

➢ For high vibration-isolation performance…

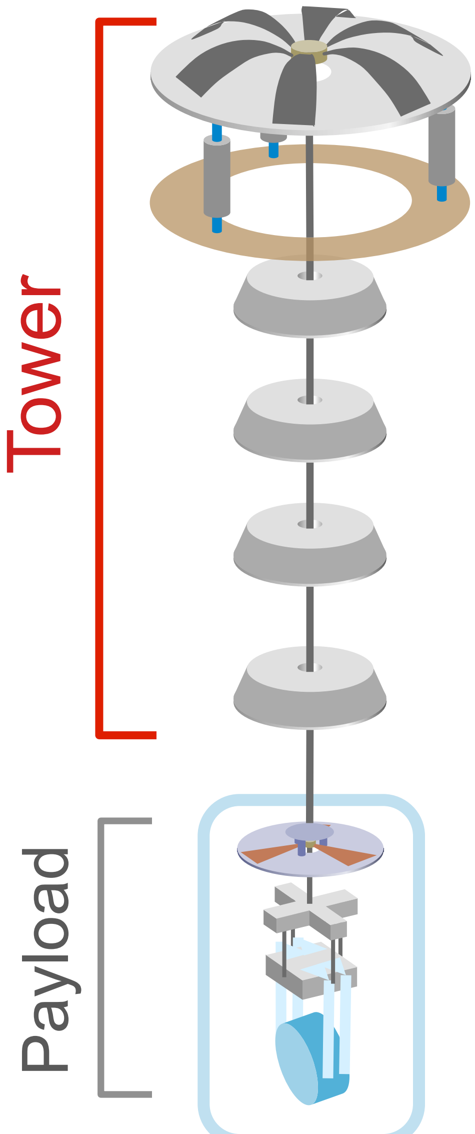
Lowering resonant freq.



Cascading



Scope of This Study



Tower: VIS

- Hardware installation
- System characterization
- Real-time control model construction
- Modeling
- Damping control

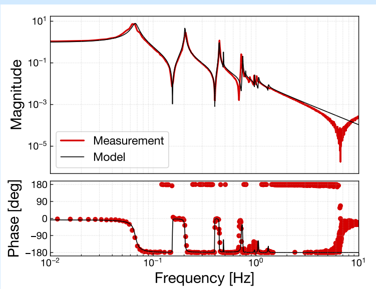
Payload：CRY

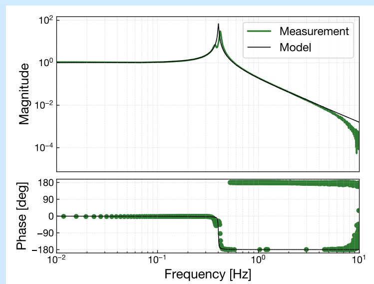
TARGET

To construct a Type-A tower satisfying the basic requirements

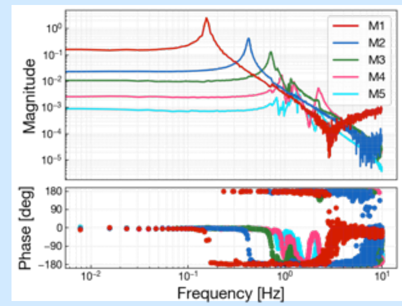
What I Did

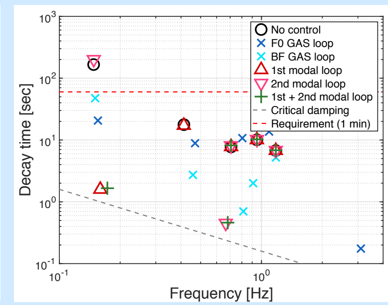
Transfer function measurement



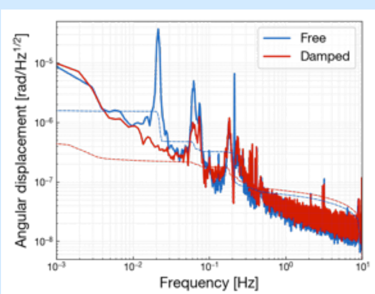


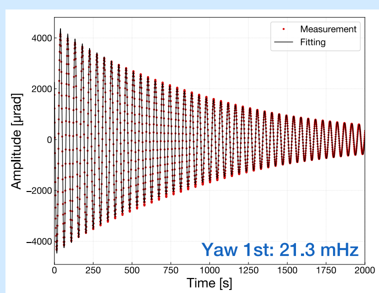
Modal Damping in GAS chain



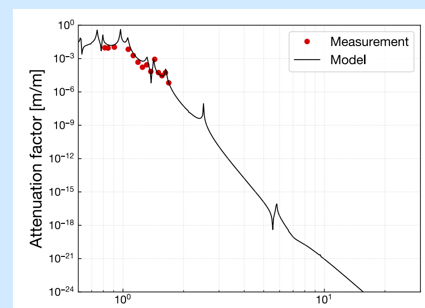


Torsion mode damping



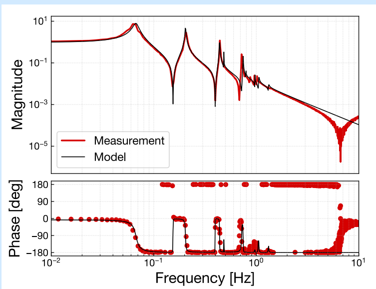


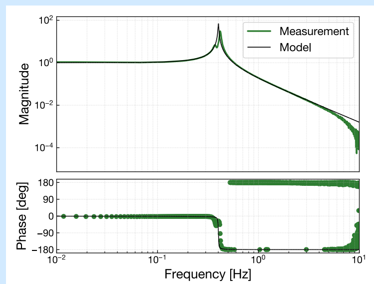
Vibration isolation ratio measurement (full suspension)



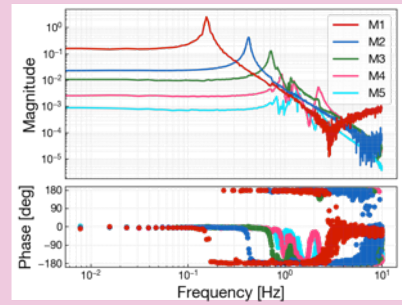
Topic of this talk!

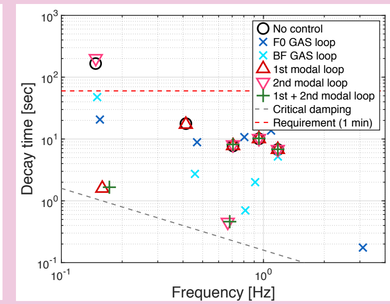
Transfer function measurement



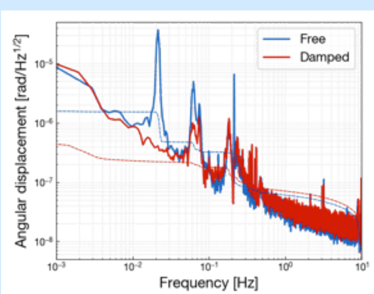


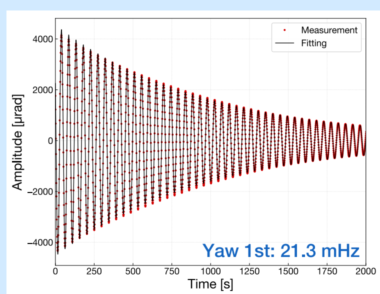
Modal Damping in GAS chain



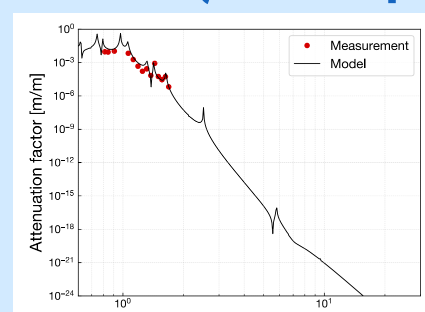


Torsion mode damping



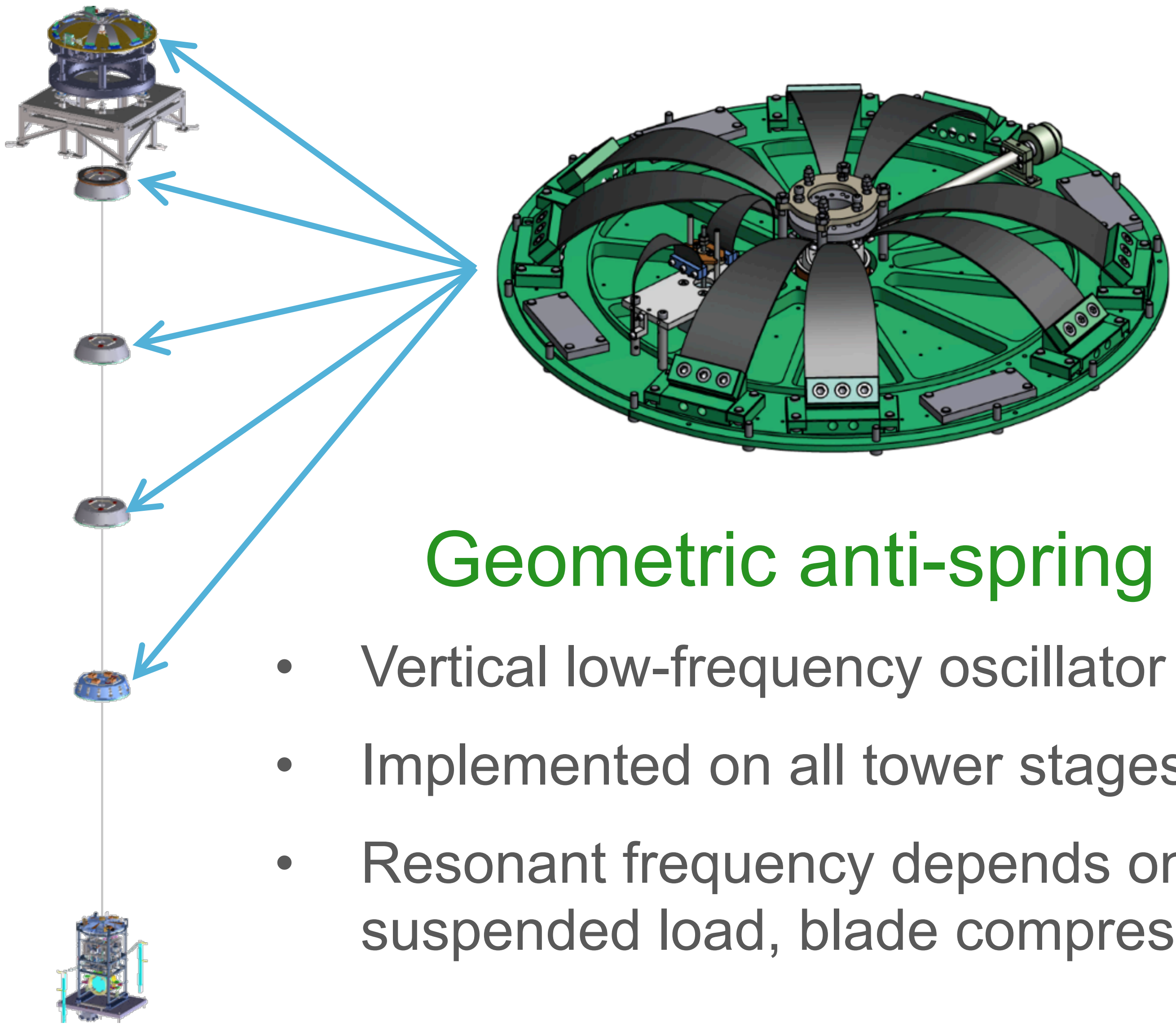


Vibration isolation ratio measurement (full suspension)



Modal damping in GAS vertical modes

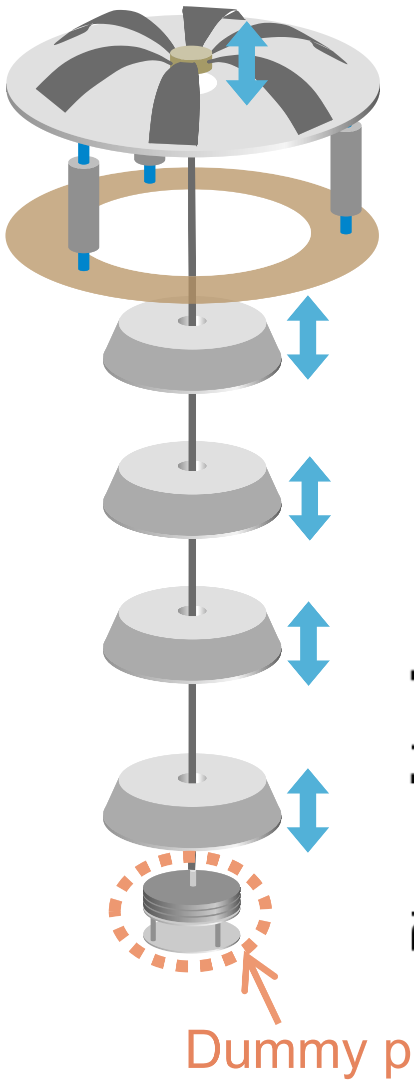
GAS Filter

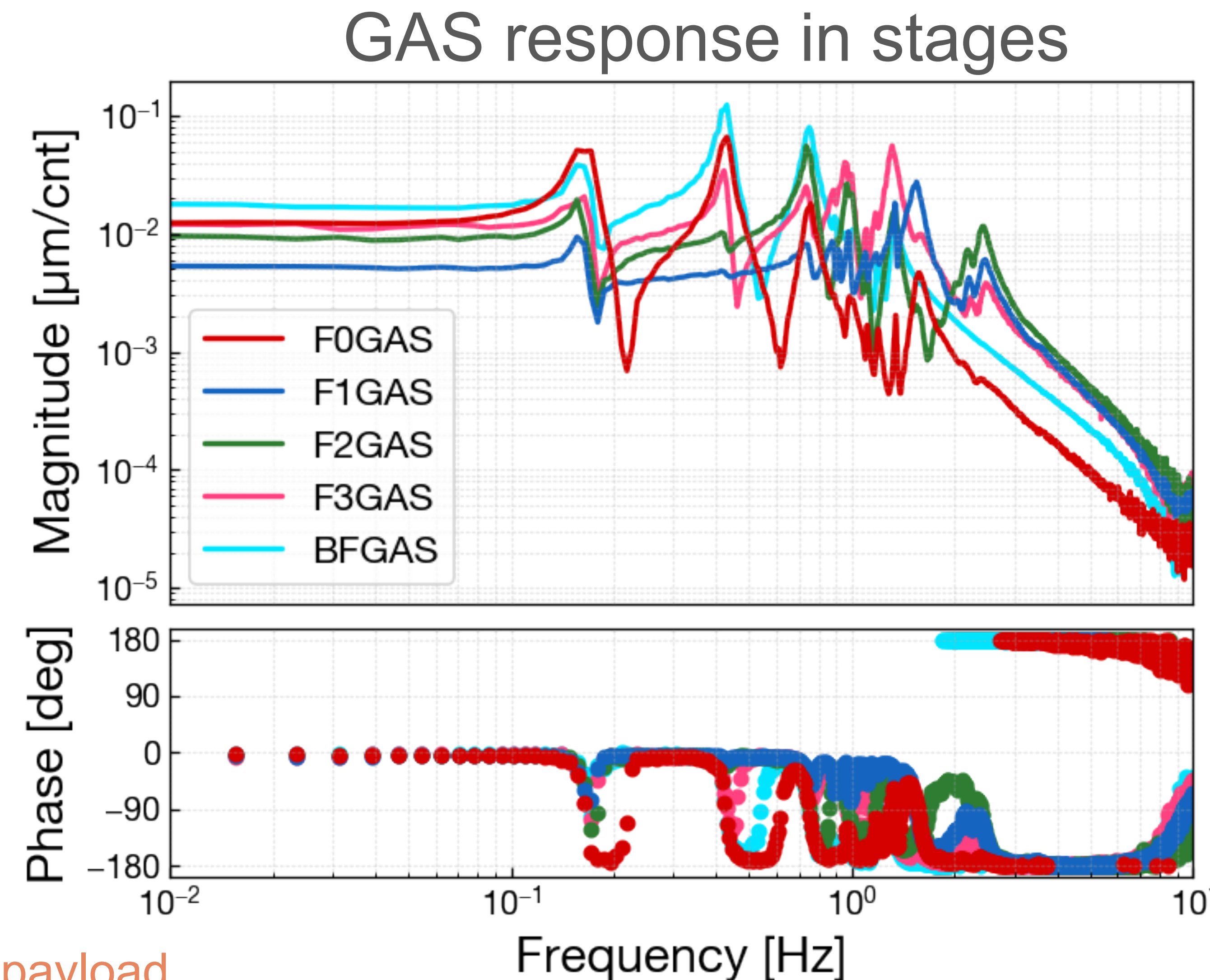


Geometric anti-spring filter

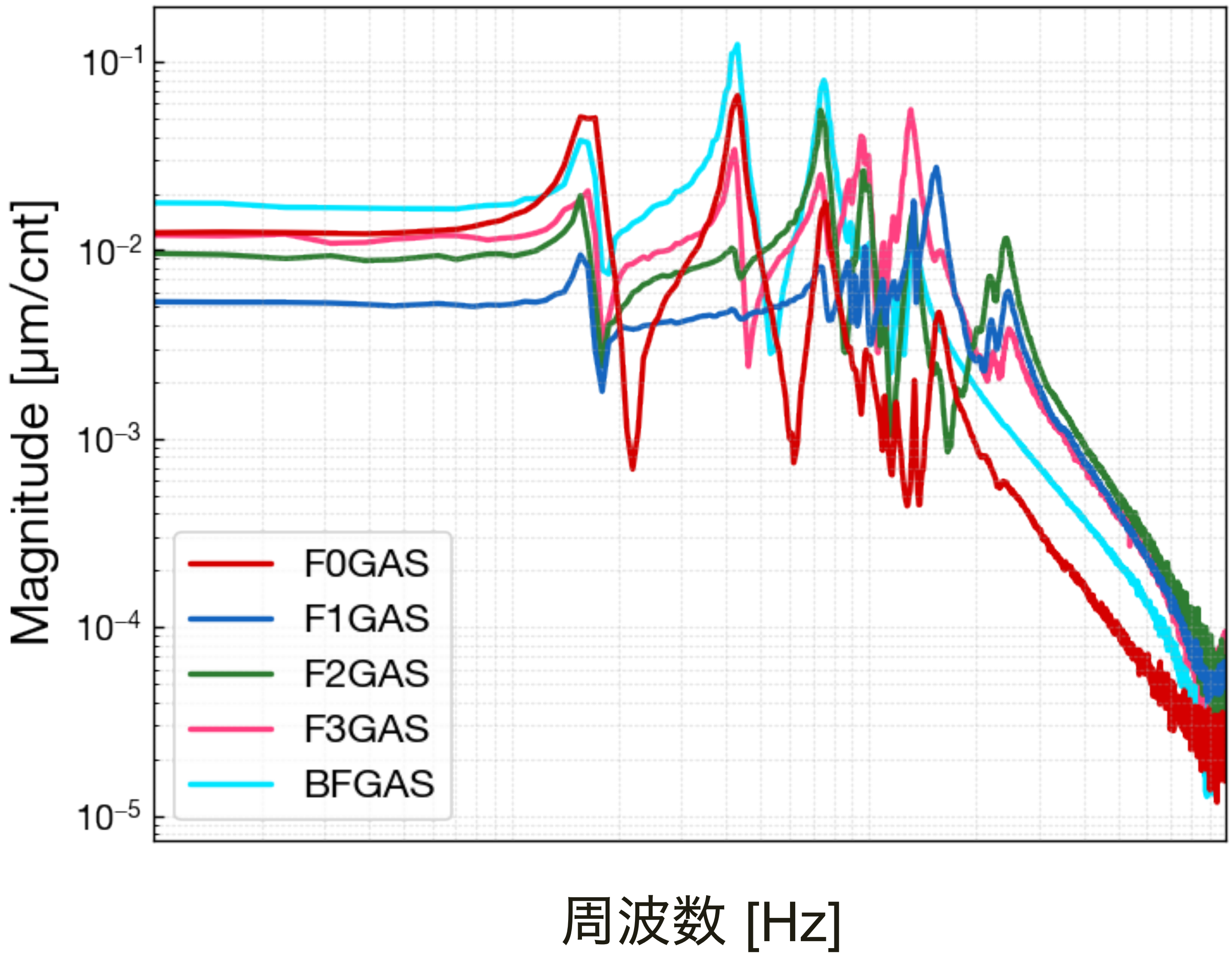
- Vertical low-frequency oscillator
- Implemented on all tower stages
- Resonant frequency depends on suspended load, blade compression, etc…

GAS Vertical Control

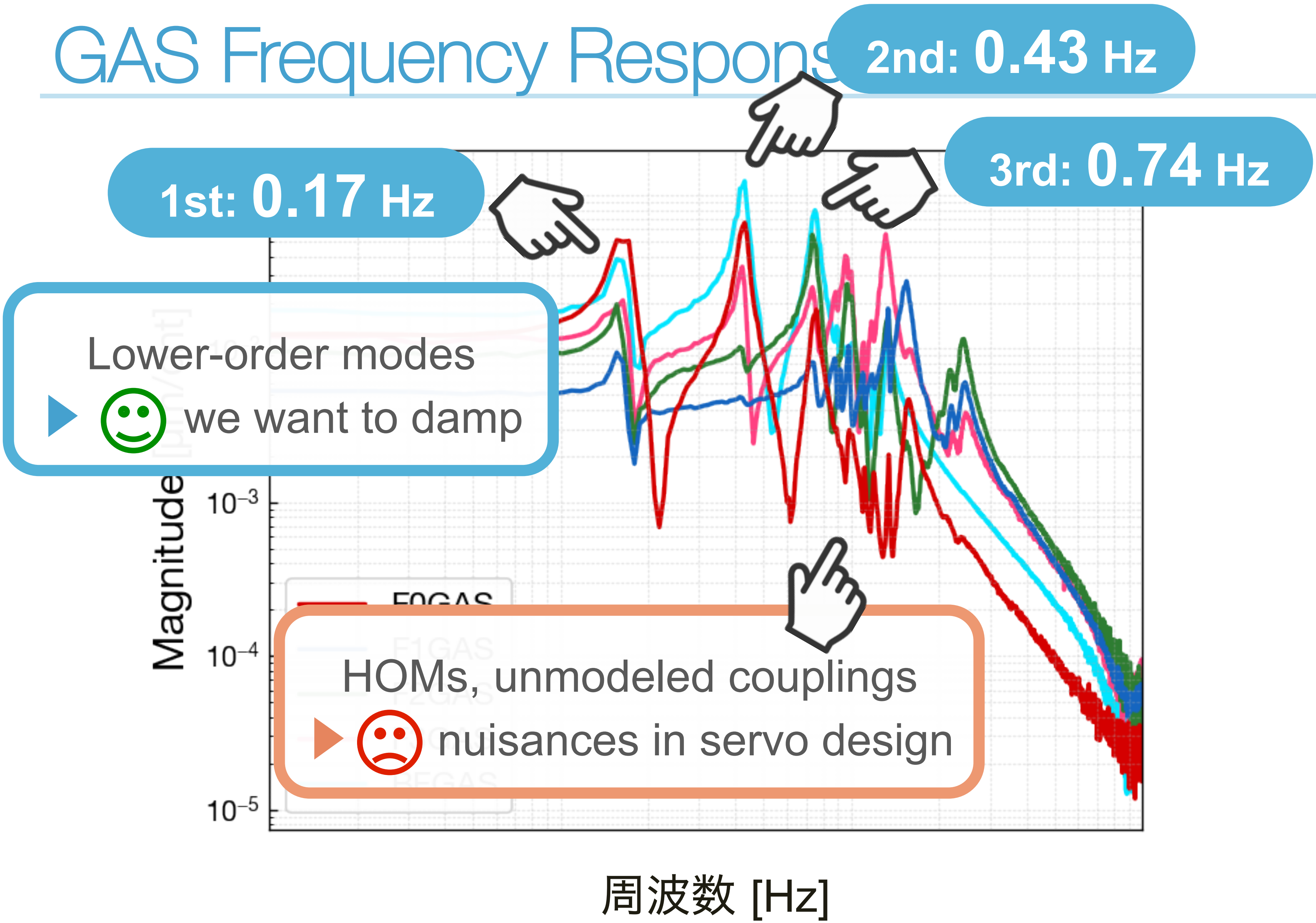




GAS Frequency Responses



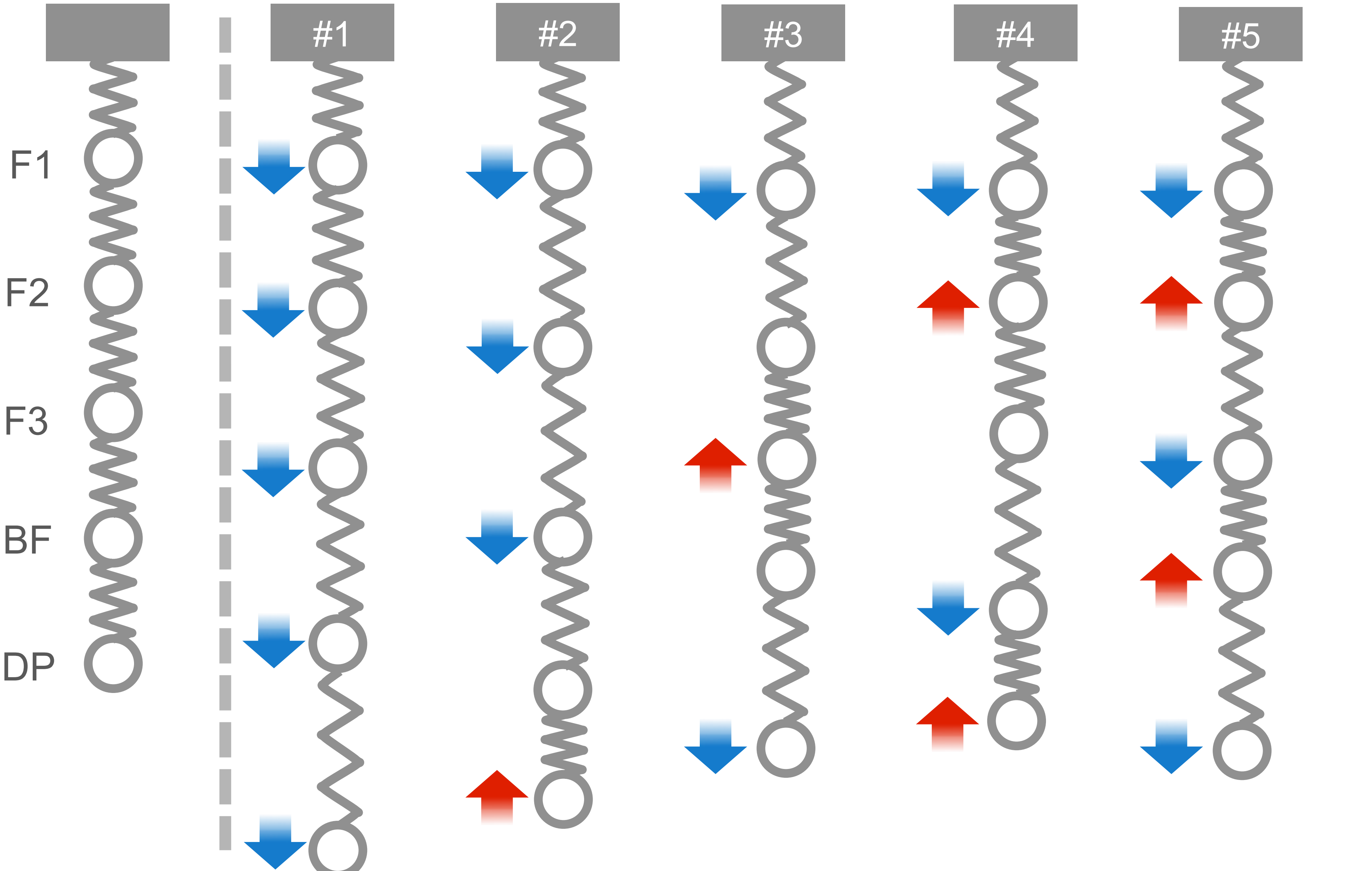
GAS Frequency Response



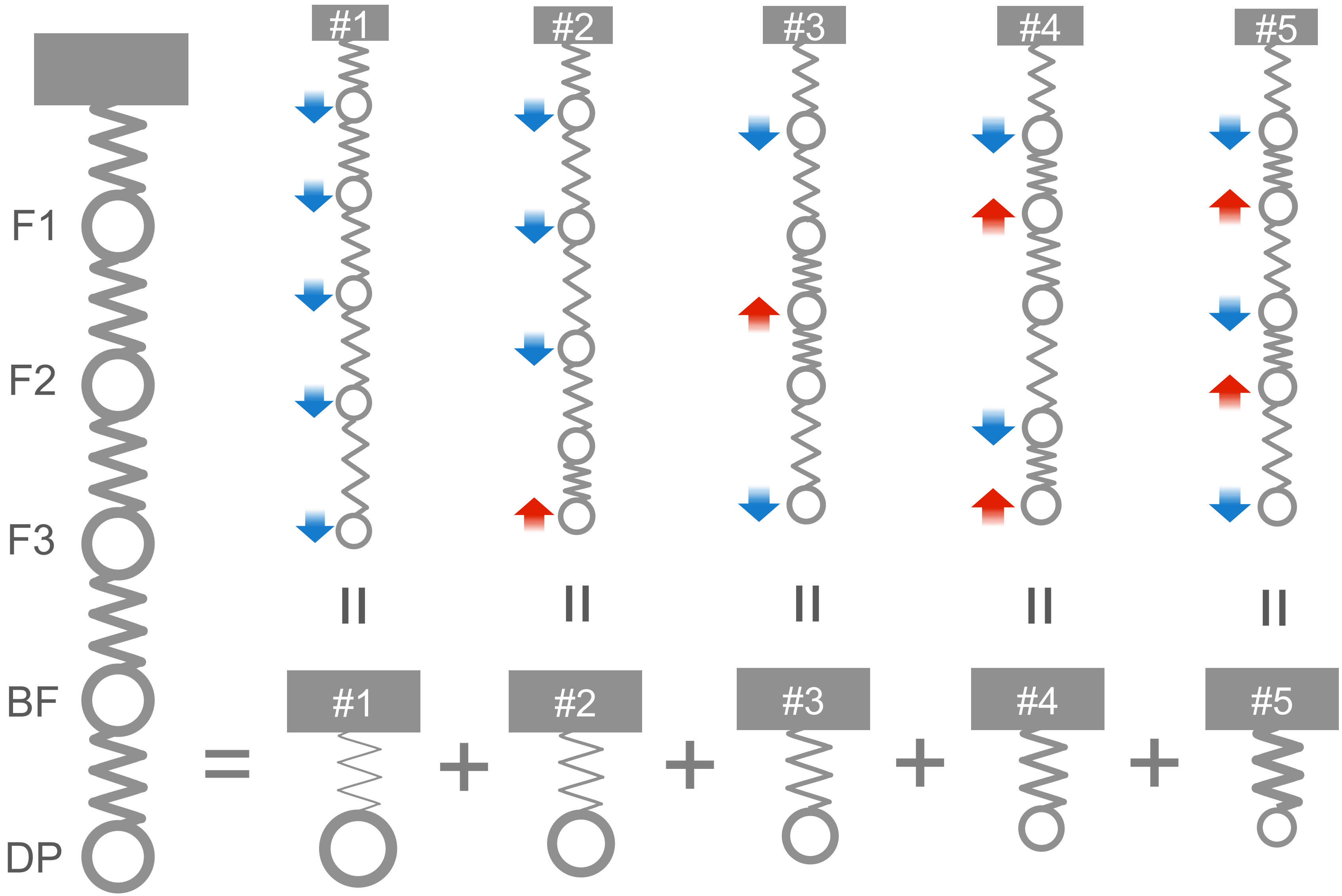
Can we damp specific modes independently…?

Modal damping

Mode shapes in GAS



Concept of Modal Decomposition



Modal Decomposition

$$\begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \\ \eta_5 \end{bmatrix} = \boldsymbol{\Phi}^{-1} \boldsymbol{M} \begin{bmatrix} V_{\mathrm{F0GAS}} \\ V_{\mathrm{F1GAS}} \\ V_{\mathrm{F2GAS}} \\ V_{\mathrm{F3GAS}} \\ V_{\mathrm{BFGAS}} \end{bmatrix}$$

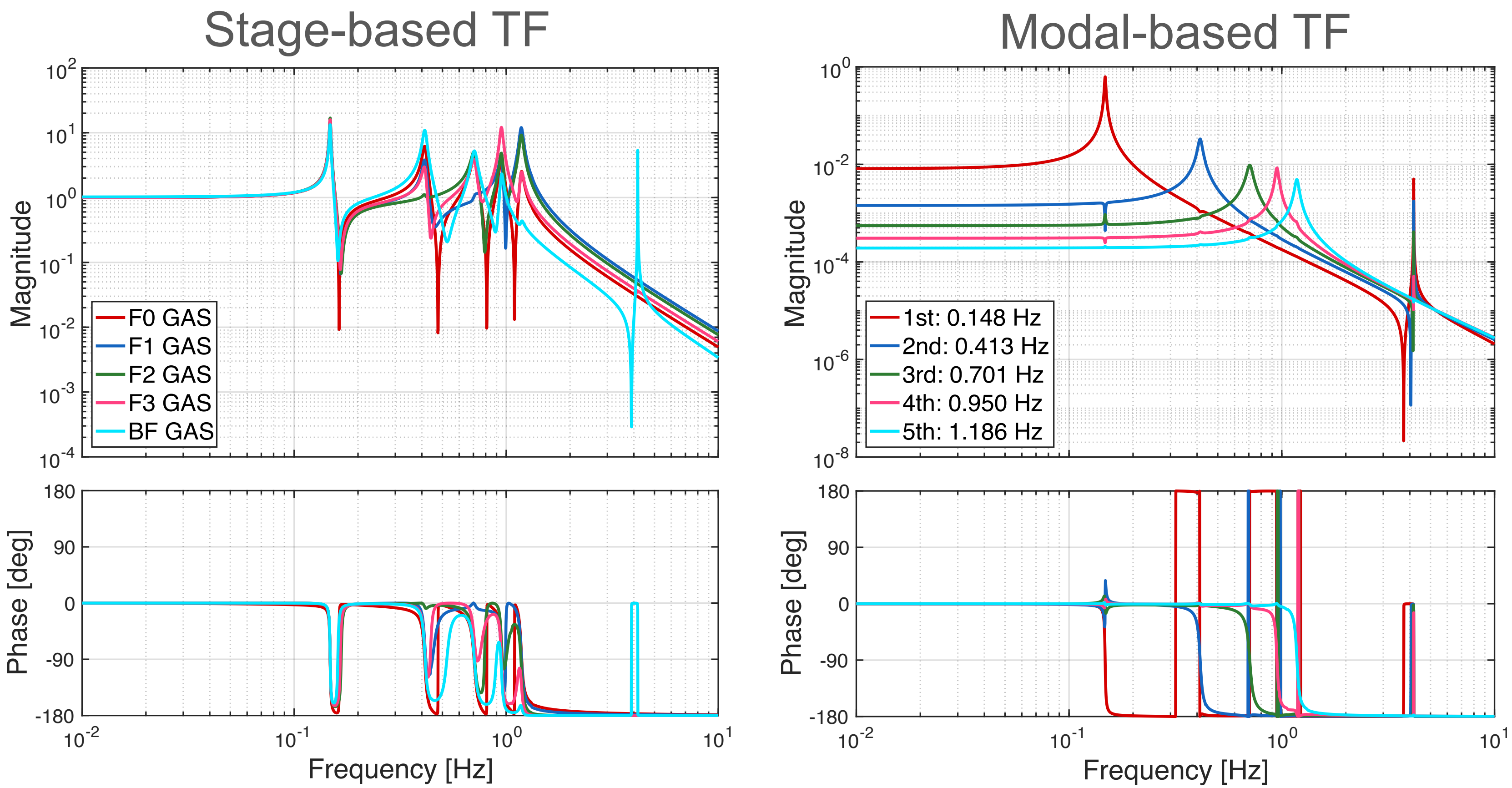
Modal basis

Sensor basis

$\boldsymbol{\Phi}$: **Eigenmode matrix** (modal basis → Cartesian basis) calculated from 3D rigid-body model

$\boldsymbol{M}$: Sensing matrix

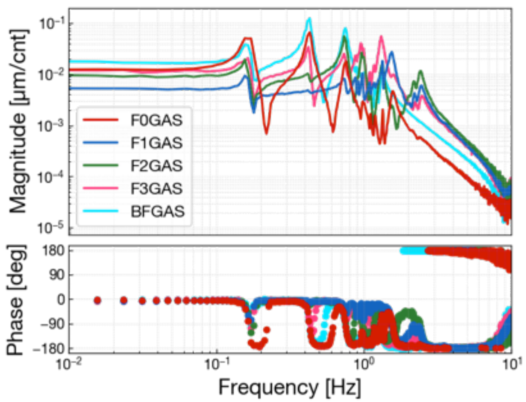
Modal Decomposition in Model



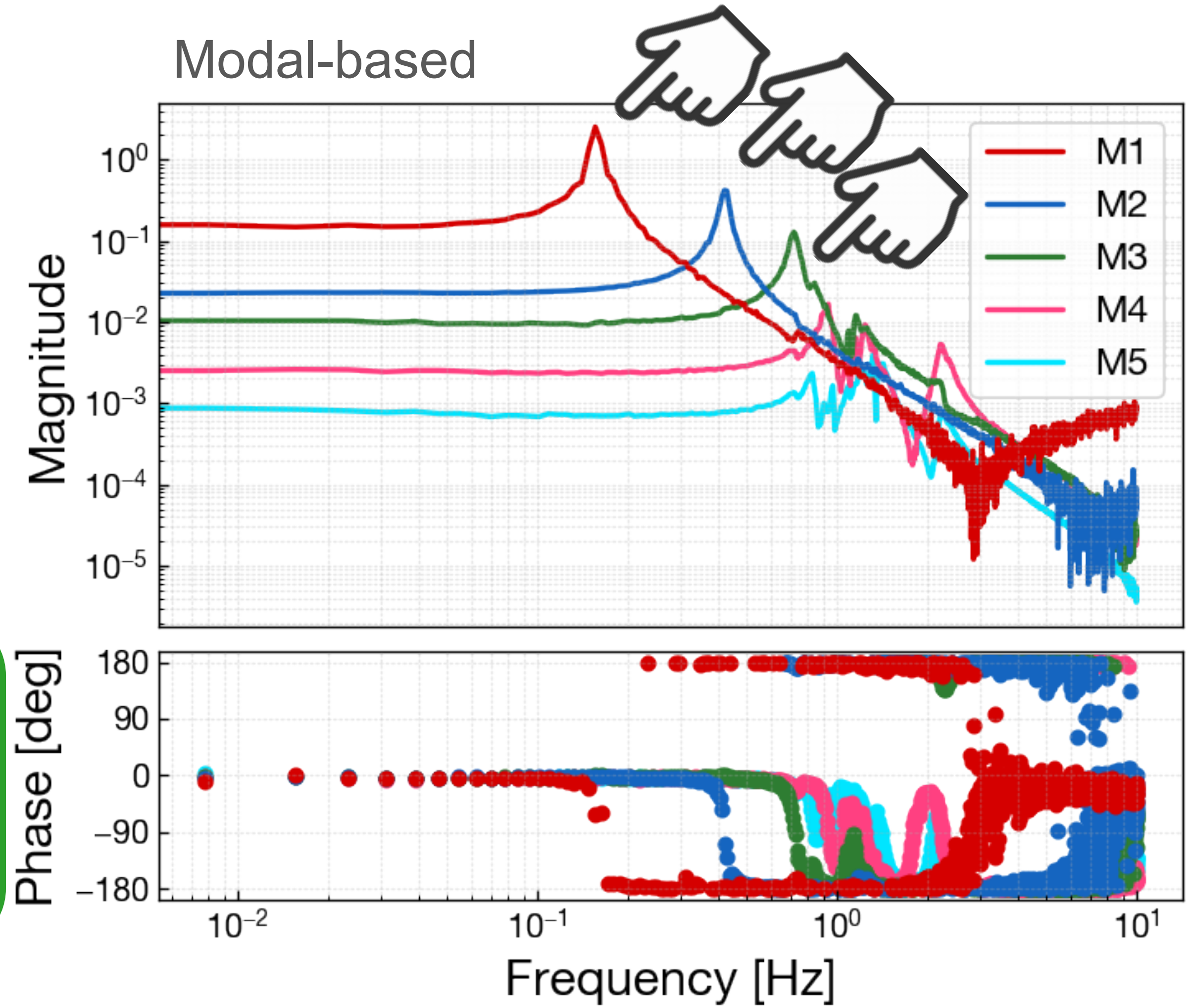
Decoupled into a set of single pendulum responses

Measured Modal Decomposition

Stage-based

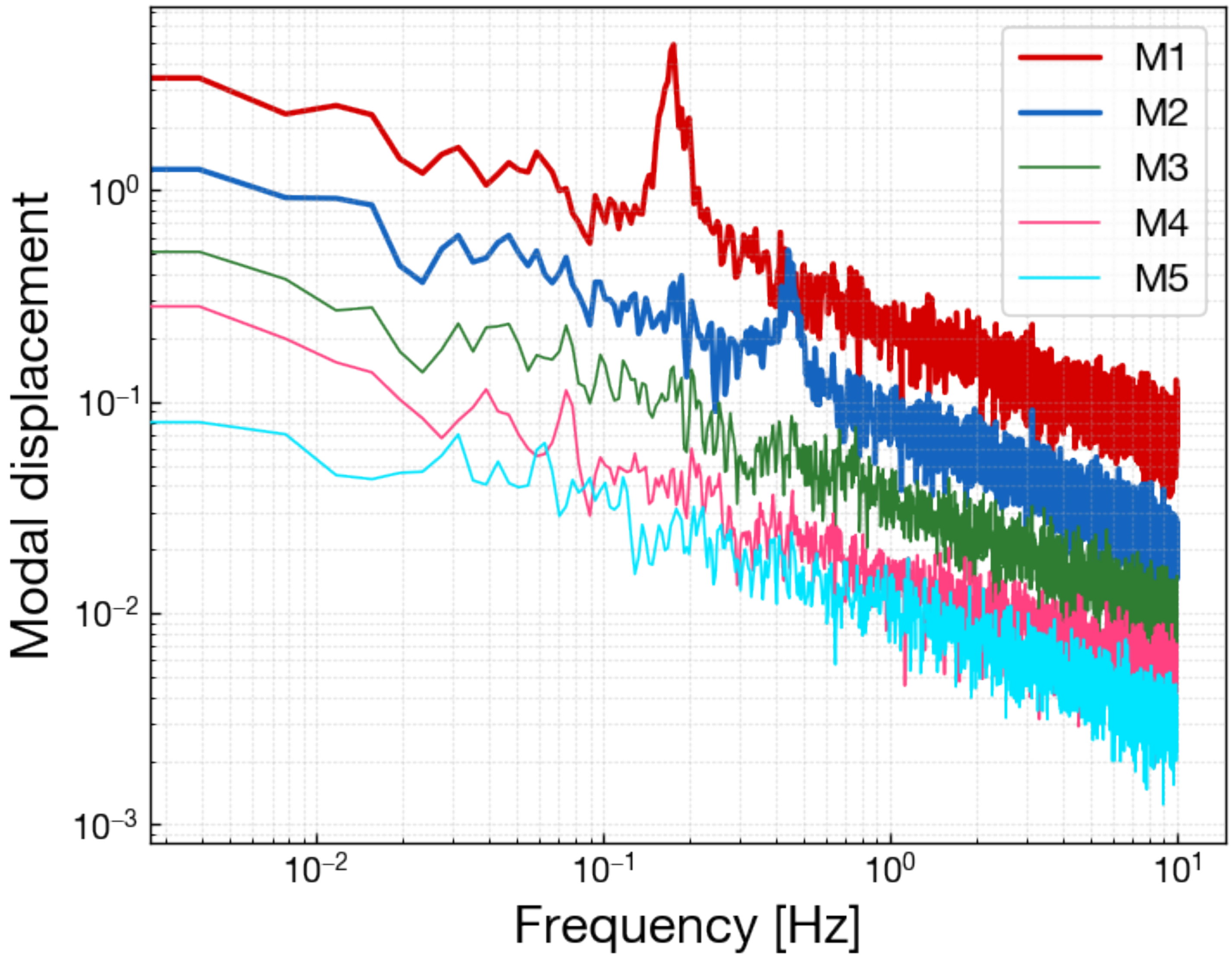


Modal-based

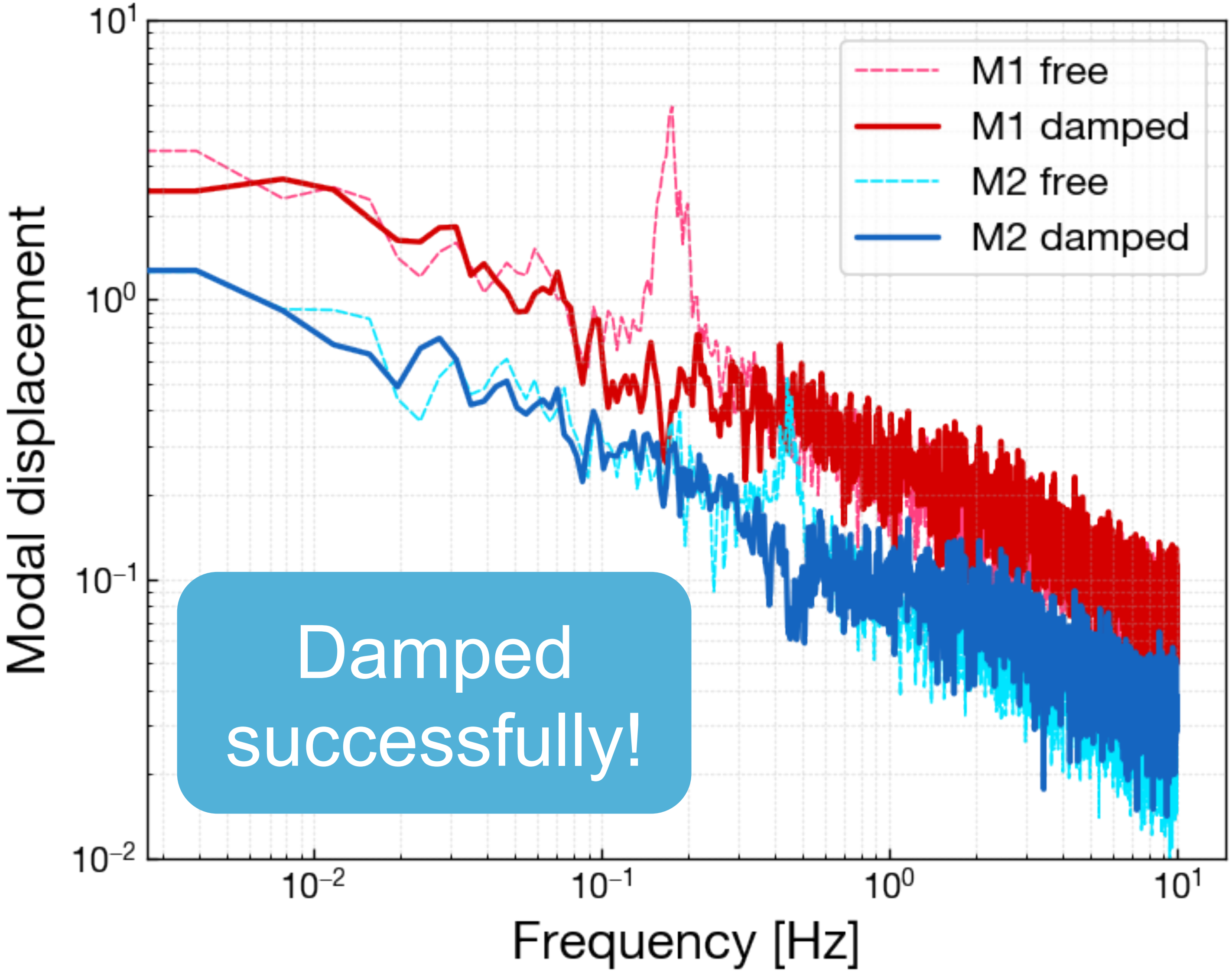


Lower-order modes well decomposed

GAS Modal Spectrum (No Control)



1^{st} + 2^{nd} Modal Loop Closed



Other Topics

Transfer function measurement

- 🙂 Gross behavior is as expected (IP, BF)
- 😐 GAS mode shape mismatch

Modal Damping in GAS chain

- 🙂 Lower-order modes decoupled
- 🙂 Modal damping worked
- 😐 Decay time performance: to be checked

Torsion mode damping

- 🙂 RMS ~ 230 nrad < req.
- 🙂 Yaw decay time < 1 min.

Vibration isolation ratio measurement (full suspension)

- 🙂 Estimated: 10^{-21} < req.
- 😐 Model vs measurement mismatch
- 😐 Only longitudinal, vertical also to be measured

Summary

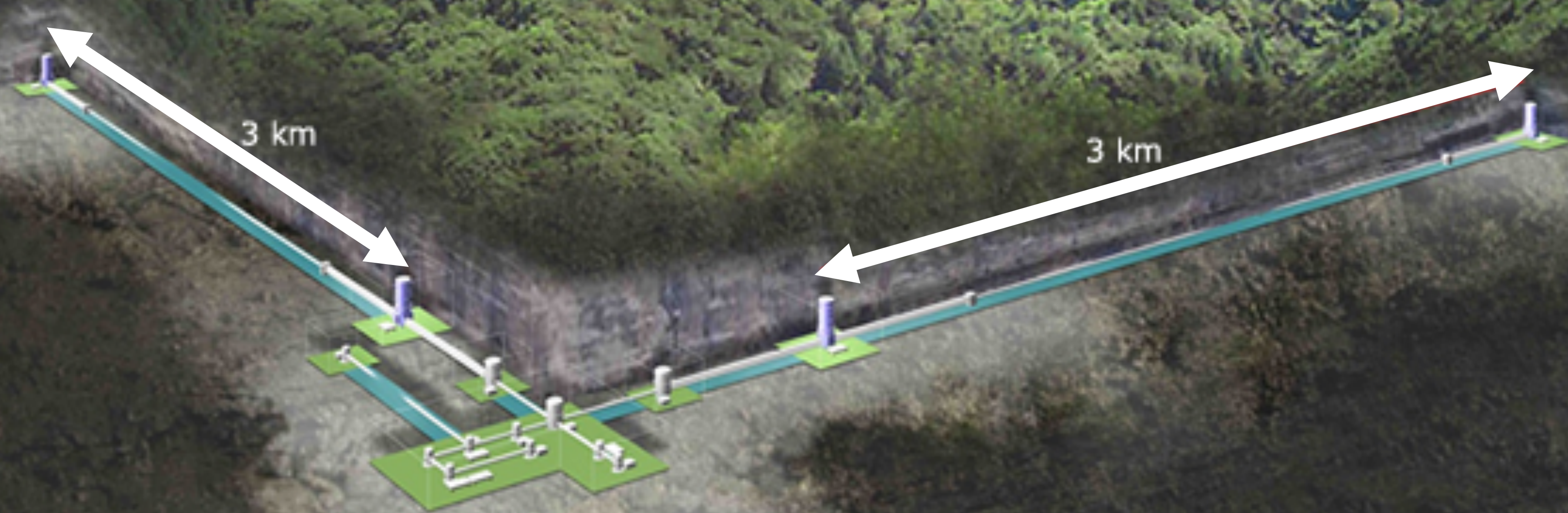
- The installed Type-A tower satisfies basic requirements for vibration isolation
- Modal damping is implemented and validated in GAS vertical mode control
- The Type-A suspension integrated with cryogenic payload is in commission

KAGRA

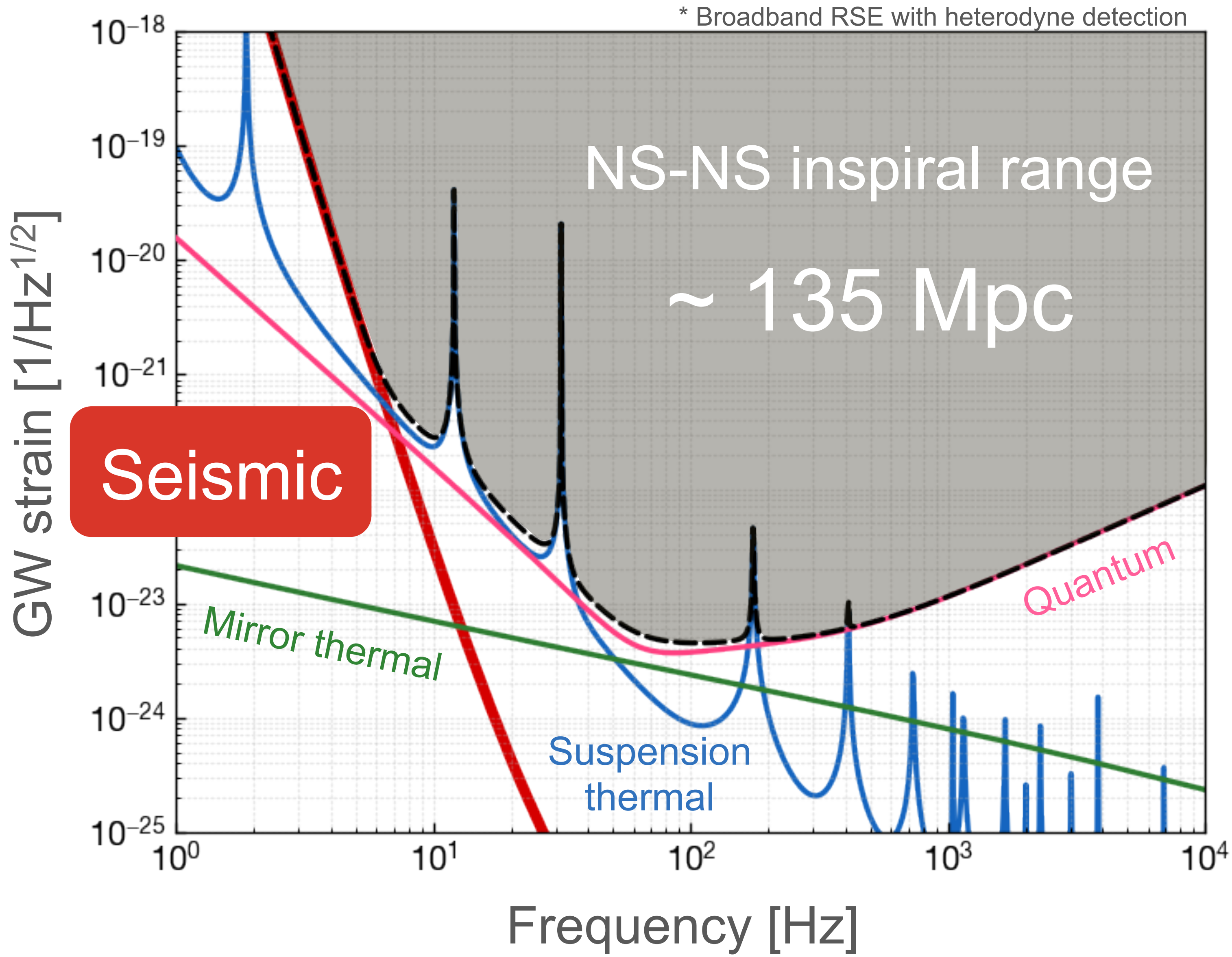
2.5th generation laser interferometer

Underground site ▶ Low seismic noise

Cryogenic sapphire mirror ▶ Low thermal noise



KAGRA Noise Breakdown



KAGRAの現状

2017年1月 ~ 2018年3月

大型防振システムのインストール・試験

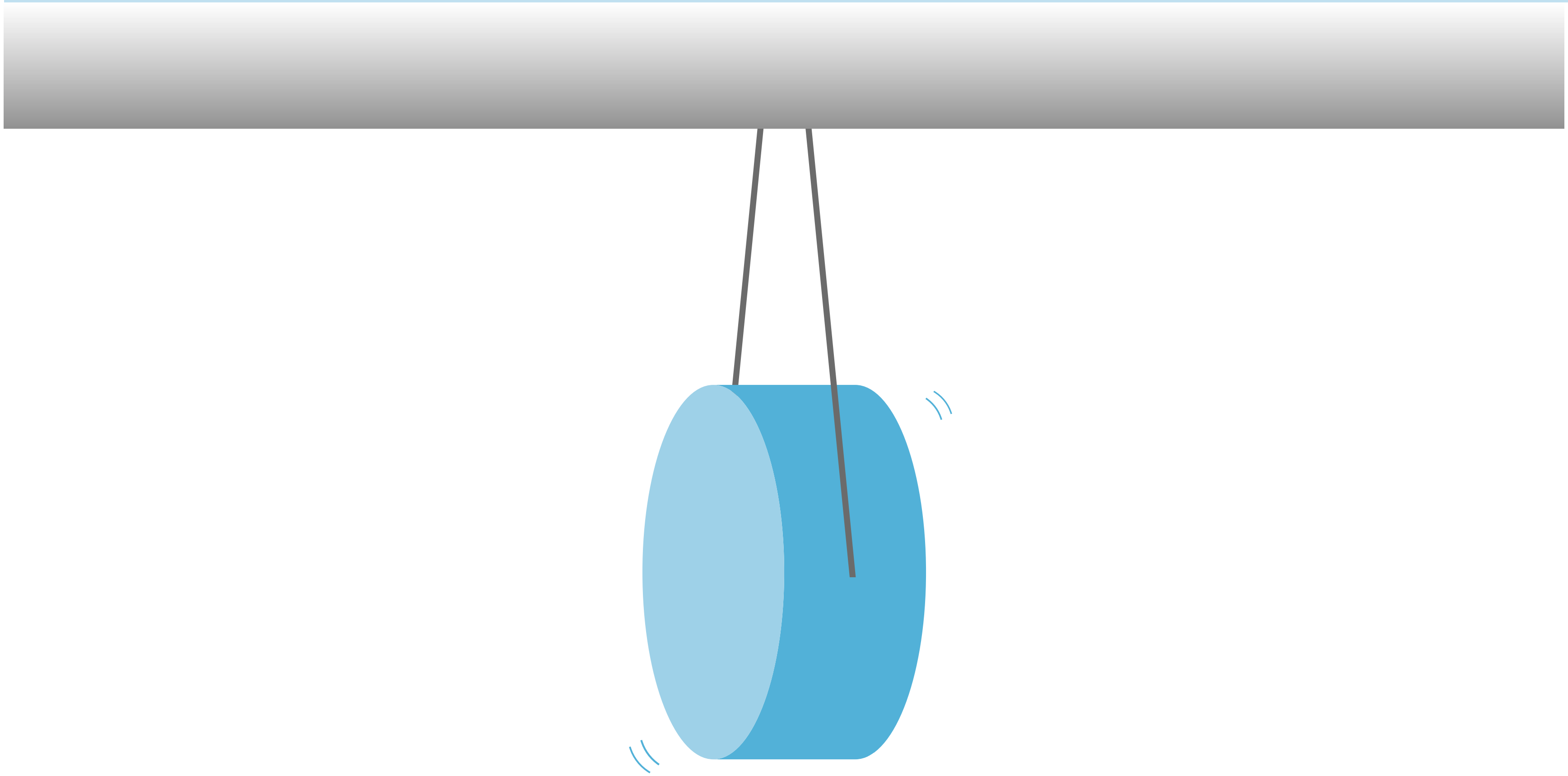
2018年4月28日 ~ 5月7日

低温Michelson干渉計でのengineering run

現在〜2019年

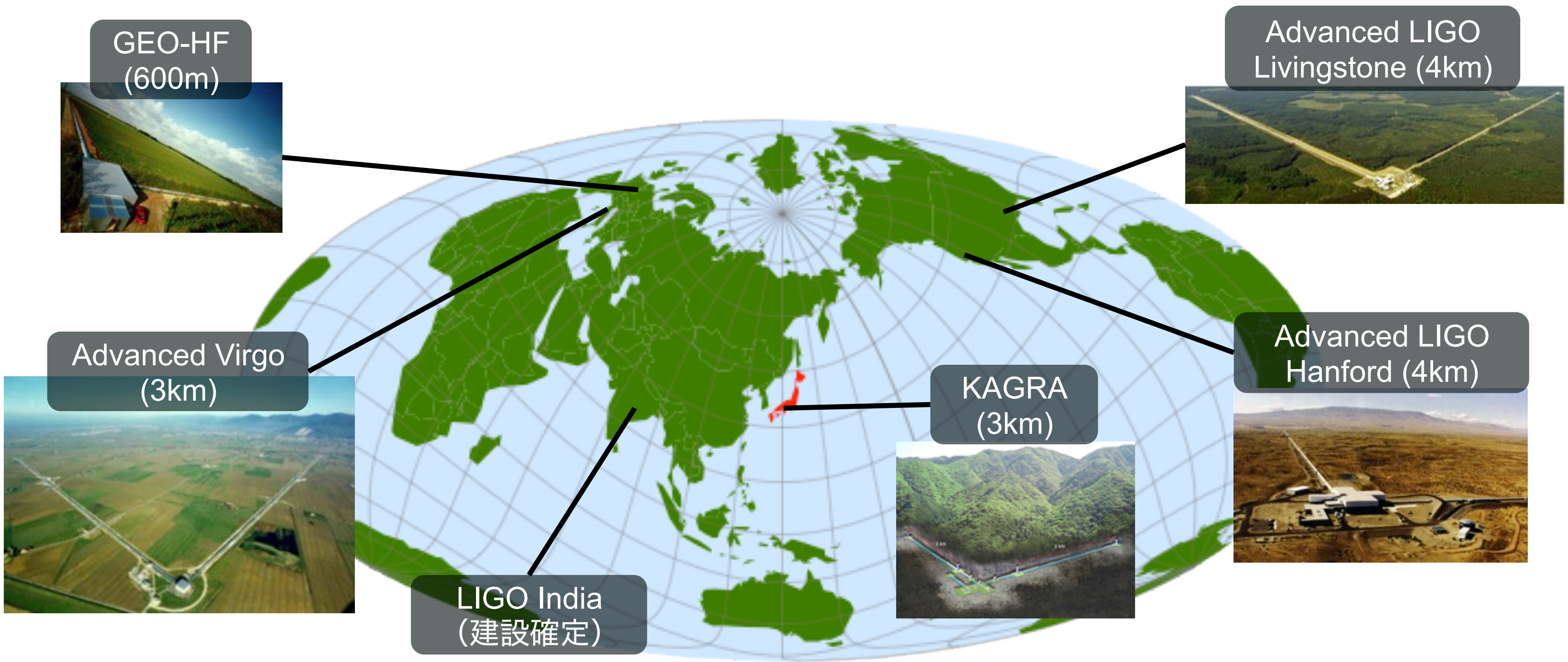
LIGO + Virgo observation run-3 (O3) 参加に向けて感度向上のためのアップグレード中

振り子による受動防振



地面から鏡へ伝わる振動 $\propto f_0{}^2 / f^2$

KAGRAの位置付け

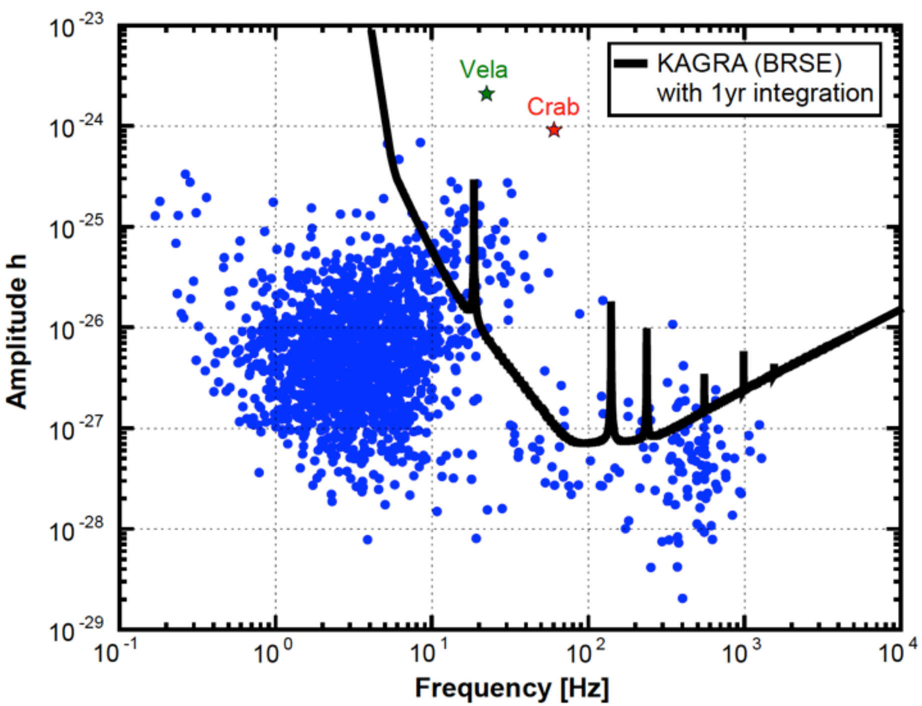


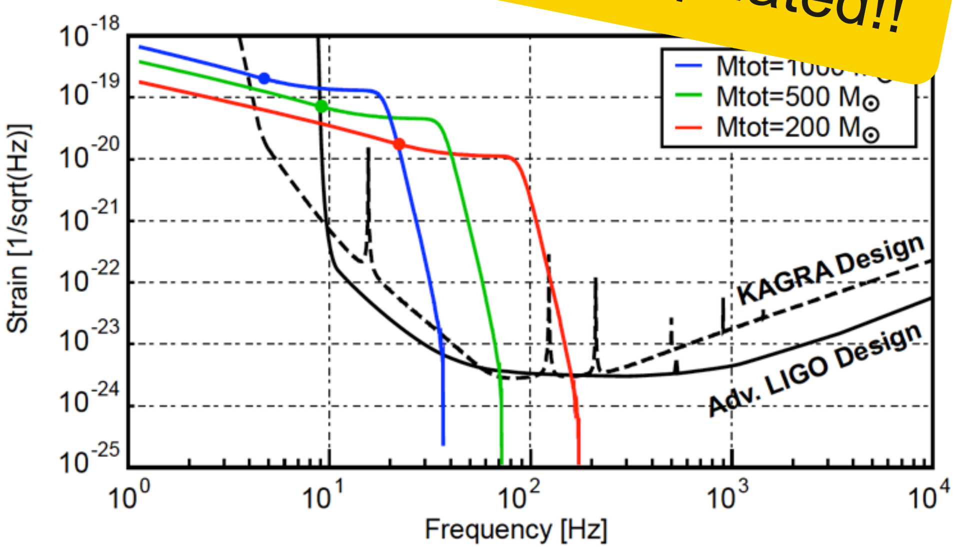
- Adv. LIGO + Adv. Virgo + KAGRA での同時観測シナリオを計画中、一刻も早い本格稼働が望まれている
- 地下環境＋低温技術 ▶ 第3世代望遠鏡への応用

低周波帯における感度改善の意義

- コンパクト連星合体のパラメータ決定推定精度の向上
- 非対称な中性子星の自転
- 中間質量ブラックホール連星の合体

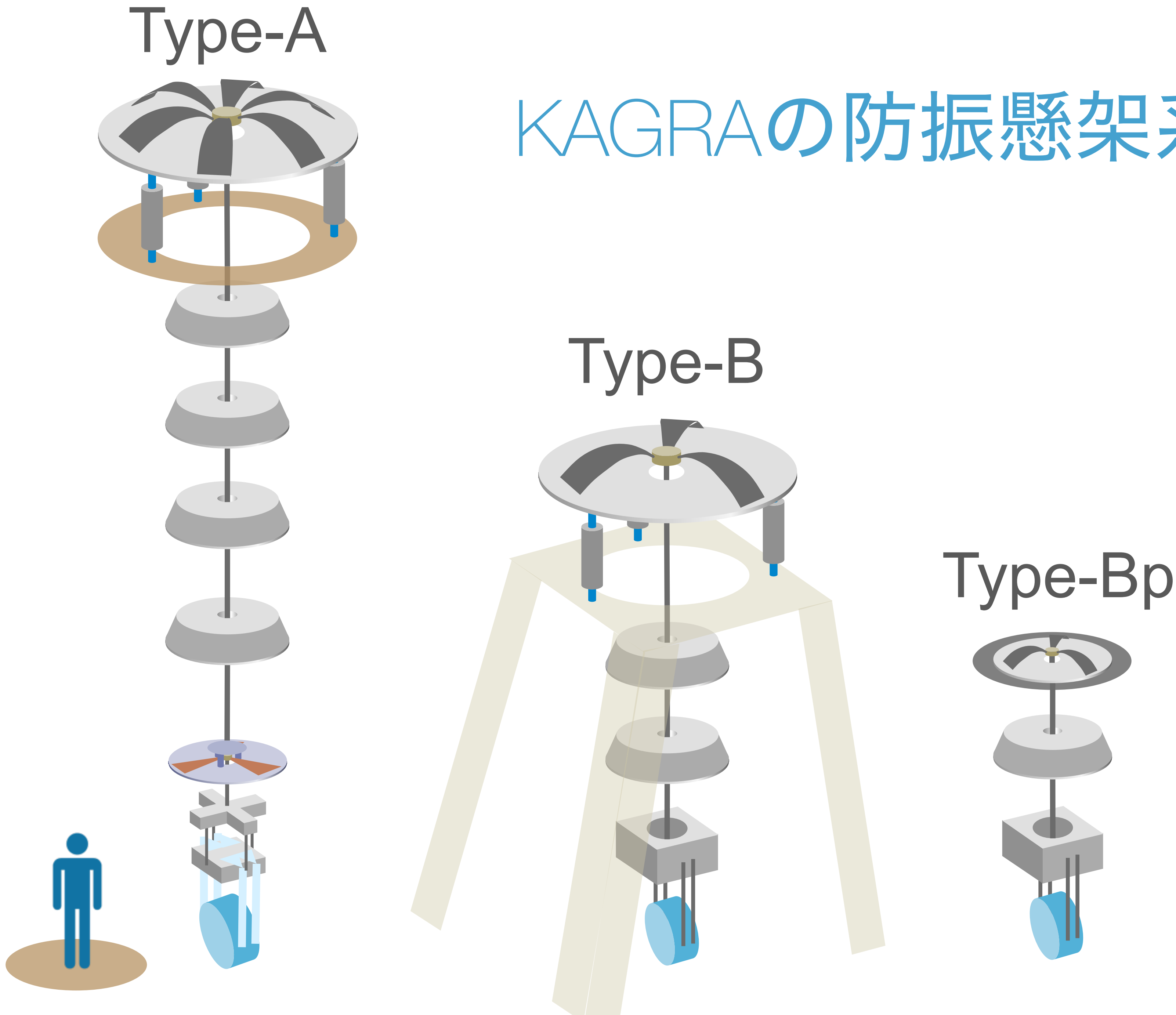
and more...



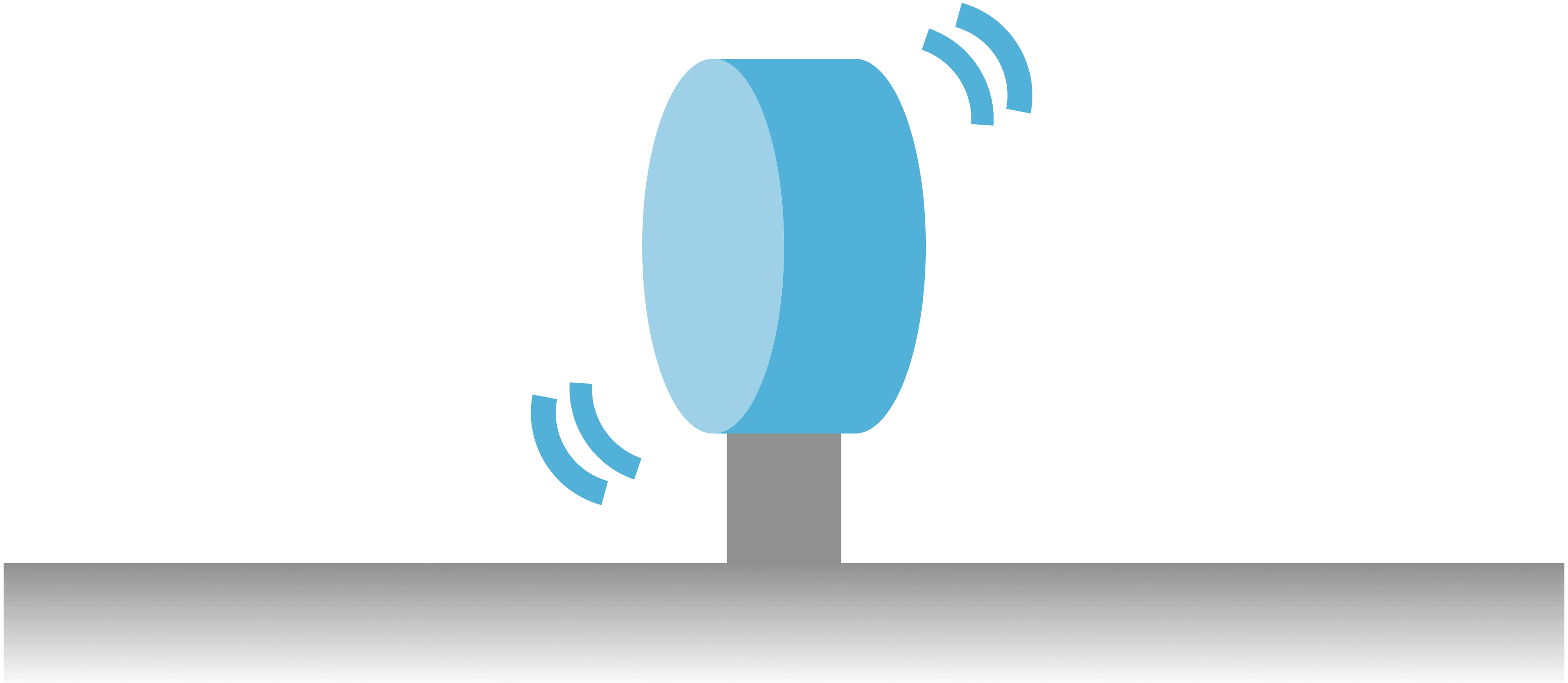


To be updated!!

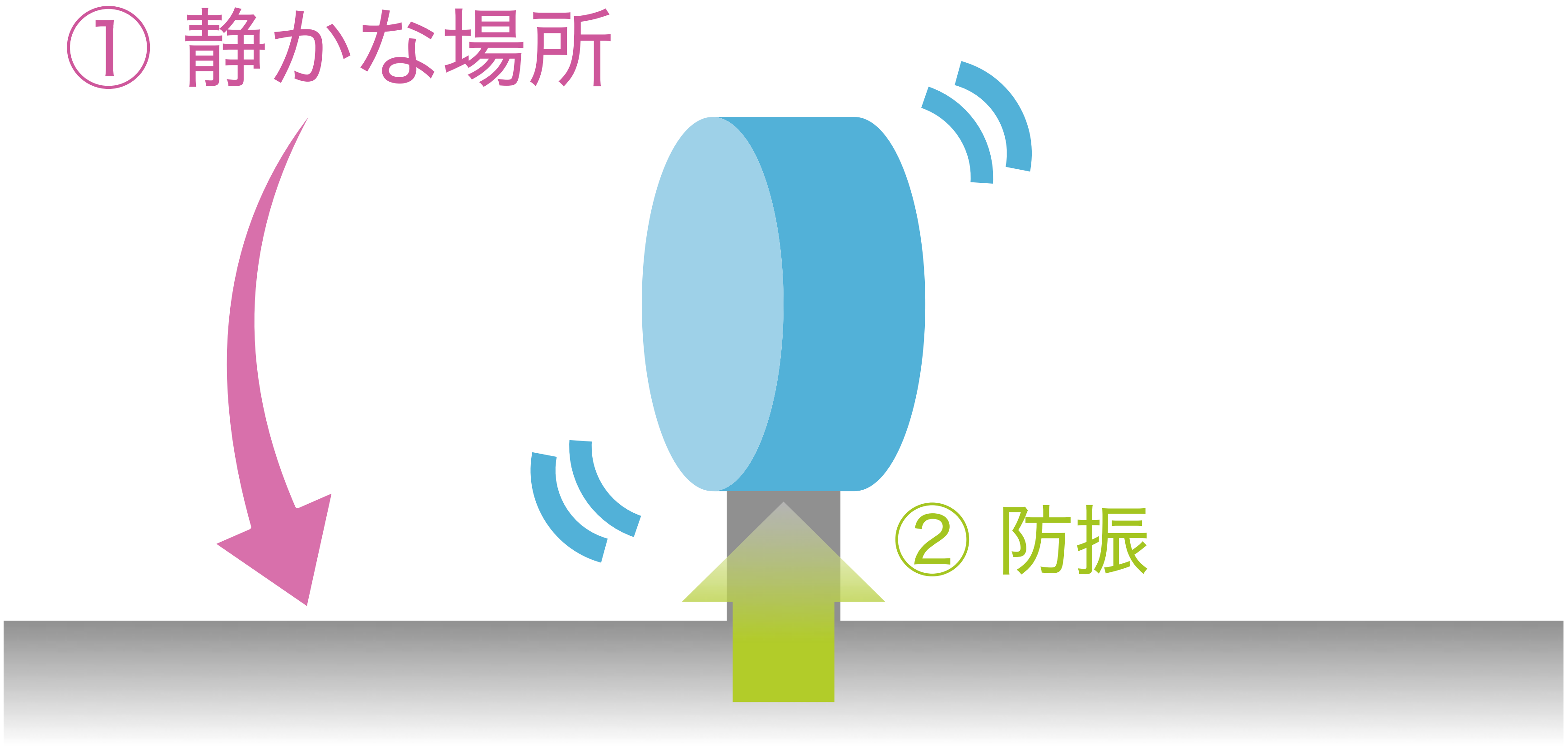
KAGRAの防振懸架系



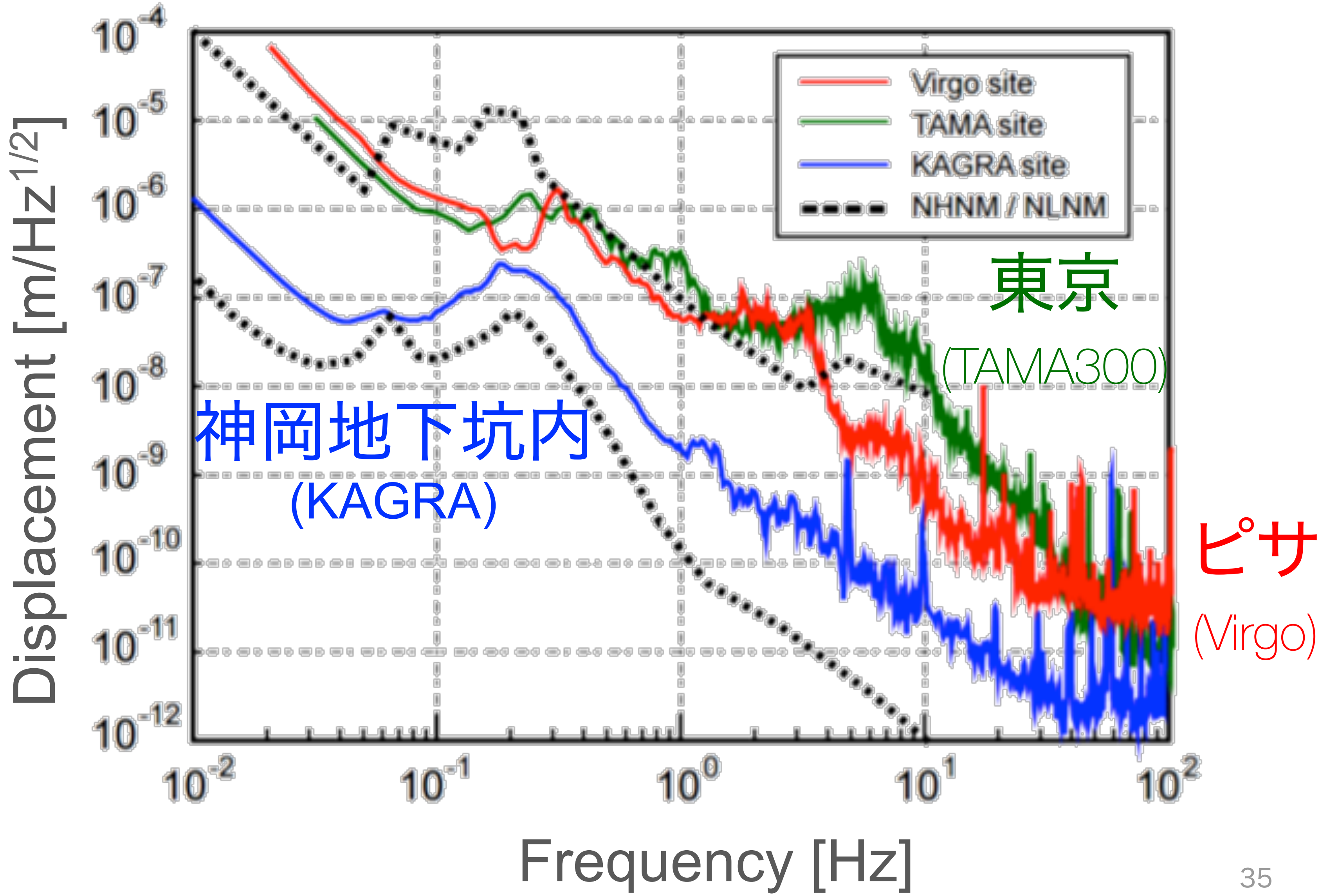
地面振動雑音とは



地面振動雑音を減らすには？

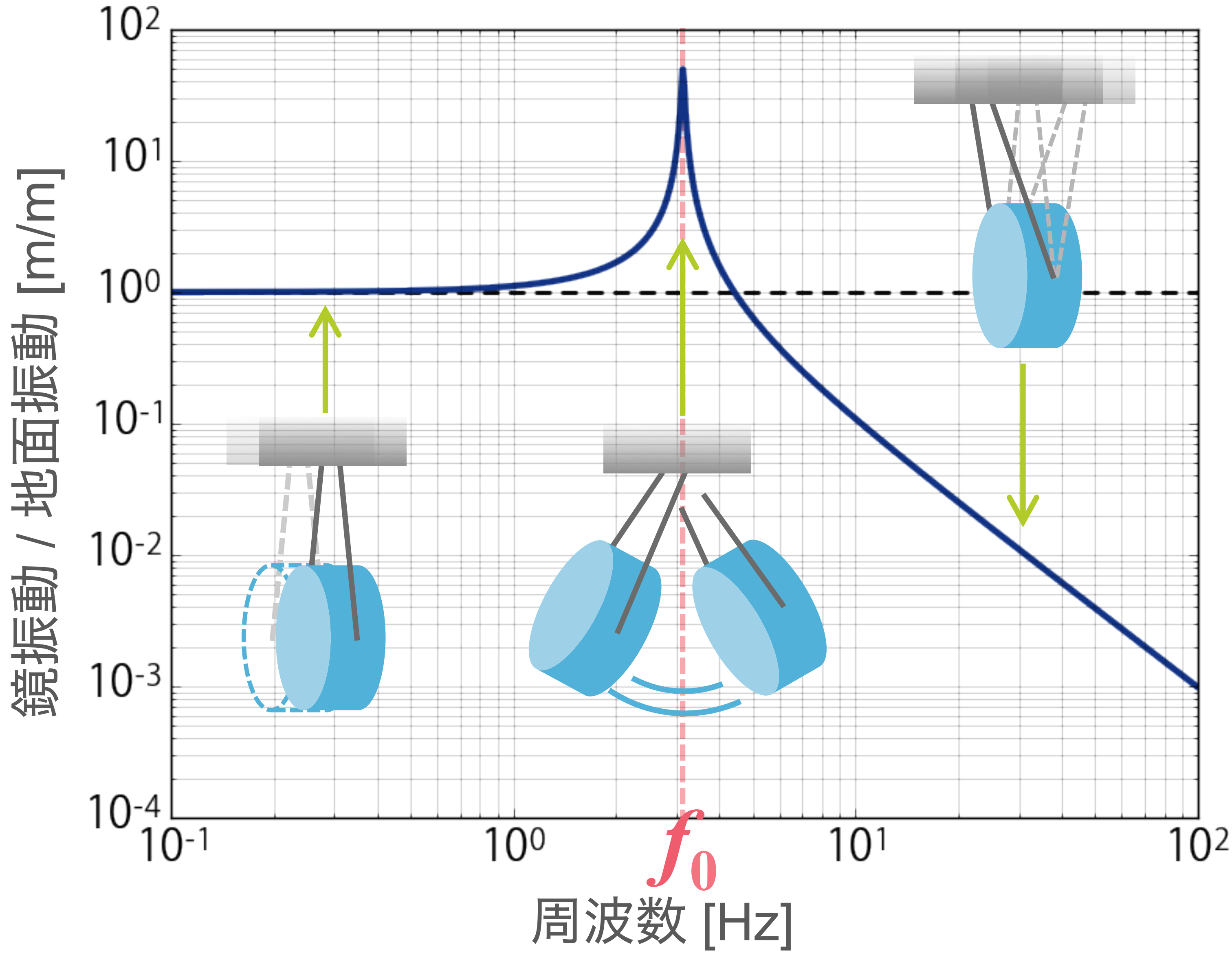


① 地下は静か

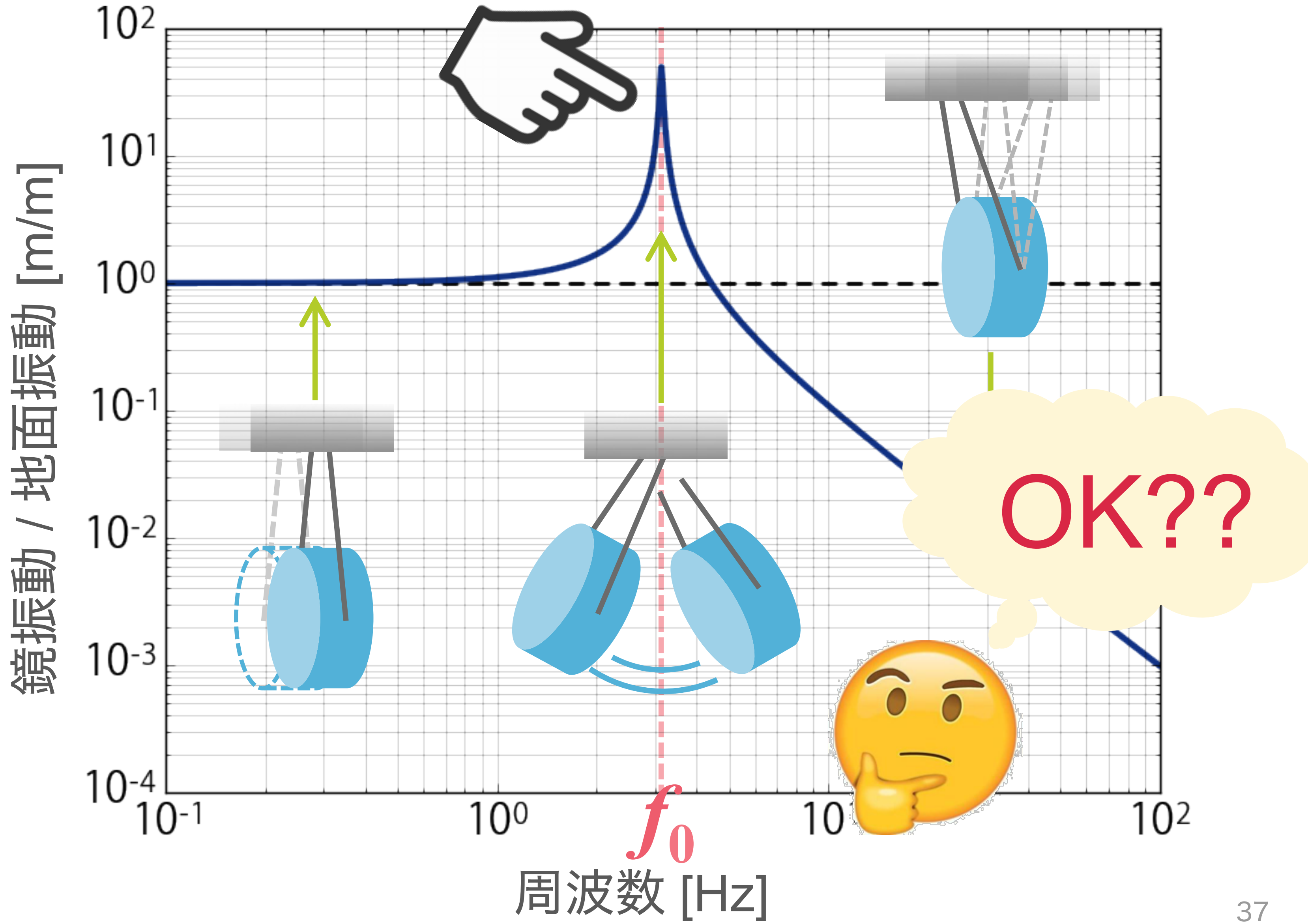


Virgo site
TAMA site
KAGRA site
NHNM / NLNM
東京
(TAMA300)
神岡地下坑内
(KAGRA)
ピサ
(Virgo)
Displacement [m/Hz^1/2]
Frequency [Hz]

振り子の周波数応答

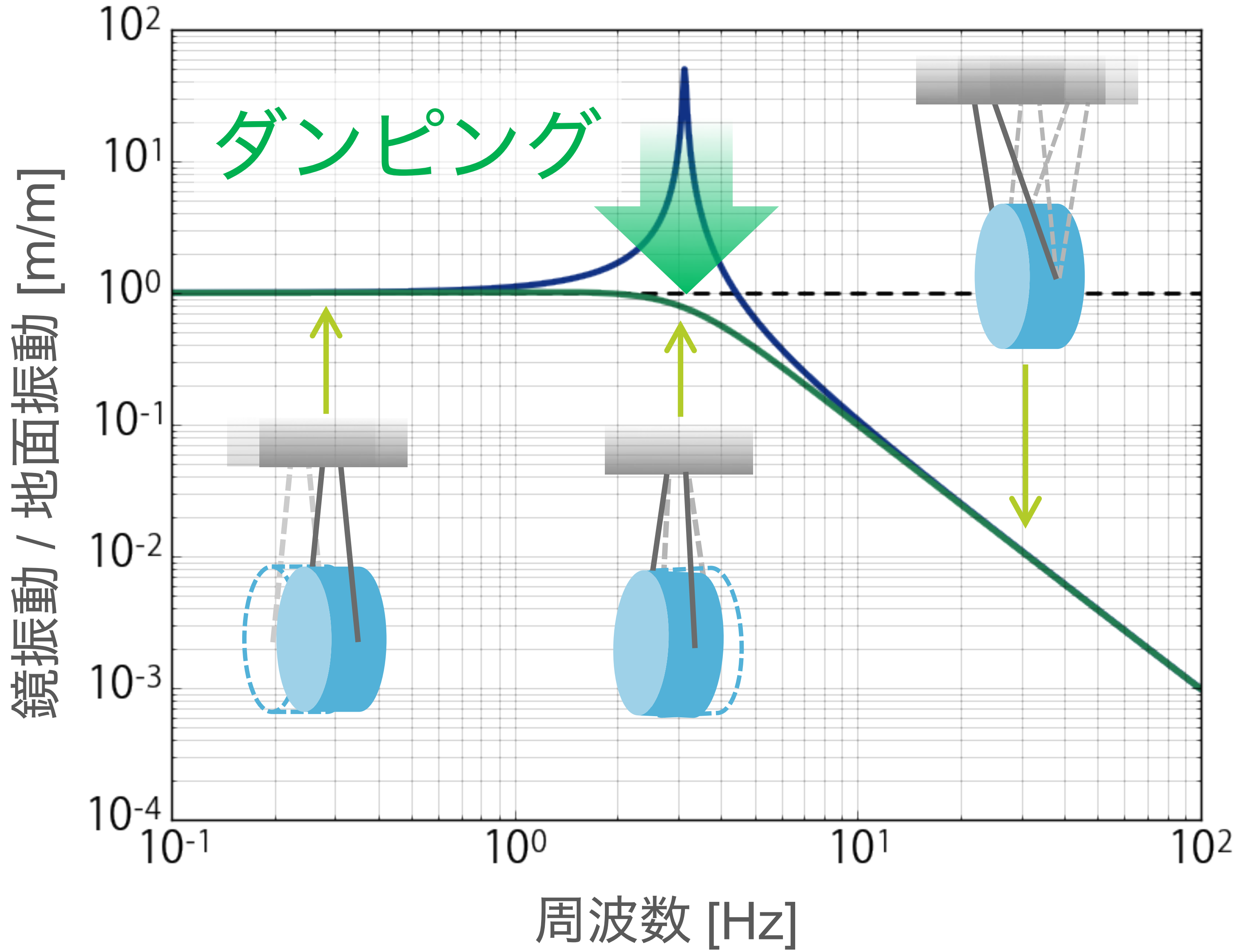


振り子の周波数応答

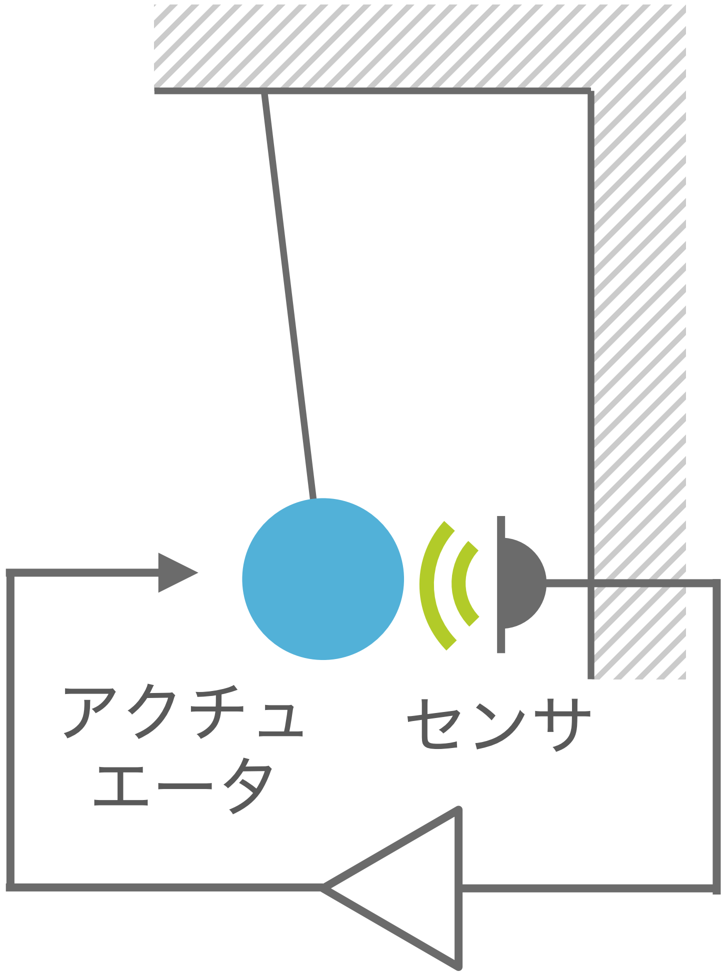


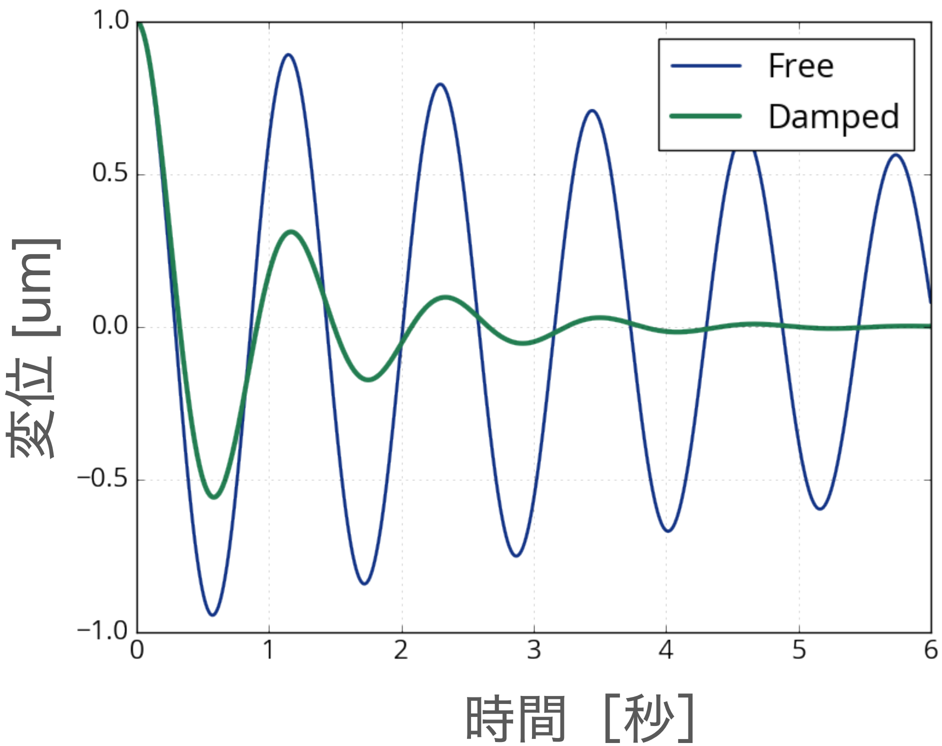
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
鏡振動 / 地面振動 [m/m]
10^{-1}
10^{0}
10^{1}
10^{2}
f_0
周波数 [Hz]
OK??

共振を抑制するには...



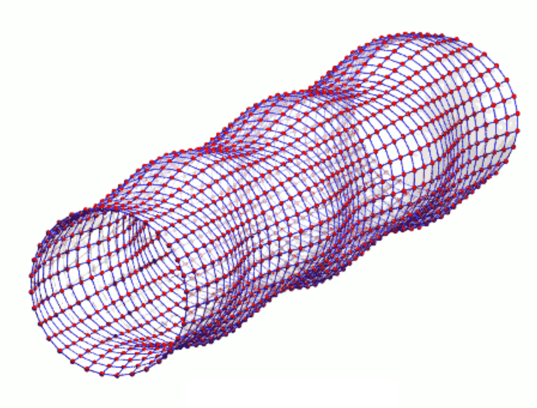
ダンピング制御



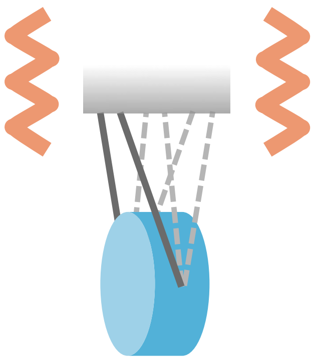


フィードバックされる力 ∝ マスの変位

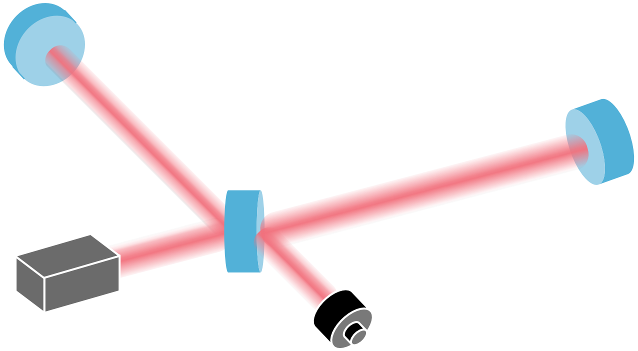
防振懸架系の役割



1. 重力波に対する
   自由落下応答



2. 地面振動からの防振

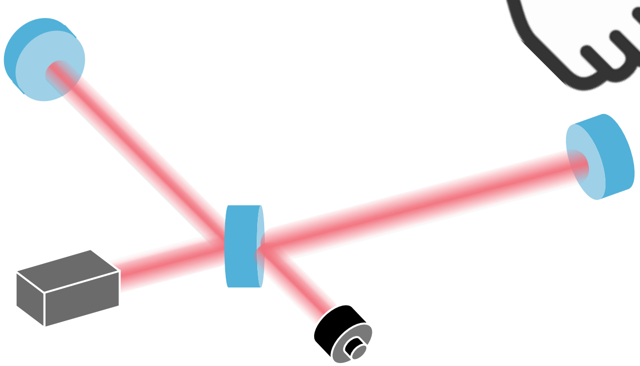


3. 干渉計の制御性能

Why Are Mirrors Suspended?

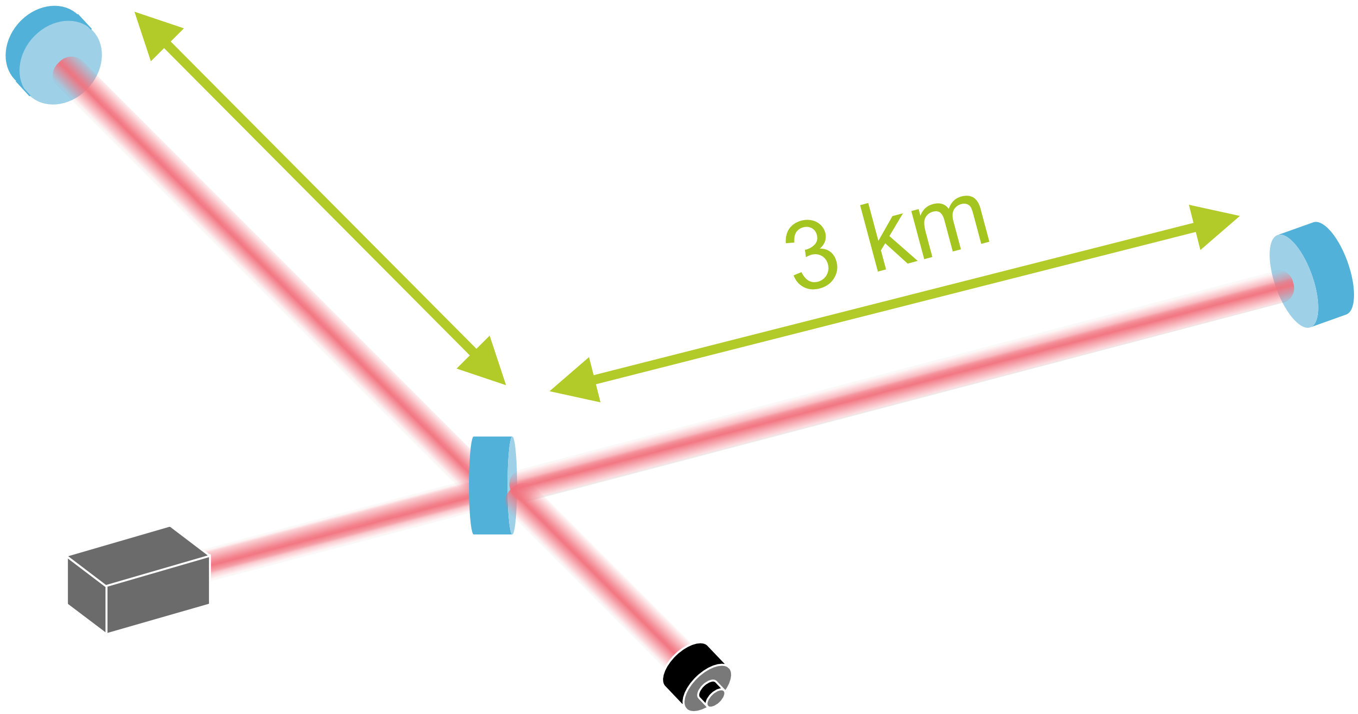
1. Geodesic (free-falling) response to GW

2. Vibration isolation

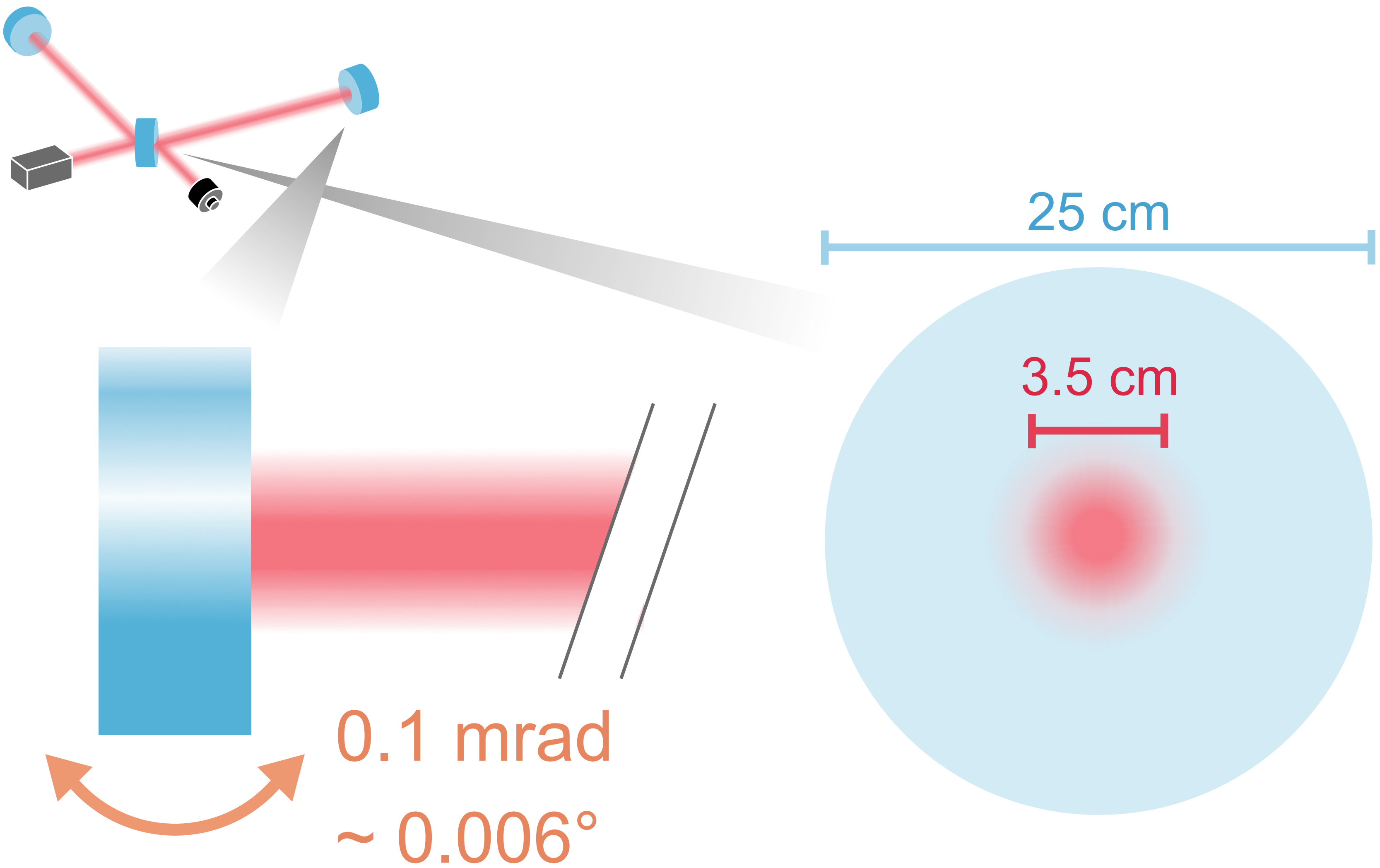


3. Interferometer control

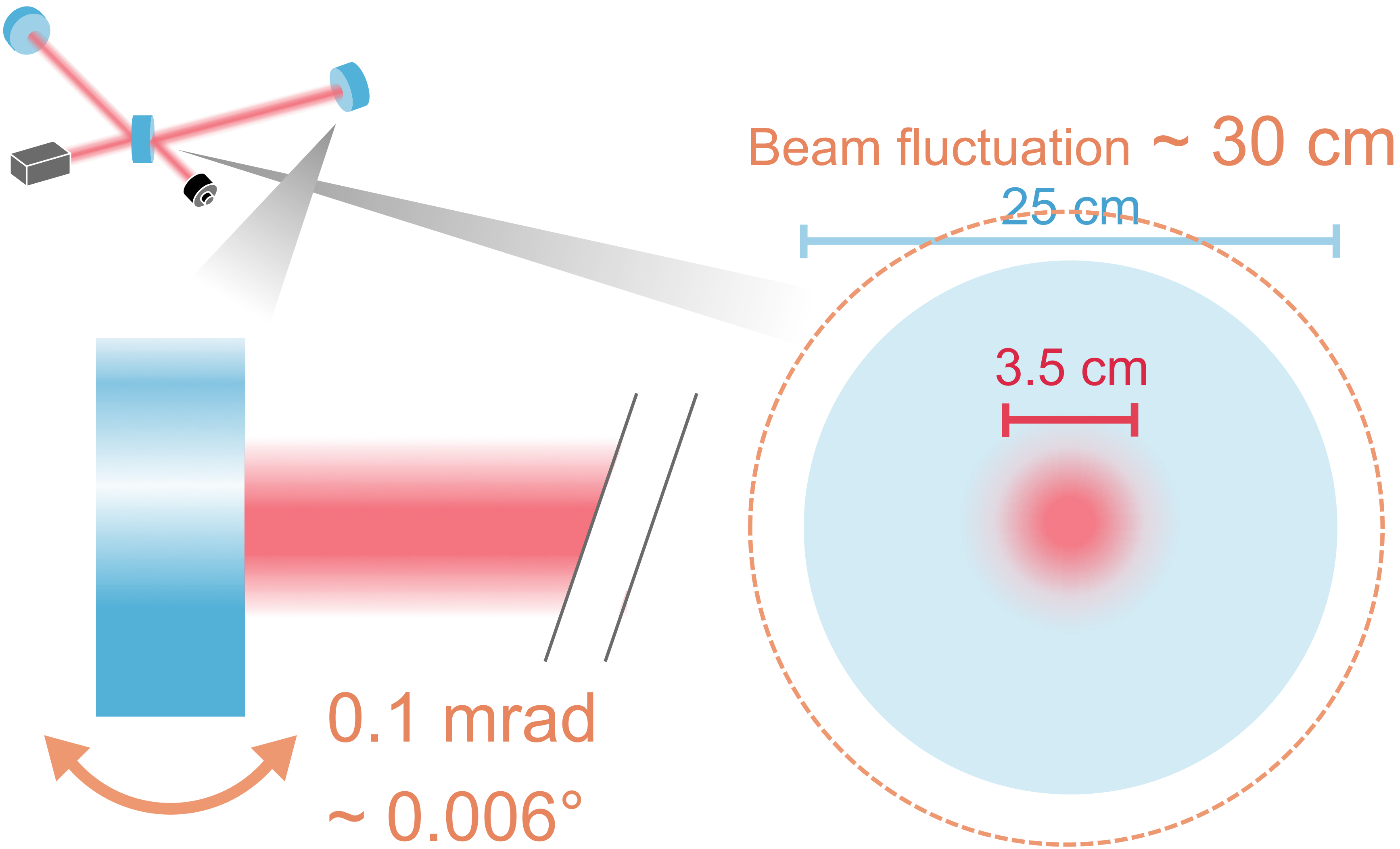
Michelson Interferometer



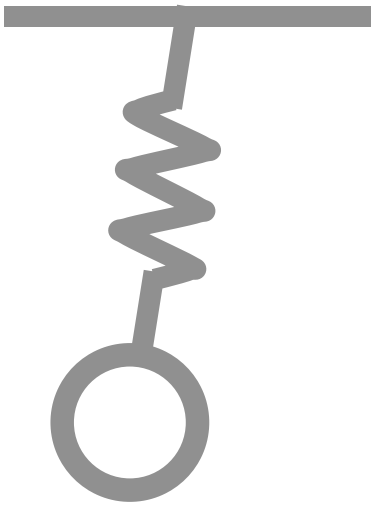
Mirror Alignment



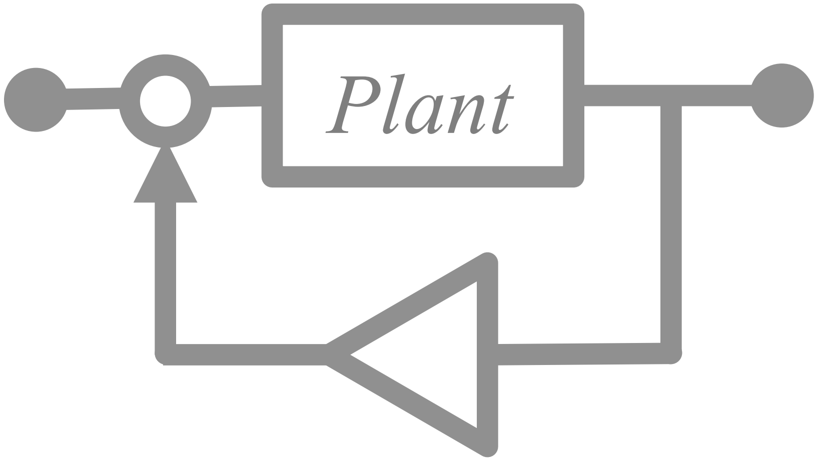
Mirror Alignment



防振懸架系の性能評価



機械的パラメータ
の同定

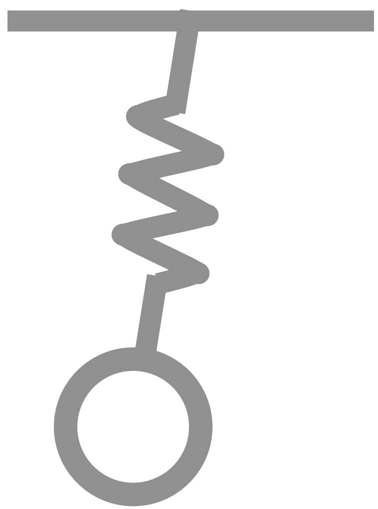


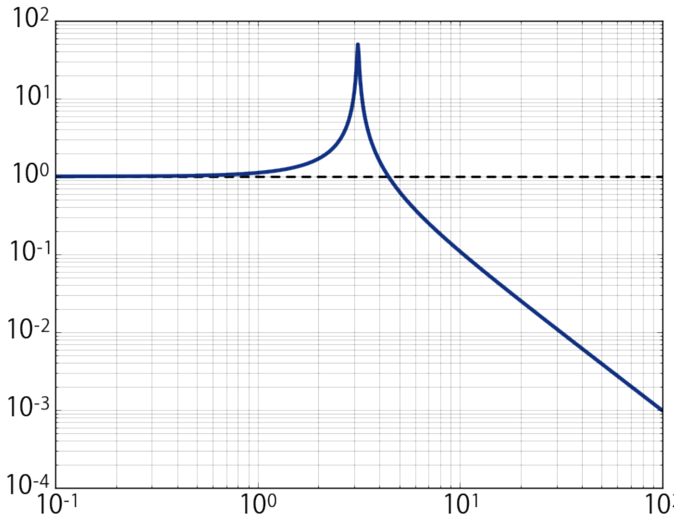
制御系設計

▶ 防振性能

▶ 制御性能

機械的パラメータの同定

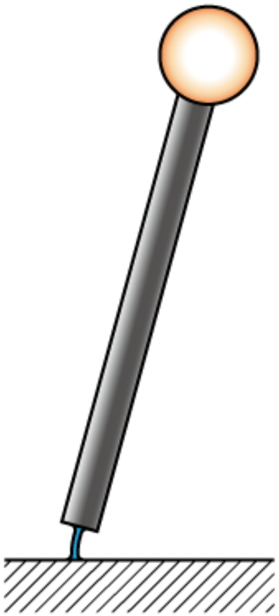




- 固有振動モード周波数
- 振動のQ値

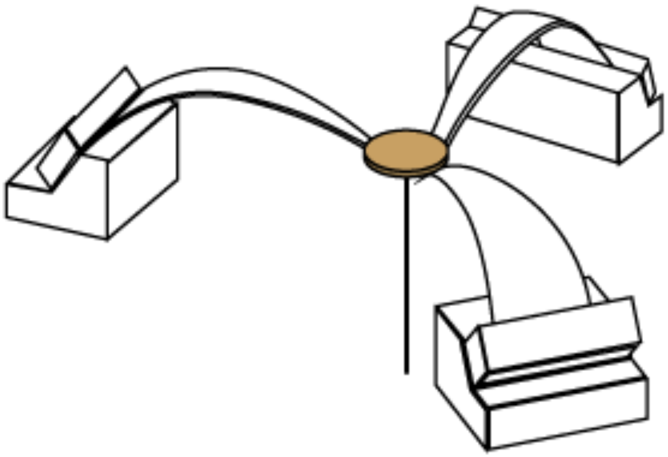
- 伝達関数の測定
- 3D剛体モデルシミュレーションとの比較

Anti-spring Mechanisms



Inverted pendulum (IP)

~ 0.07 Hz in horizontal

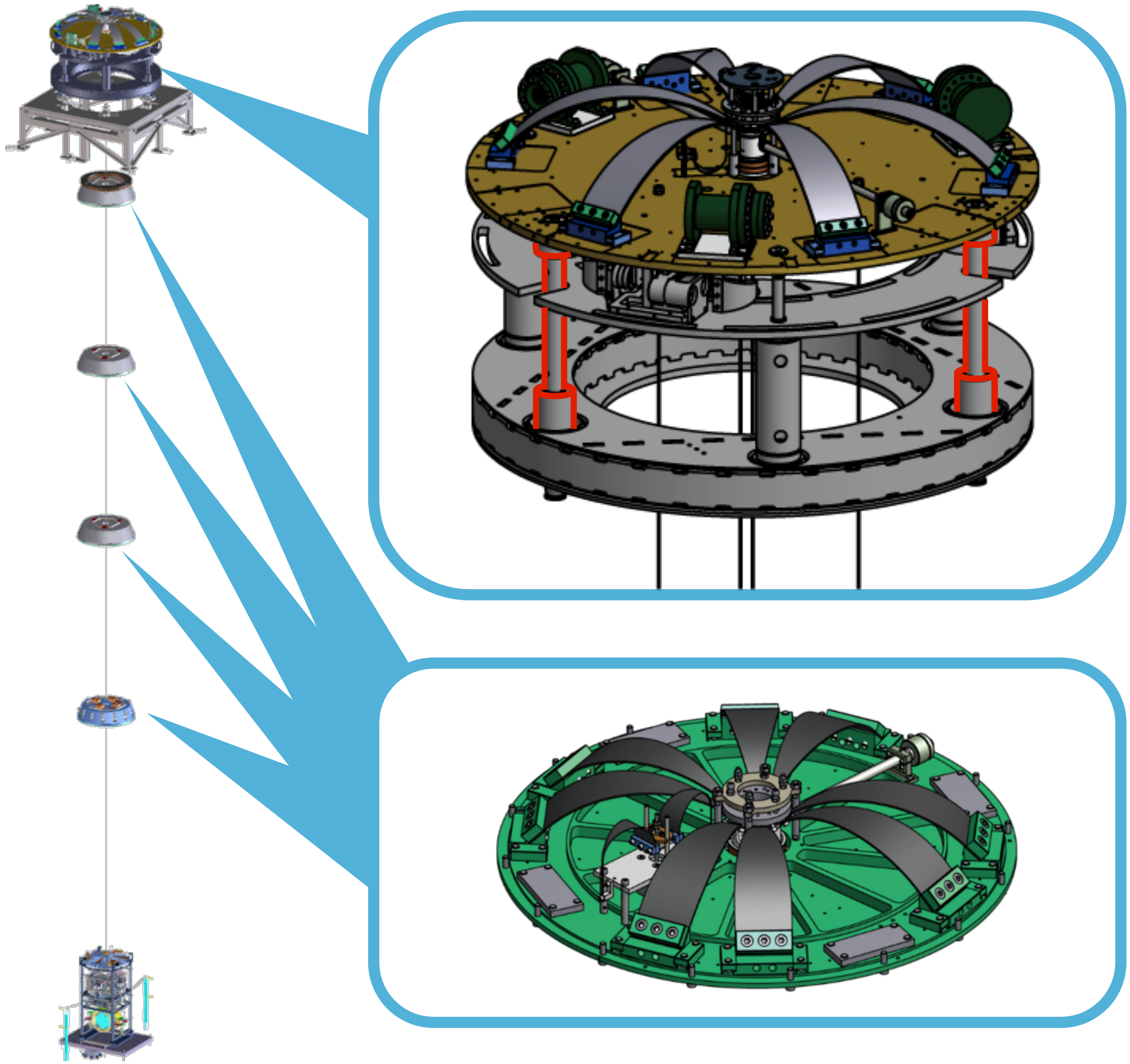


Geometric anti-spring (GAS)

~ 0.3 Hz in vertical

▶ Adjustable resonant frequency

Anti-spring Mechanisms



IP

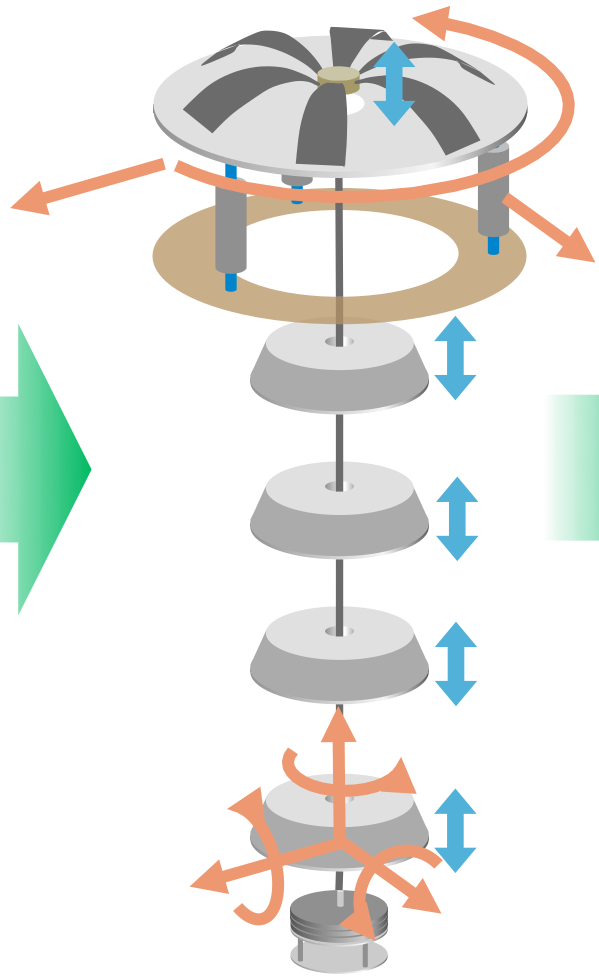
Top stage

GAS

All tower stages

伝達関数の測定

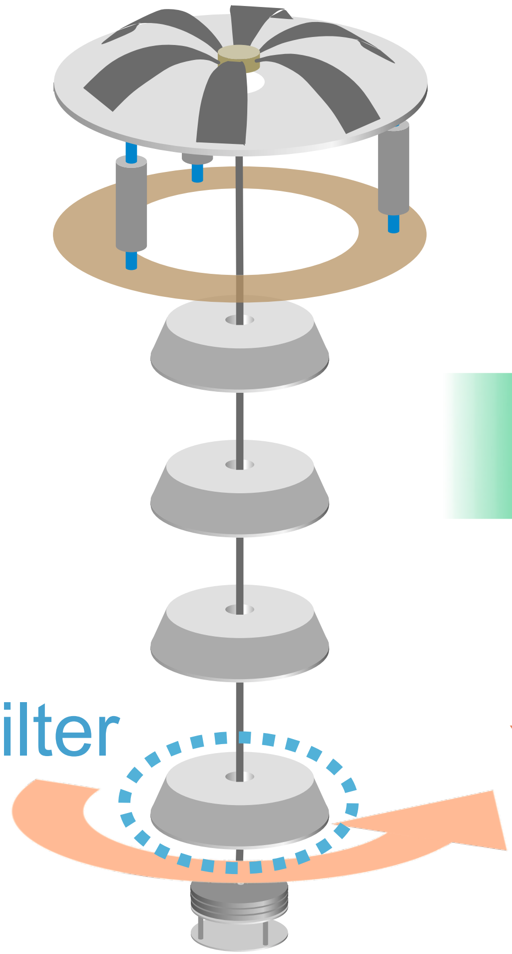
力
or
トルク



並進変位
or
角度変位

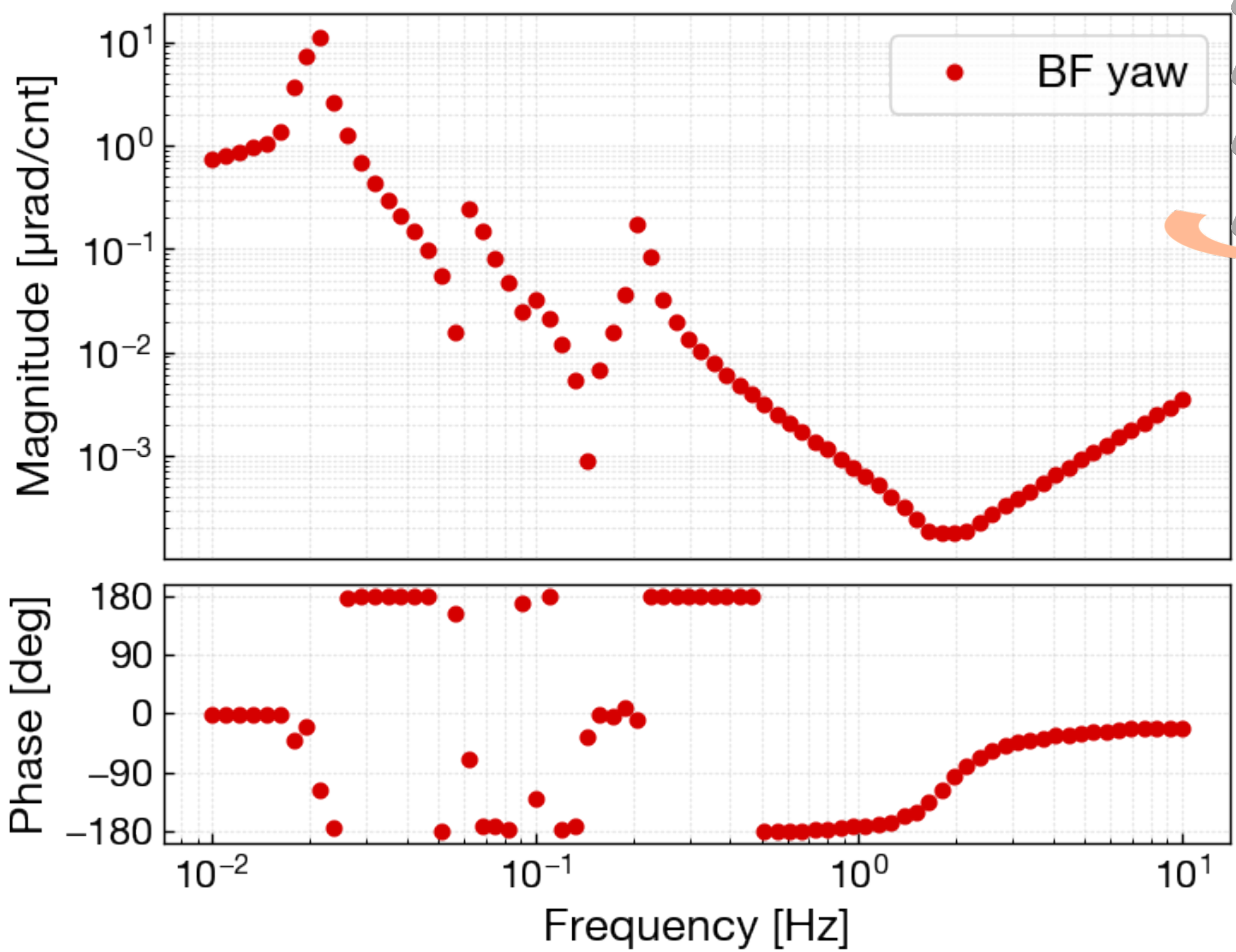
伝達関数の測定

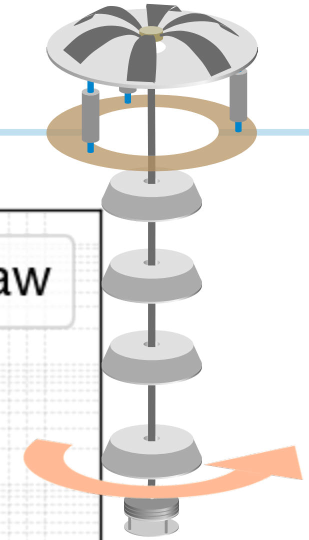
力
or
トルク



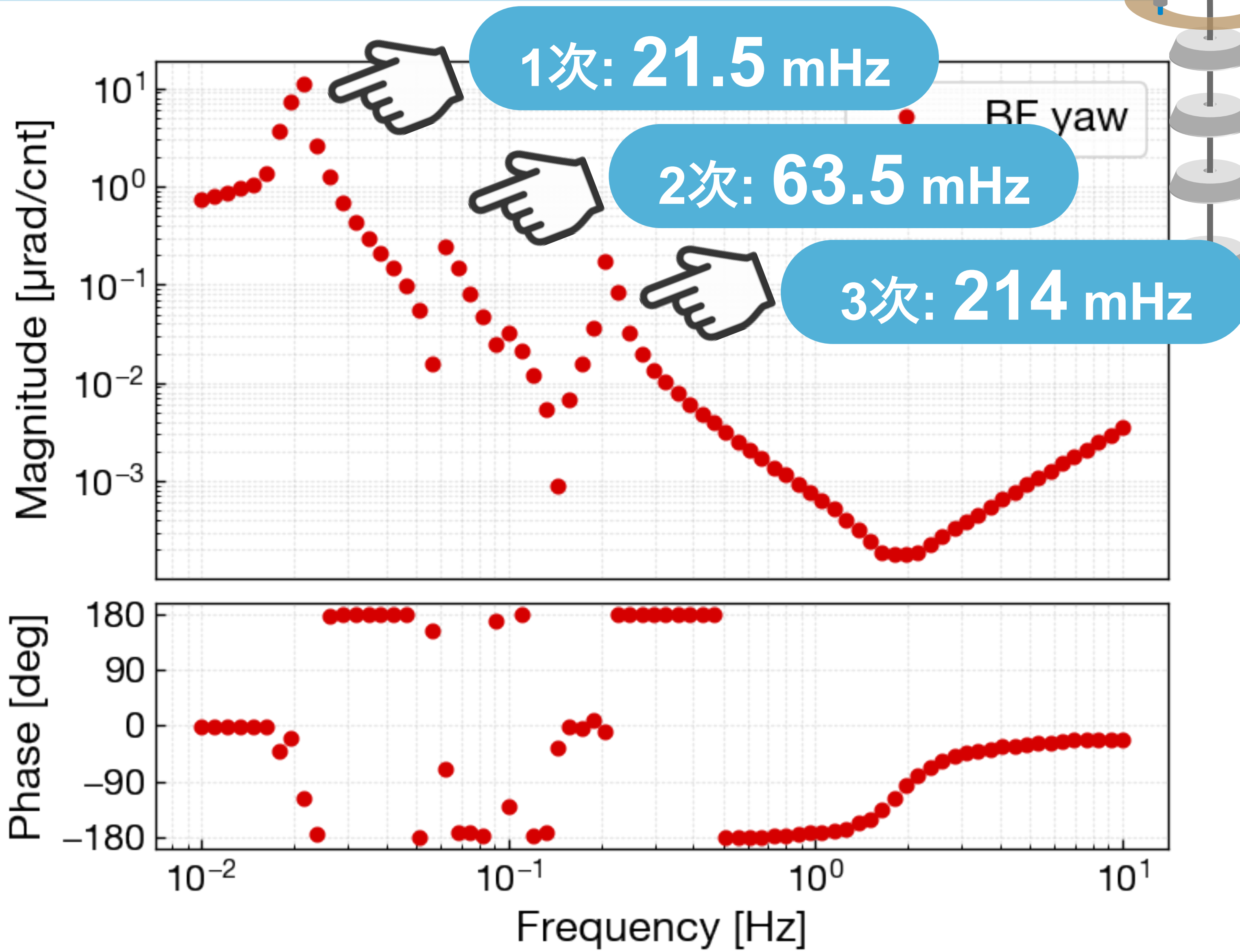
並進変位
or
角度変位

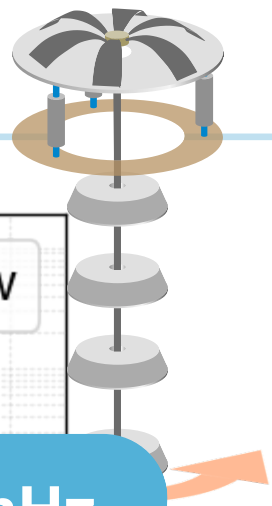
トルク角度伝達関数 (BF Yaw)



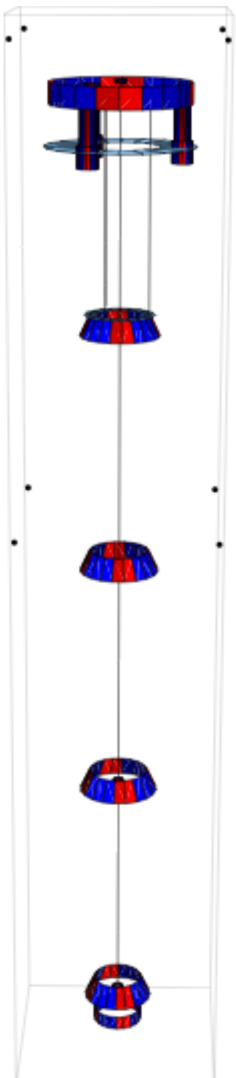


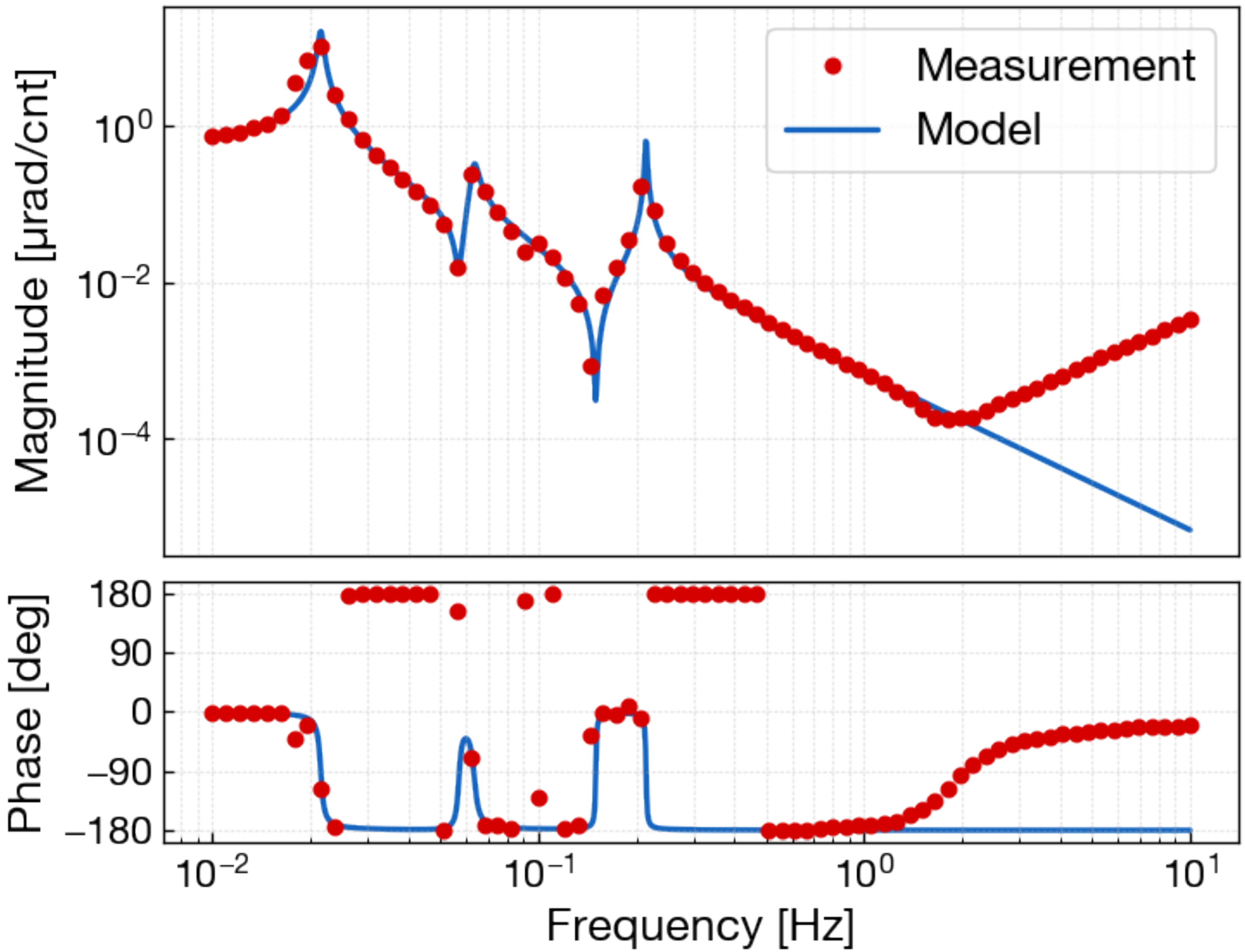
トルク角度伝達関数 (BF Yaw)





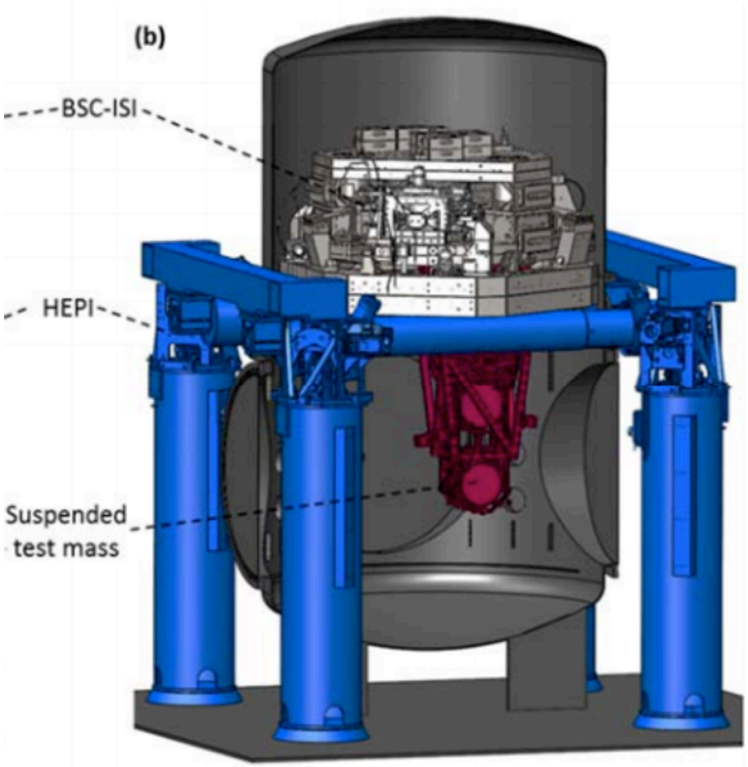
モデルとの比較





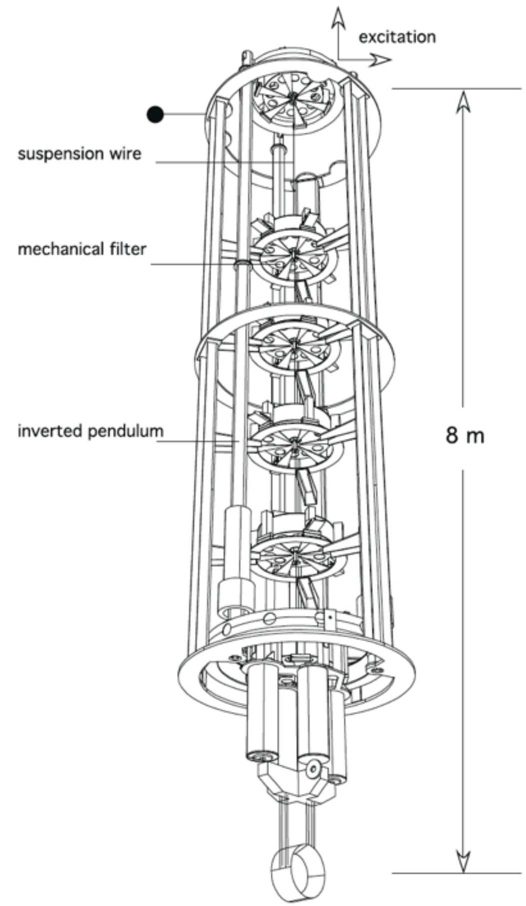
Measurement
Model
Magnitude [μrad/cnt]
10^{0}
10^{-2}
10^{-4}
Phase [deg]
180
90
0
−90
−180
10^{-2}
10^{-1}
10^{0}
10^{1}
Frequency [Hz]

重力波分野における防振システム



LIGO: Quad suspension

~ 10^{-12} m/Hz$^{1/2}$ @ 10 Hz



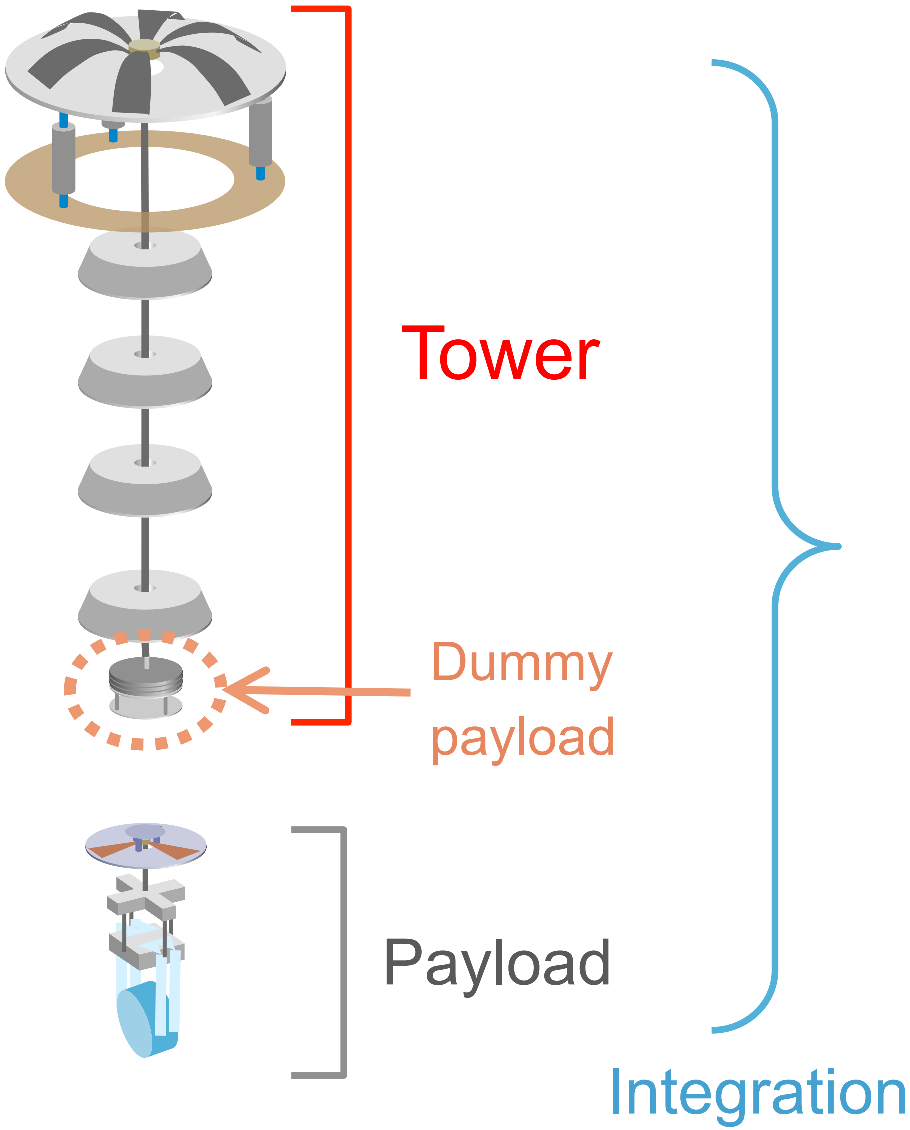
Virgo: Superattenuator

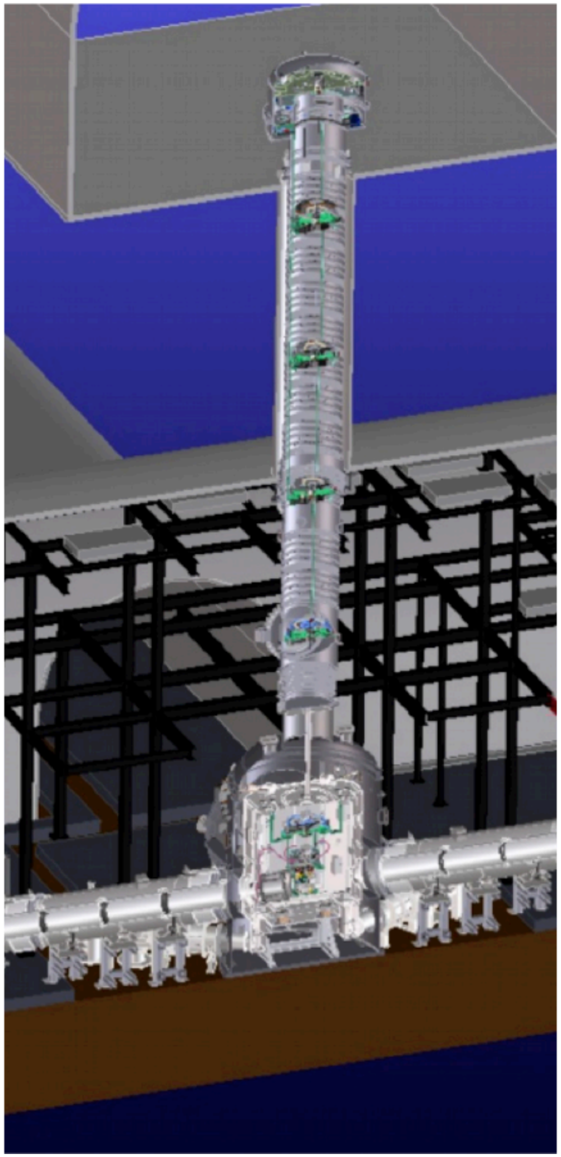
~ 10^{-23} m/Hz$^{1/2}$ @ 10 Hz

Requirements for Type-A Suspension

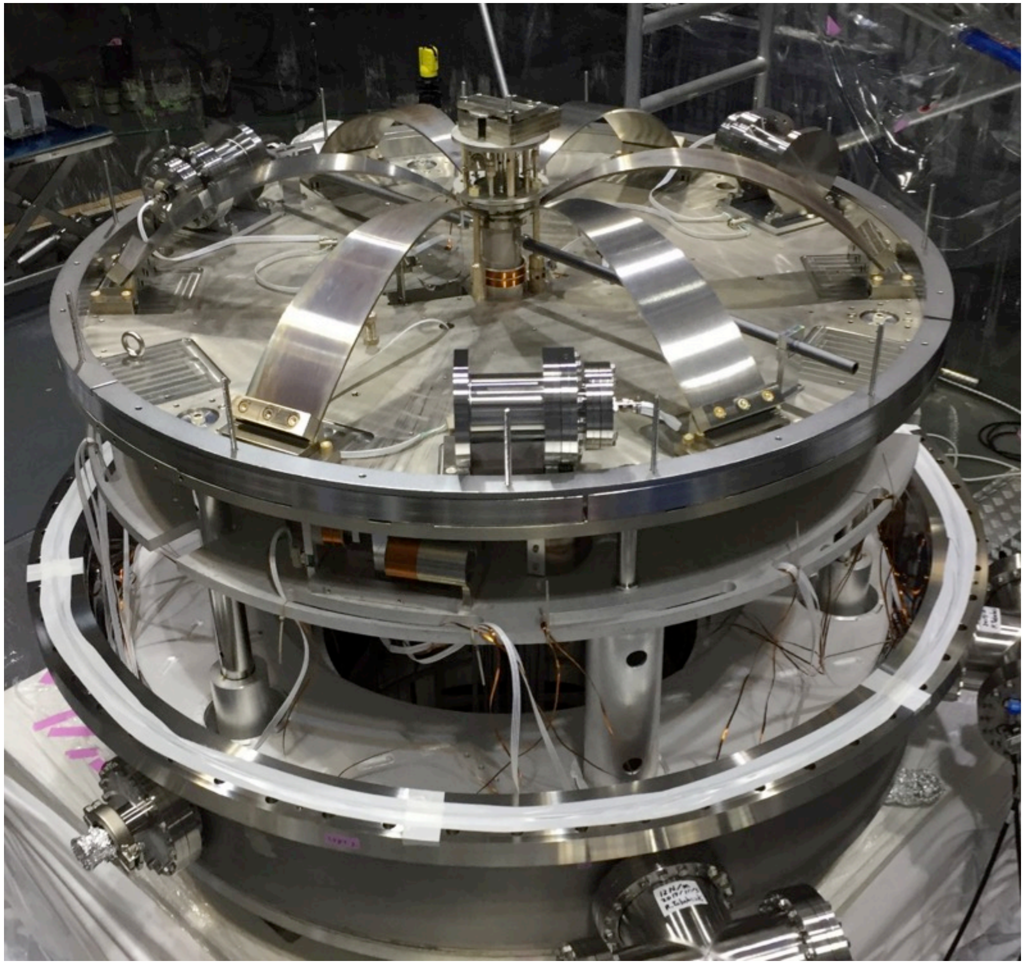
		Value	Notes
Mech.	Displacement noise (long.)	< 8×10^{-20} m/Hz$^{1/2}$	@ 10 Hz, x10 margined
	Displacement noise (vert.)	< 8×10^{-18} m/Hz$^{1/2}$	@ 10 Hz, x10 margined
Control	$1/e$ decay time	< 60 sec	
	RMS velocity (long.)	< 0.01 μm	
	RMS displacement	< 1 mm	
	RMS angle (pitch, yaw)	< 0.3 μrad	
	Control noise (long.)	< 1×10^{-19} m/Hz$^{1/2}$	

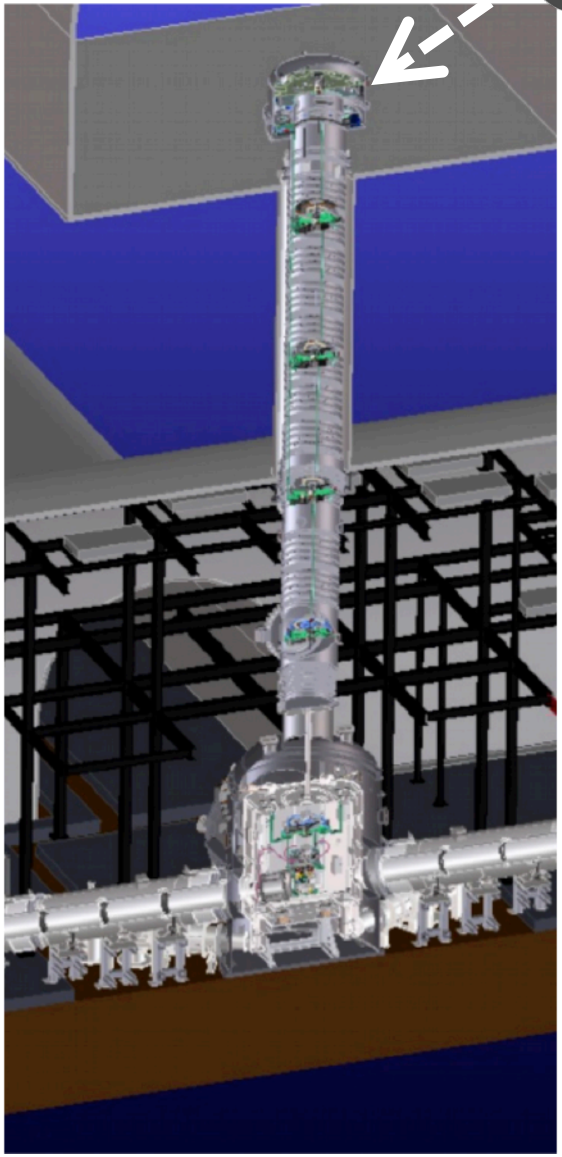
Installation



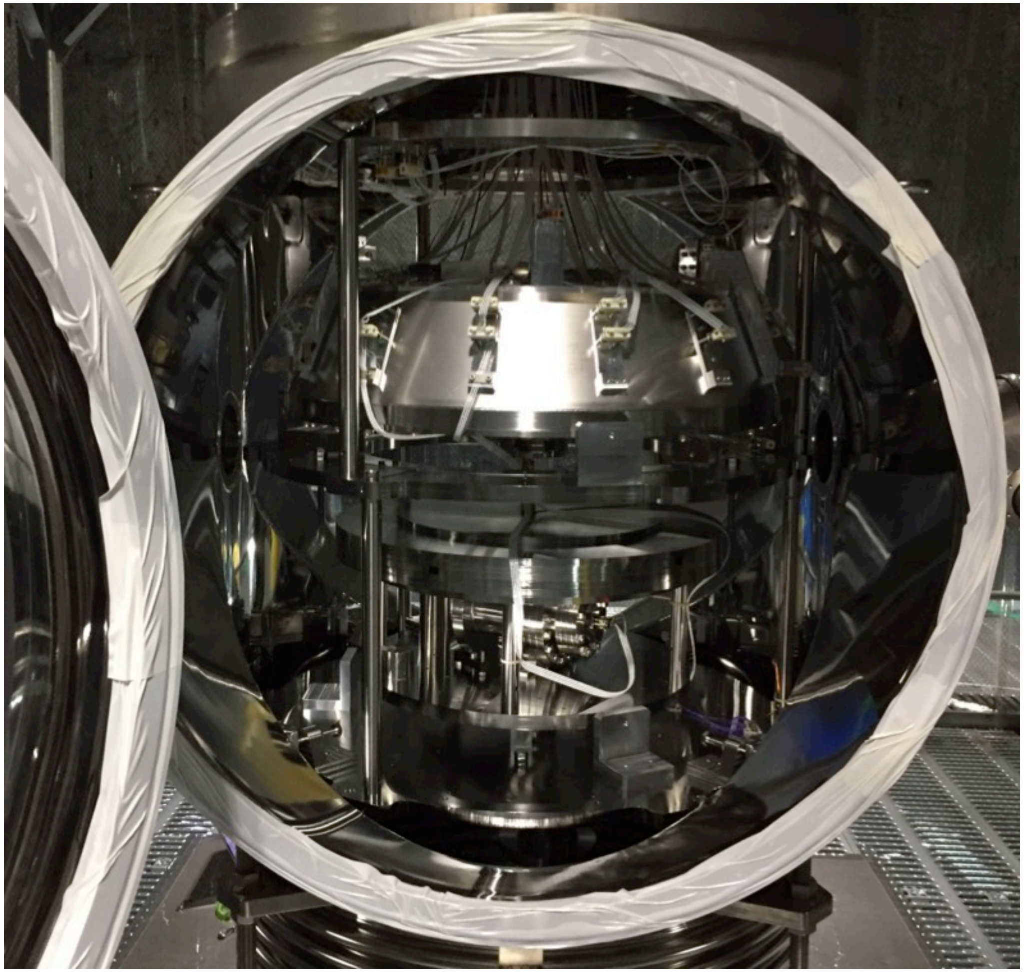


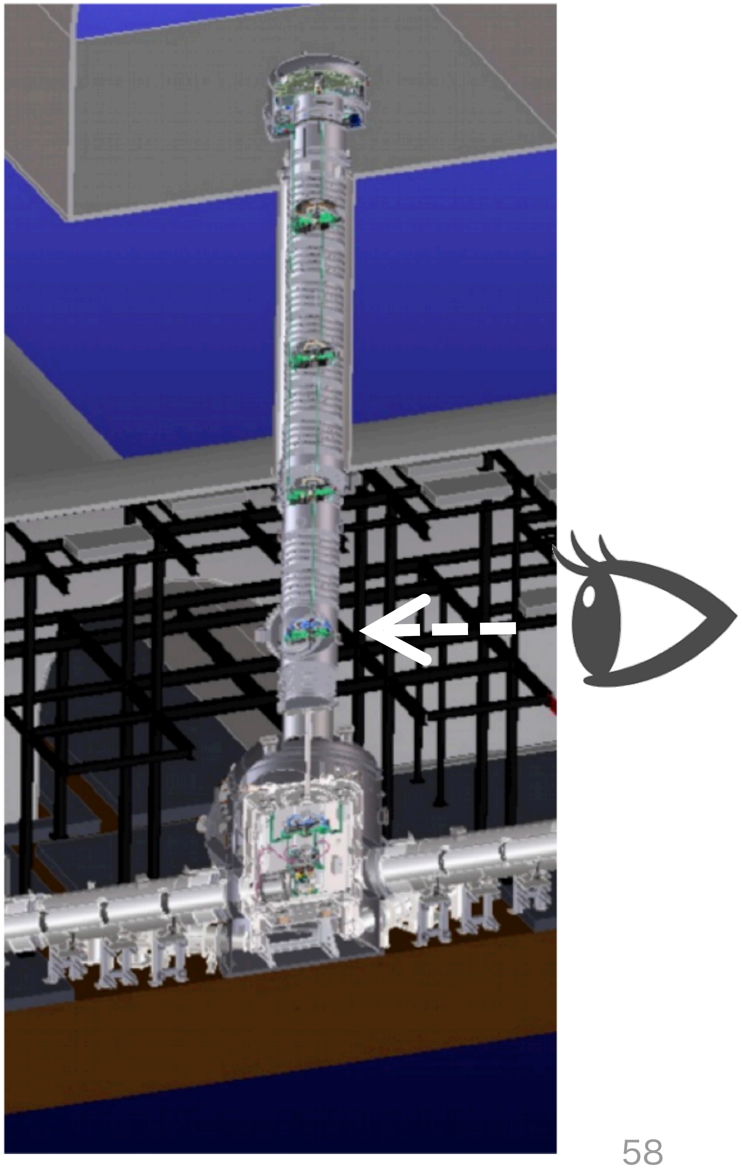
Installation





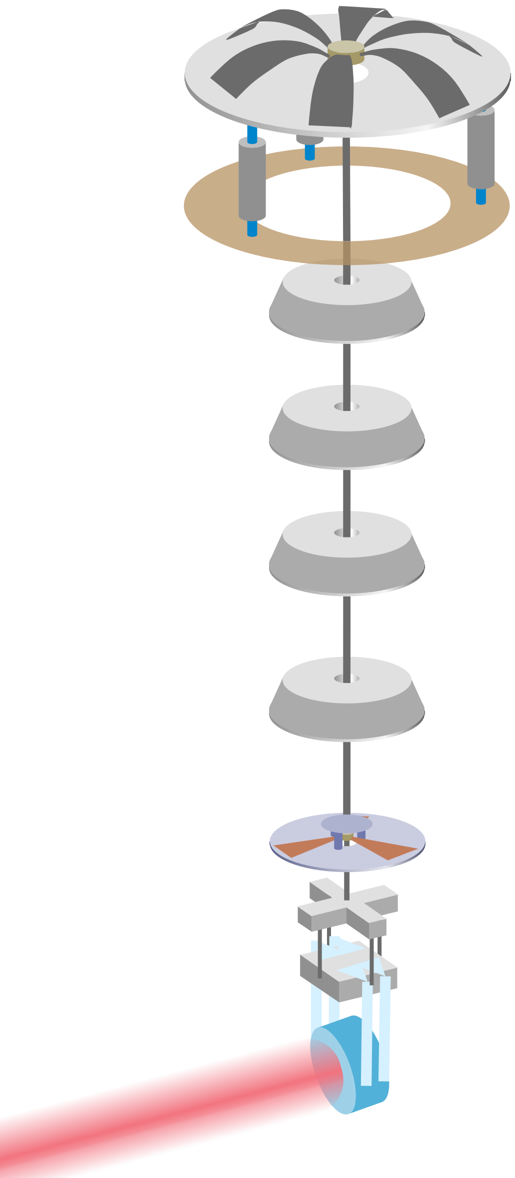
Installation

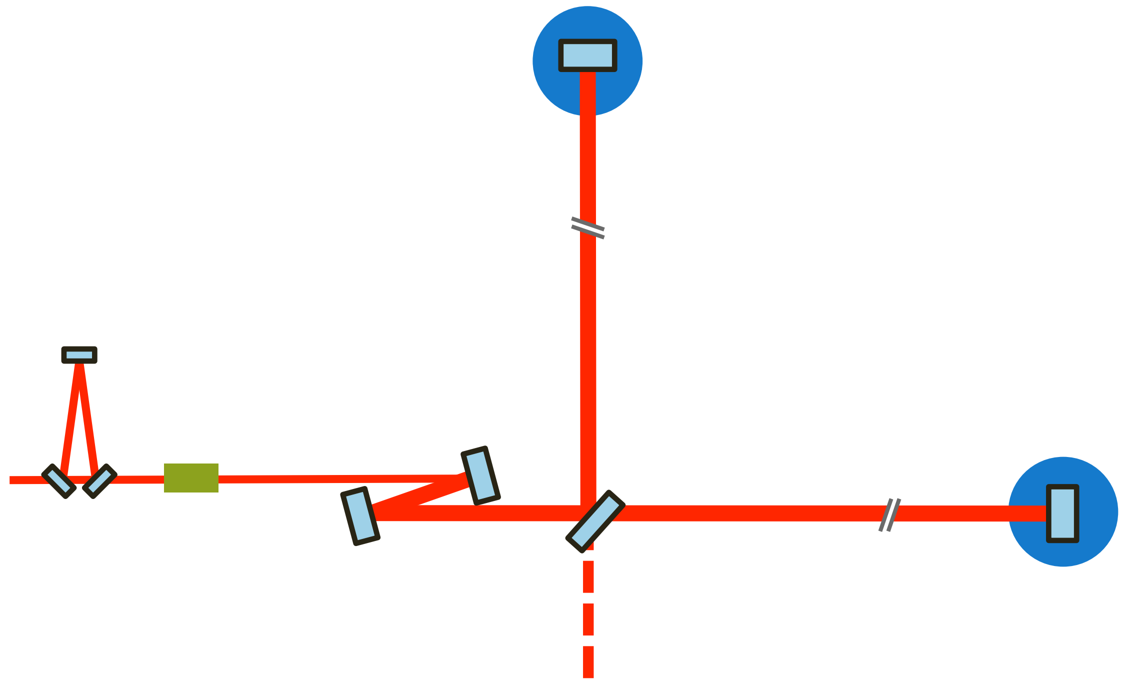




防振性能の評価

Seismic Attenuation Measurement

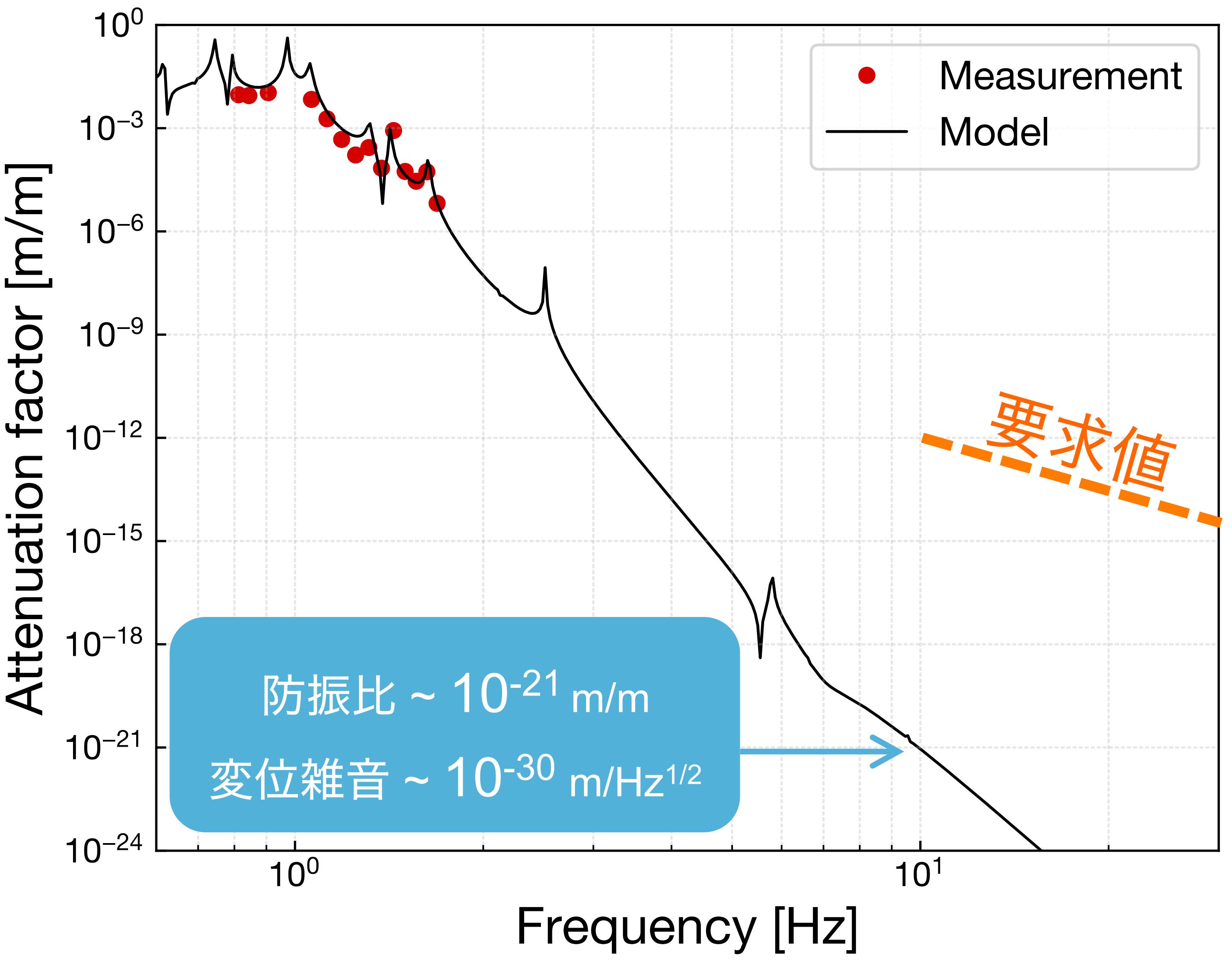




低温Michelson干渉計で防振比の測定

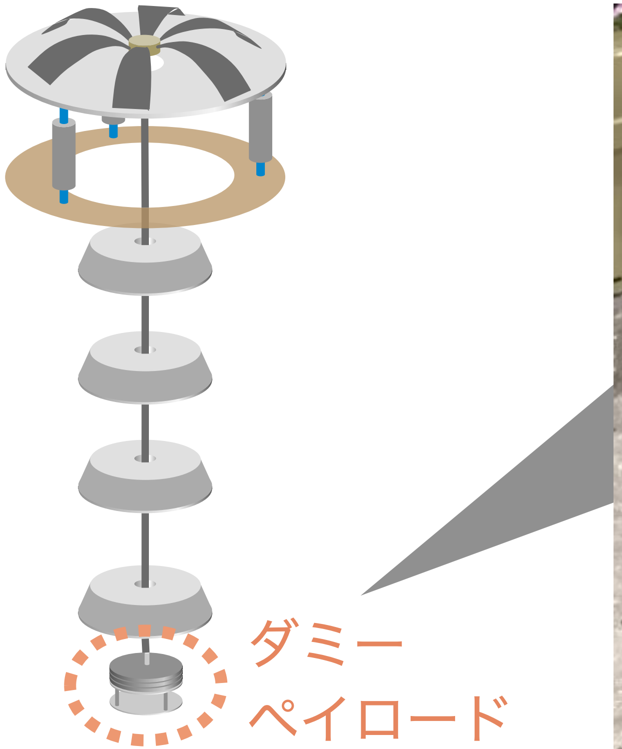
一部帯域で測定 ▶ モデルから全帯域を推定

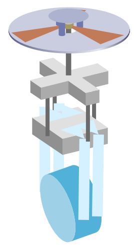
防振比の測定結果

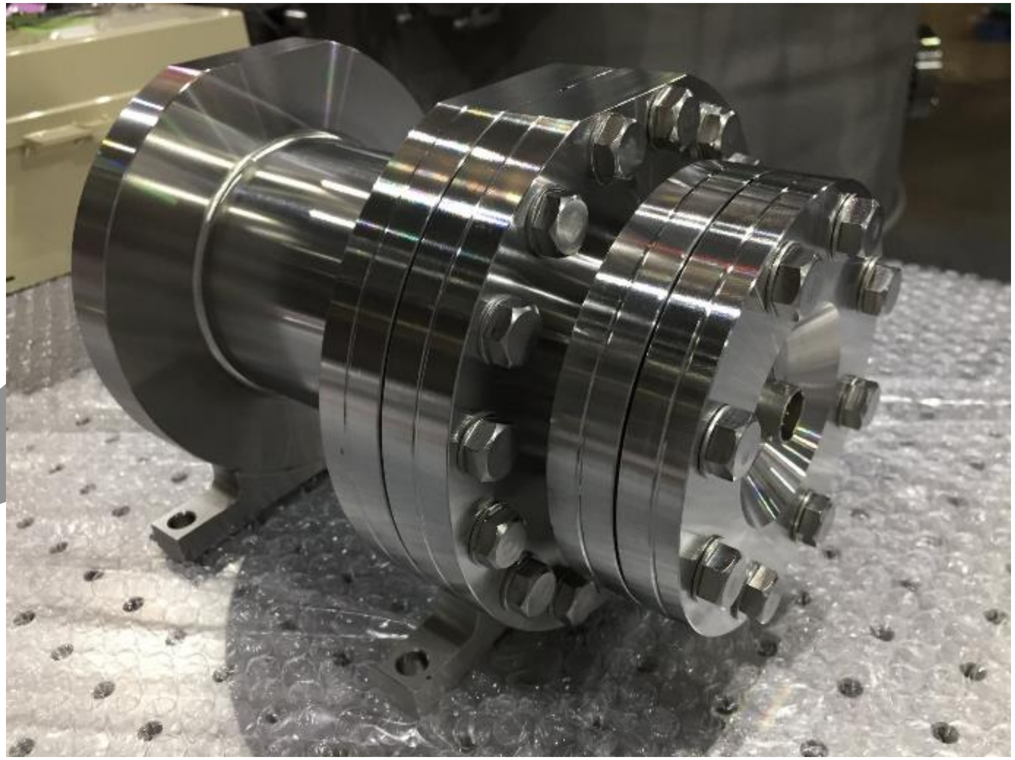


Measurement
Model
Attenuation factor [m/m]
Frequency [Hz]
10^0
10^−3
10^−6
10^−9
10^−12
10^−15
10^−18
10^−21
10^−24
10^0
10^1
要求値
防振比 ~ 10^-21 m/m
変位雑音 ~ 10^-30 m/Hz^1/2

ダミーペイロードでの残留RMS



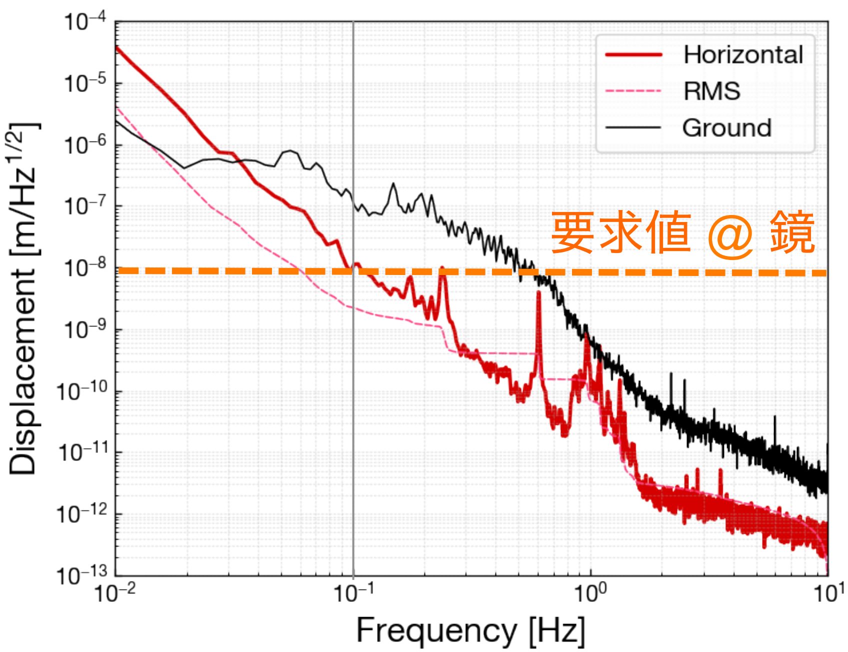


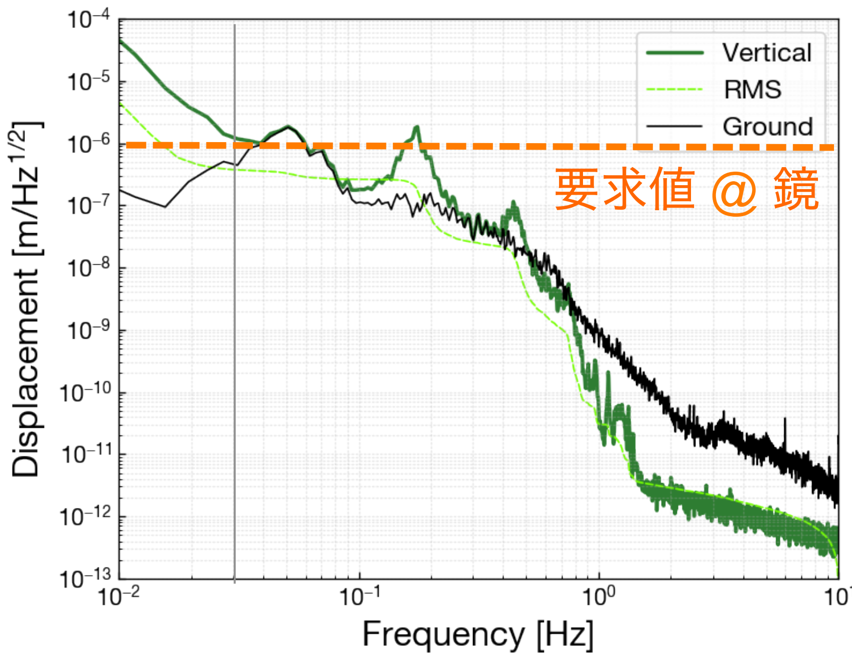


Geophone （速度センサ）x2

- 水平方向と鉛直方向のRMSを評価

RMS Residual Motion @ DP





Horizontal

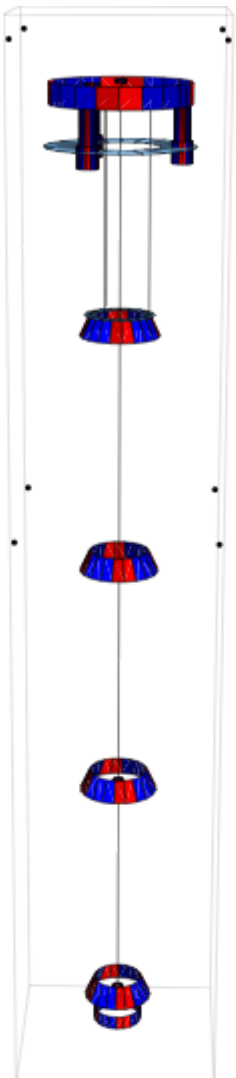
2.2×10^{-9} m (> 0.1 Hz)

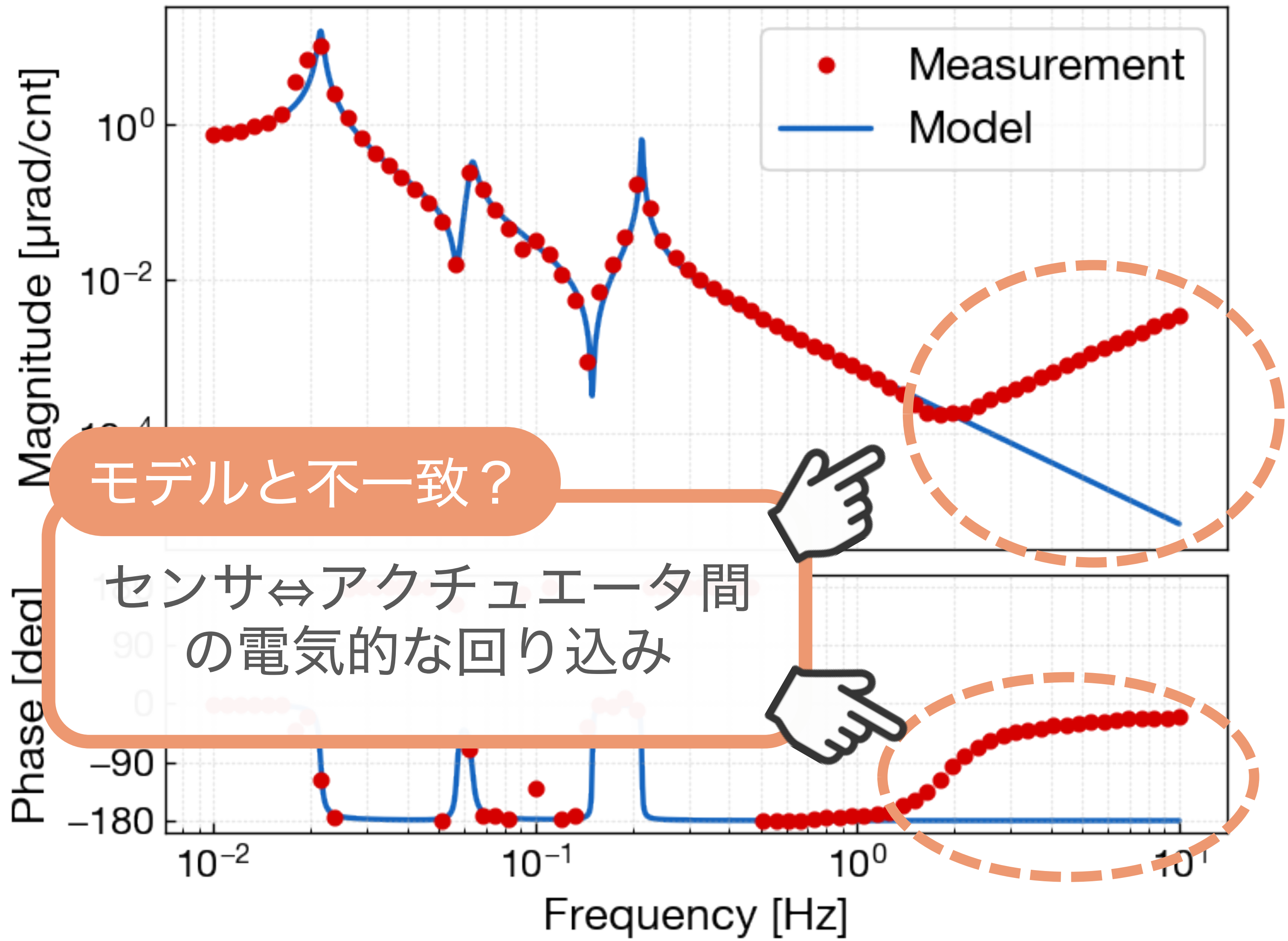
Vertical

3.9×10^{-7} m (> 0.03 Hz)

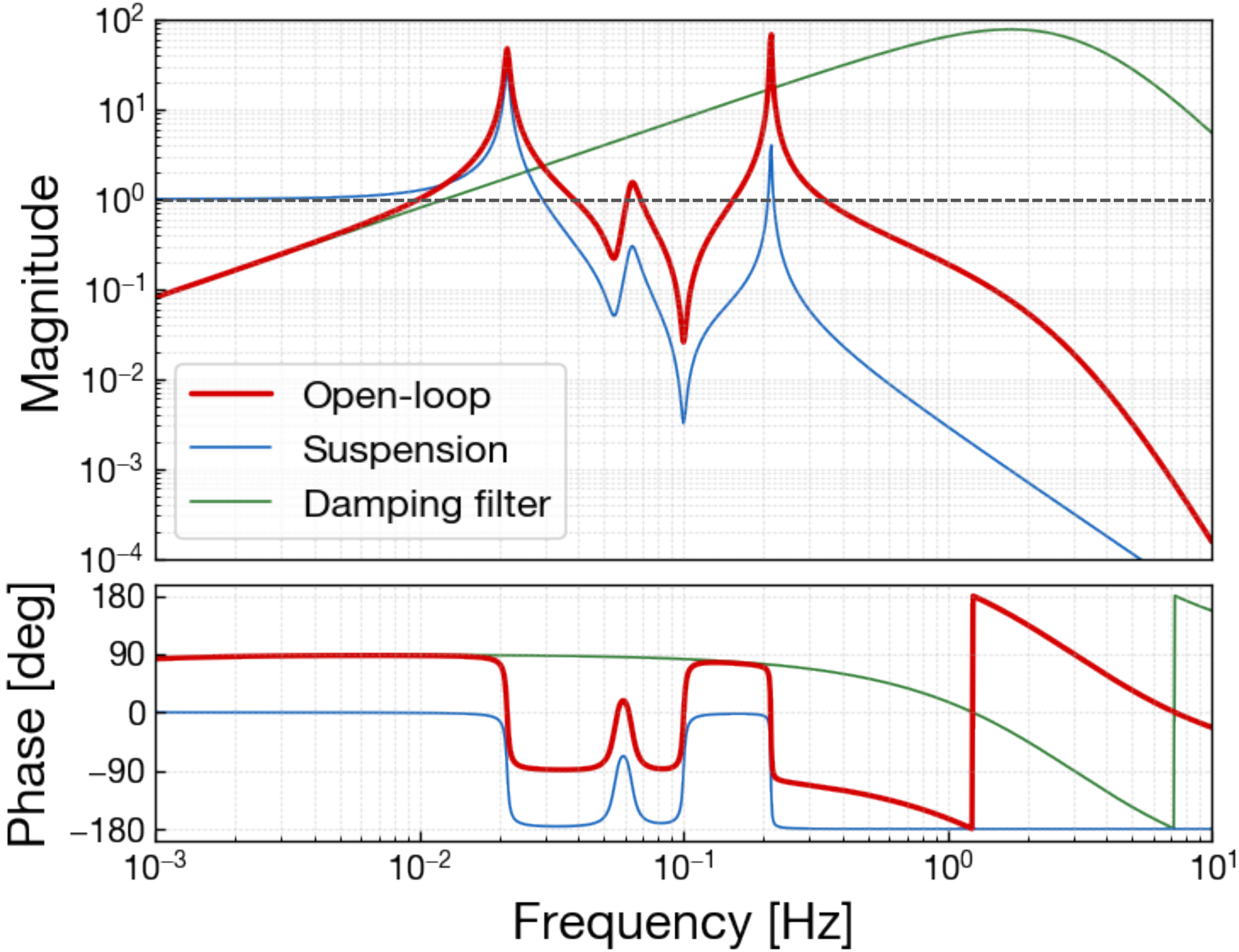
タワー部の性能としては OK ▶ ペイロード接続後再評価

モデルとの比較

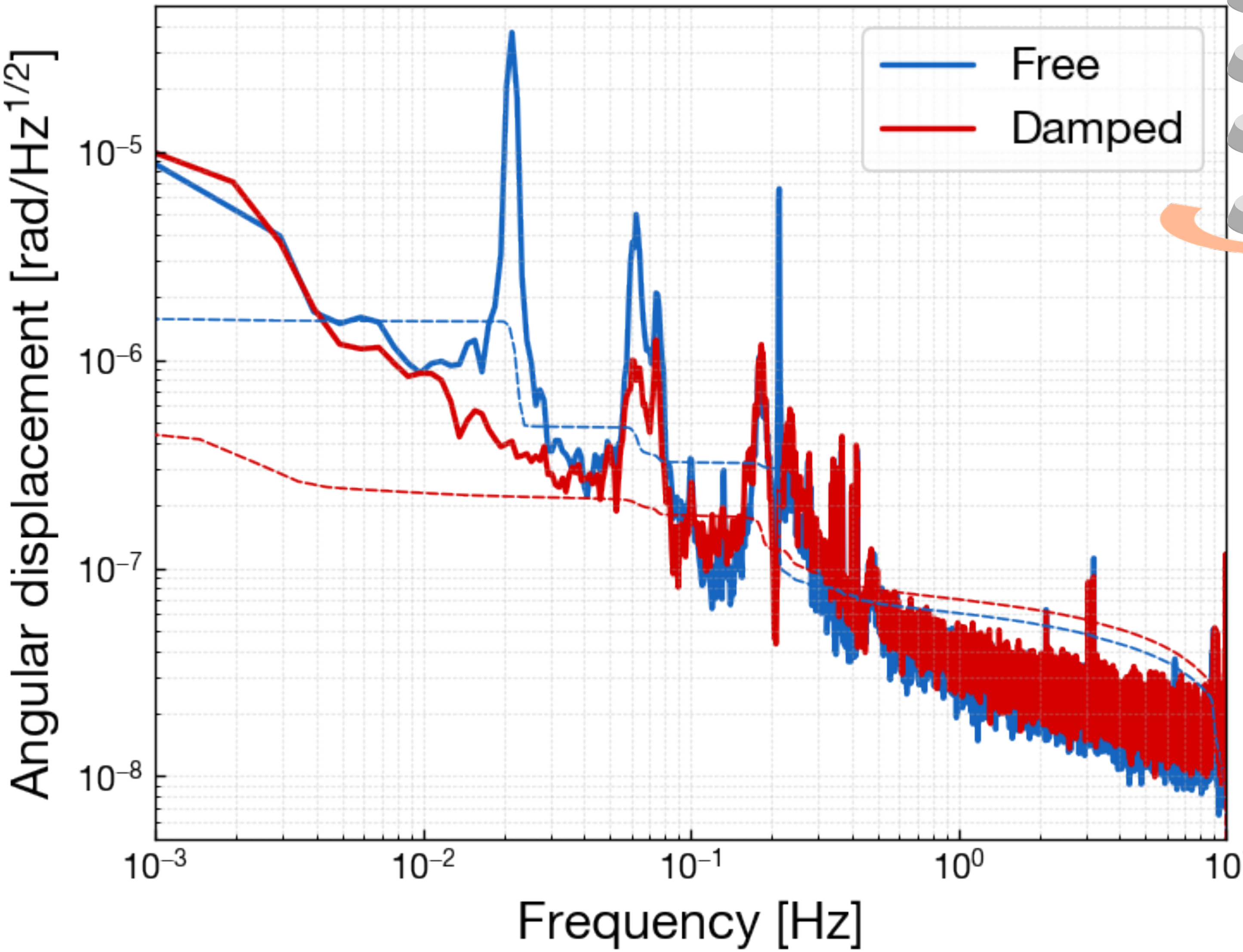


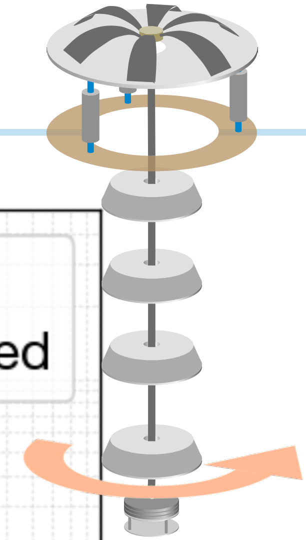

Measurement
Model
Magnitude [μrad/cnt]
10^{0}
10^{-2}
Phase [deg]
−90
−180
10^{-2}
10^{-1}
10^{0}
Frequency [Hz]
モデルと不一致？
センサ⇔アクチュエータ間
の電気的な回り込み

ダンピング制御 - 開ループ伝達関数

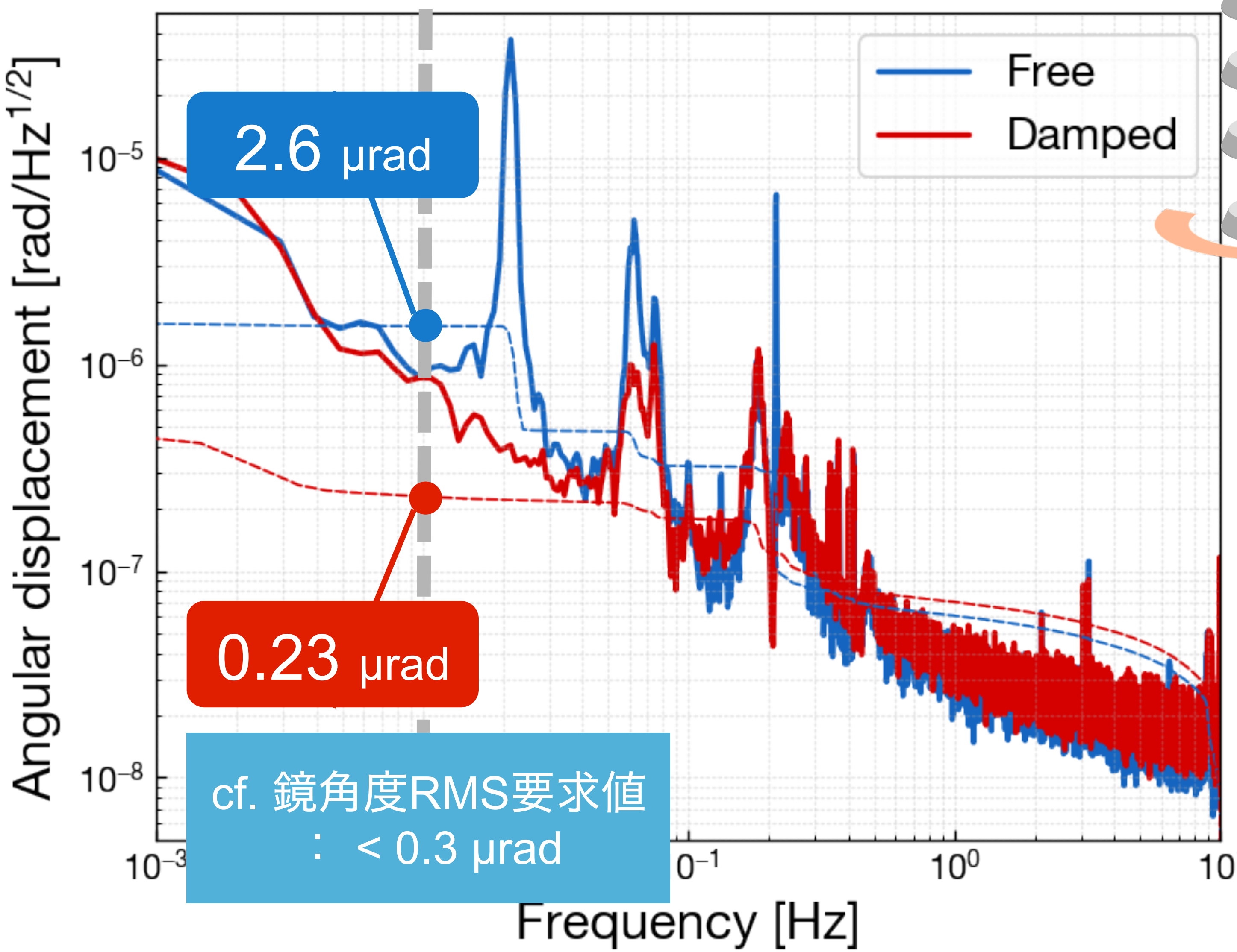


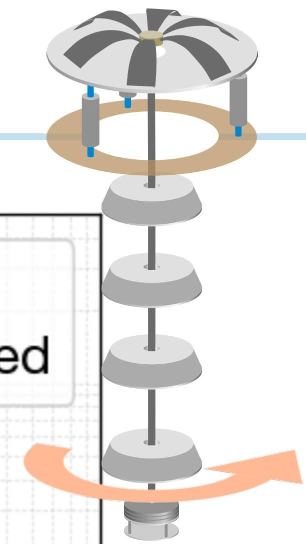
ダンピング制御の結果


Angular displacement [rad/Hz^1/2]
10^-5
10^-6
10^-7
10^-8
10^-3
10^-2
10^-1
10^0
10^1
Frequency [Hz]
Free
Damped



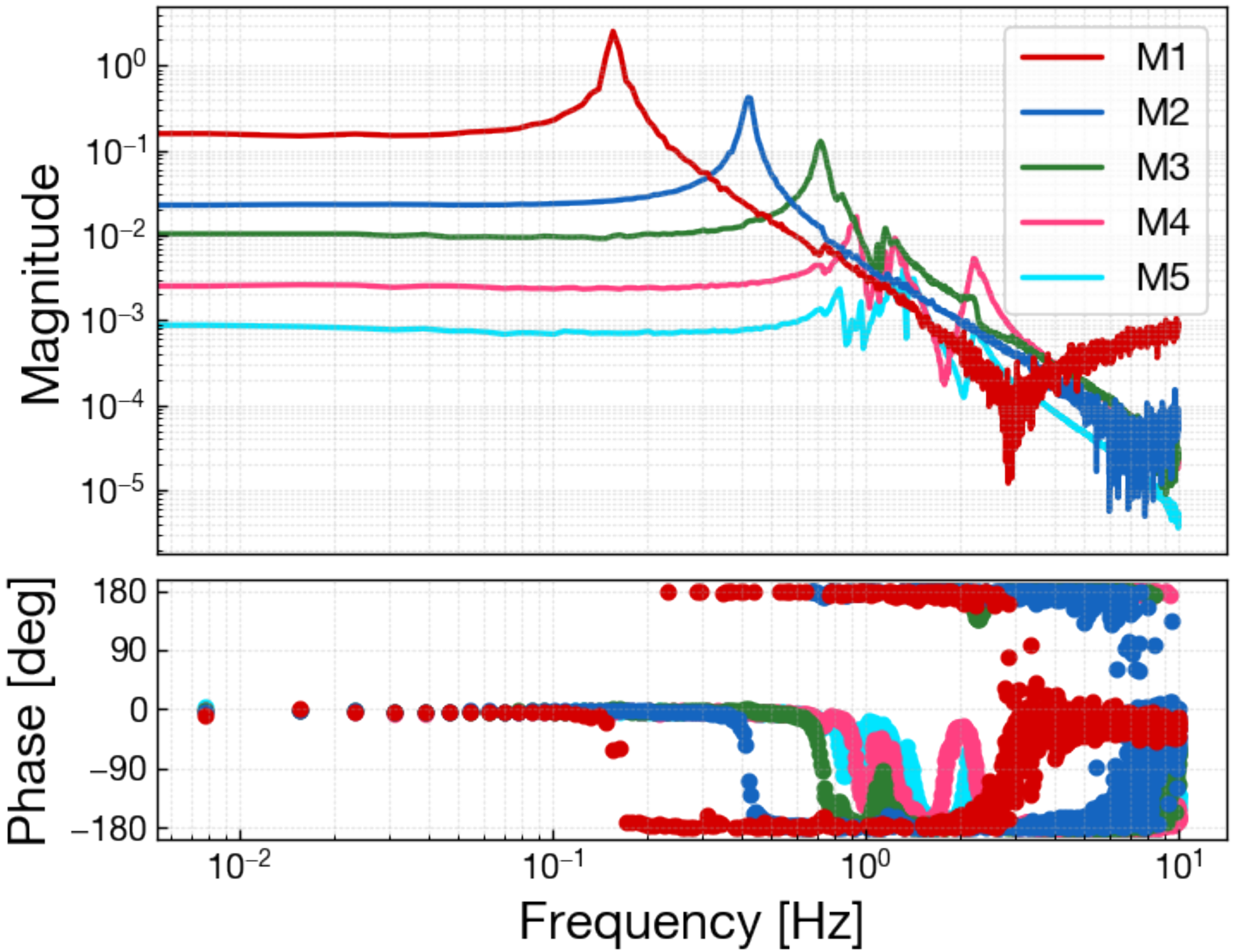
ダンピング制御の結果



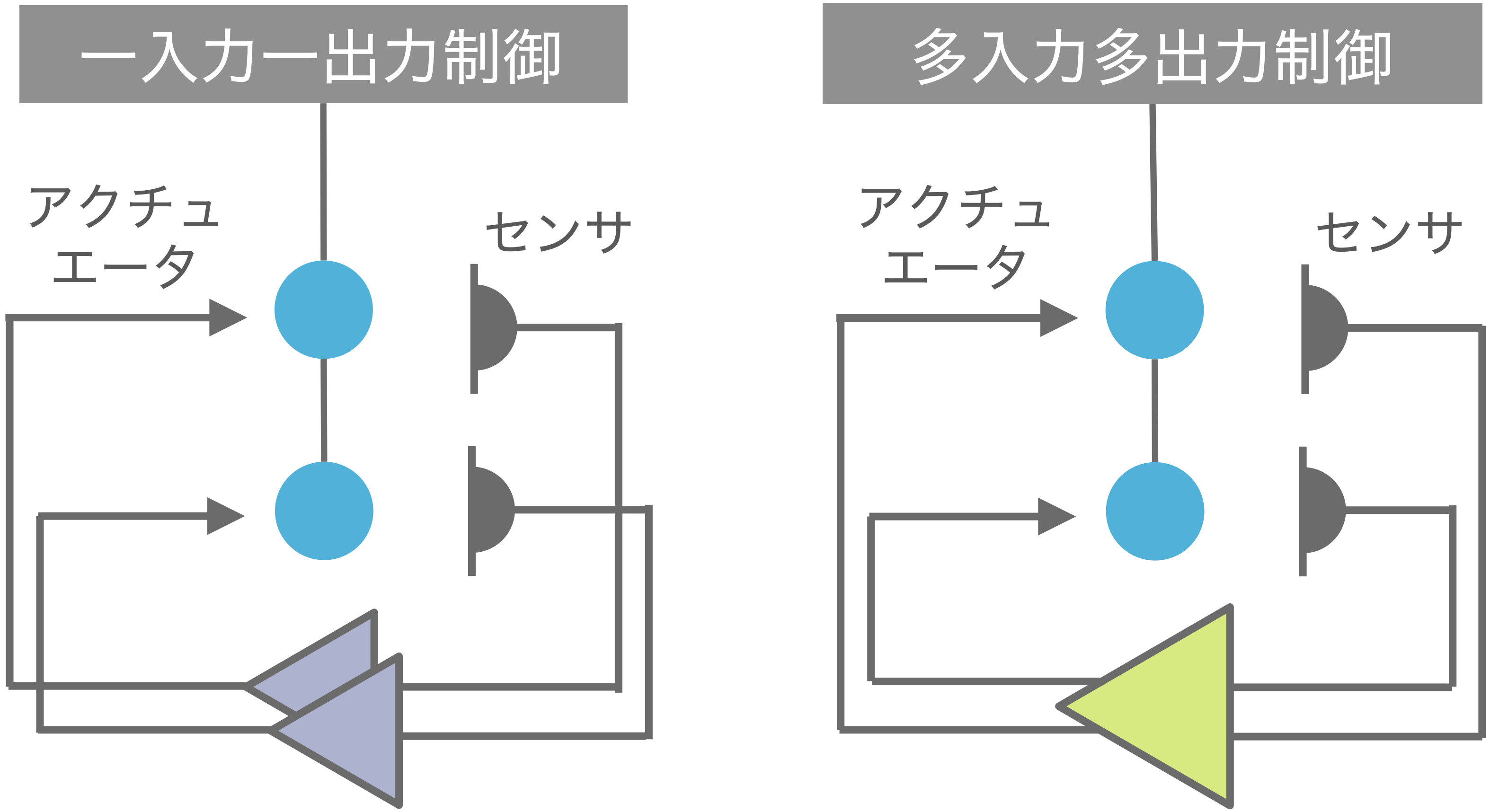


cf. 鏡角度RMS要求値
： < 0.3 μrad

モード座標系での力変位伝達関数



多入力多出力(MIMO)制御とは？



- センサ信号をそれぞれの段のアクチュエータにフィードバック
- 測定した伝達関数をベースにPIDフィルタを設計

- 各段のセンサ信号をまとめて処理してフィードバック信号を分配
- 状態空間モデルと評価関数をベースに最適レギュレータを設計

最適制御

状態空間モデル

$$\dot{\boldsymbol{x}}(t) = A\underline{\boldsymbol{x}(t)} + B\underline{\boldsymbol{u}(t)}$$
$$\boldsymbol{y}(t) = C\underline{\boldsymbol{x}(t)} + D\underline{\boldsymbol{u}(t)}$$

状態変数　入力

評価関数 $J = \int_0^{t_\mathrm{f}} \left[\boldsymbol{x}^\mathrm{T}(t)\boldsymbol{Q}\boldsymbol{x}(t) + \boldsymbol{u}^\mathrm{T}(t)\boldsymbol{R}\boldsymbol{u}(t)\right] \mathrm{d}t$

重み付け行列

➢ 最適フィードバックゲイン

$$\boldsymbol{u}(t) = -\boldsymbol{F}\boldsymbol{x}(t), \quad \boldsymbol{F} = \boldsymbol{R}^{-1}\boldsymbol{B}^\mathrm{T}\boldsymbol{P}$$

MIMO制御の長所と短所

◯ 多段フィードバックを自動的に計算

- KAGRAの防振システムのような多自由度連成振動系の制御に適する

◯ モデルをベースとした制御

- 物理パラメータの時間変化やロバスト性などを定量的に考慮できる（応用）

× 性能がモデリング精度に依存

- 実システムとモデルの誤差を減らす必要

重力波分野における現代制御

T. Accadia et al., Rev. Sci. Instrum. **82**, 094052 (2011)

- Kalmanフィルタによる Virgo倒立振り子の状態推定

M. Beker et al., Rev. Sci. Instrum. **85**, 034501 (2014)

- Virgo external optical benchの最適制御

B. Shapiro PhD Thesis (2012)

- LIGO quad suspensionの適応モーダルダンピング

D. Martynov PhD Theis (2015)

- LIGO quad suspensionの光てこ制御における H_∞制御

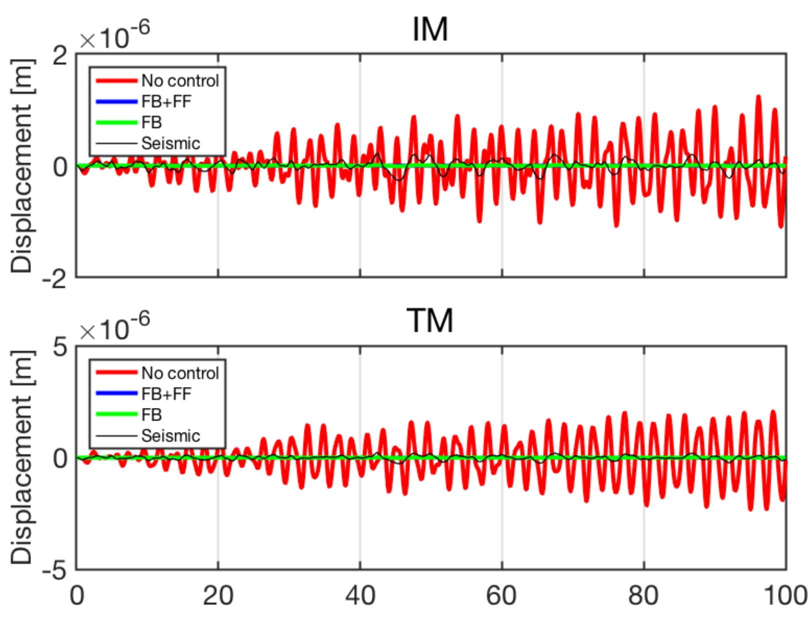
最適制御の実装に向けて

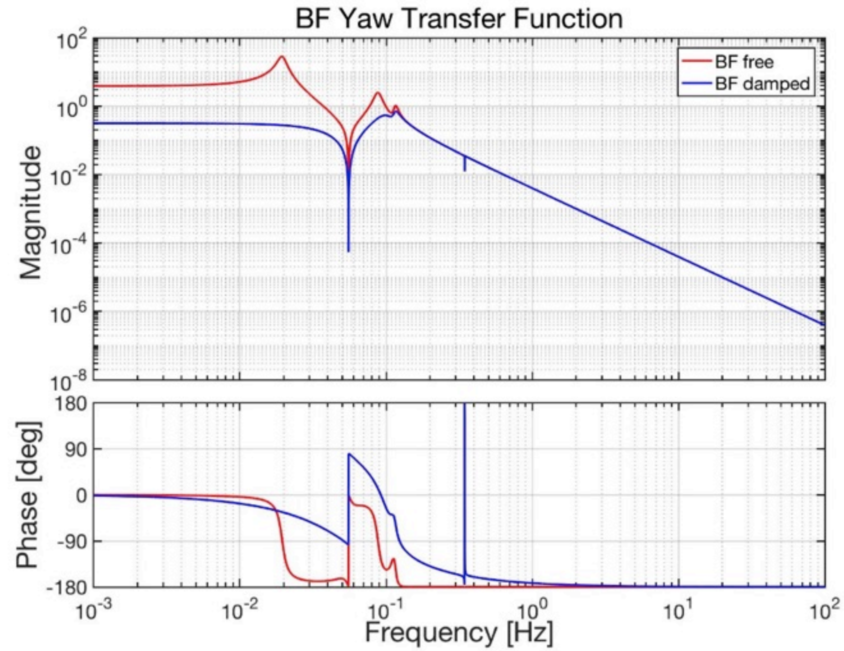
✓ 2段振り子トイモデルによる検証

✓ Type-Aモデルを用いたGASモーダルダンピング

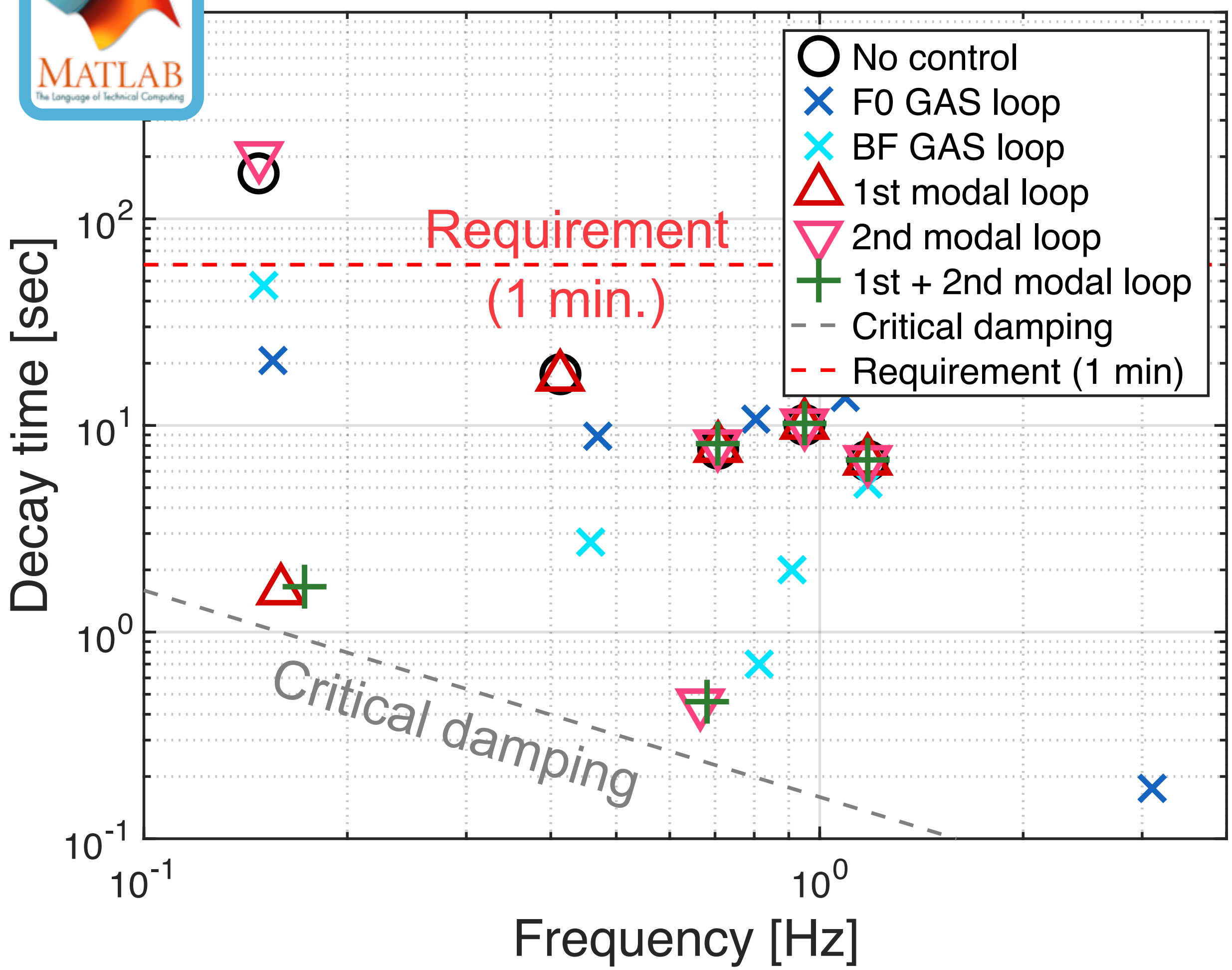
□ Type-Aモデルでの最適制御の調整

□ KAGRAディジタルシステムへ実装・性能評価

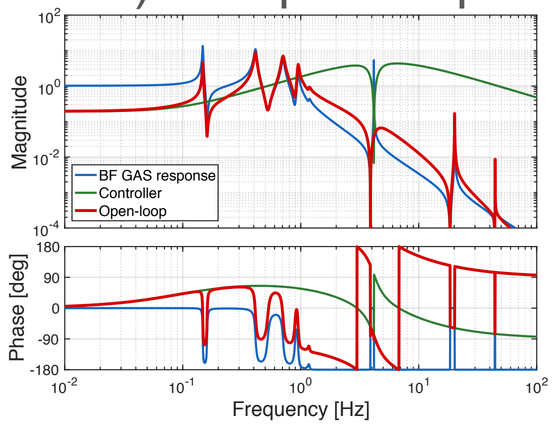




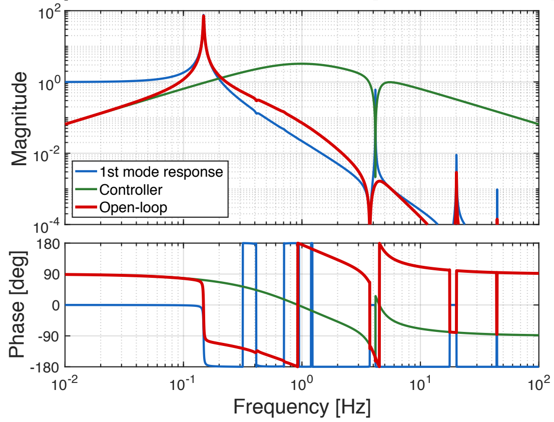
Decay Time with Damping Simulation



ex) BF open-loop



ex) 1st modal open-loop



Implementation

$$\begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \\ \eta_5 \end{bmatrix} = \boxed{\Phi^{-1}} \boldsymbol{M} \begin{bmatrix} V_{\mathrm{F0GAS}} \\ V_{\mathrm{F1GAS}} \\ V_{\mathrm{F2GAS}} \\ V_{\mathrm{F3GAS}} \\ V_{\mathrm{BFGAS}} \end{bmatrix}$$

Eigenmode matrix

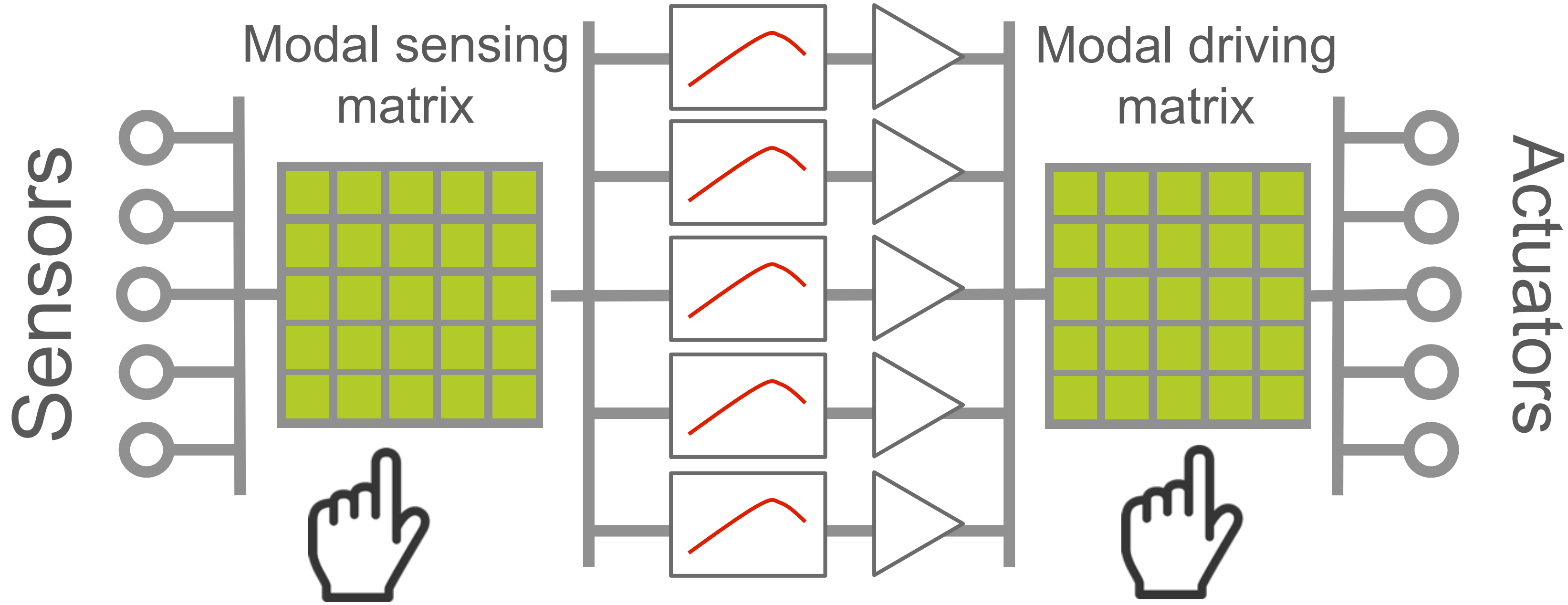
$\Phi_{\mathrm{model}} \leftrightarrow \Phi_{\mathrm{real}}$

Mismatch

▶ ☹ Imperfect mode decoupling

➢ ☺ Let's do Diagonalization!

Sensor & Actuator Diagonalization



Excited at each mode frequency

DC gain in modal transfer functions

Update the matrix to cancel coupling elements