Coil-Coil Actuator Revisited

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3/12/2021 Ando Lab Seminar

Motivation of today's topic

- Recently people who know coil-coil actuator has graduated
  - In the near future nobody will know about it!

- Before forgotten our legacy, I want to summarize it and share how it works, how we used it, …
- If you think it's enough we should write a paper about it

Abstract

- Introduction
  - ◉ Background
  - ◉ Basic Principle
- History in our lab
  - ◉ - 2011
  - ◉ - 2017
- Recent Result
  - ◉ Coupling from magnetic field
  - ◉ Formulation of thermal noise
- References
  - ◉ Shoda-san's master thesis
  - ◉ Aritomi-san's master thesis
  - ◉ My calculation memo

Actuators in GW Community

In GW community, some non-contact actuators are used:

- Coil-Magnet actuator (CMA)
  - parmament magnets + electro magnets (coils)
  - Used in ground-based detectors
  - Relatively large force
  - Magnets introduce noise coupling from ambient magnetic field

- Electrostatic actuator (ESA)
  - A pair of electrodes
  - Used in LISA, DPF, …
  - No need to put magnets
  - Smaller force, only attraction force, …

Actuators in TOBA

- For (Phase-III) TOBA,
- Coil-Magnet actuator

◉ Enough large force

◉ Large torque noise due to magnets on TM

- Electrostatic actuator

◉ Small magnetic coupling

◉ Too weak to control TM

- What we want:

◉ As large force as CMA

◉ As small magnetic noise as ESA

Magnetic Noise in Torsion Pendulums

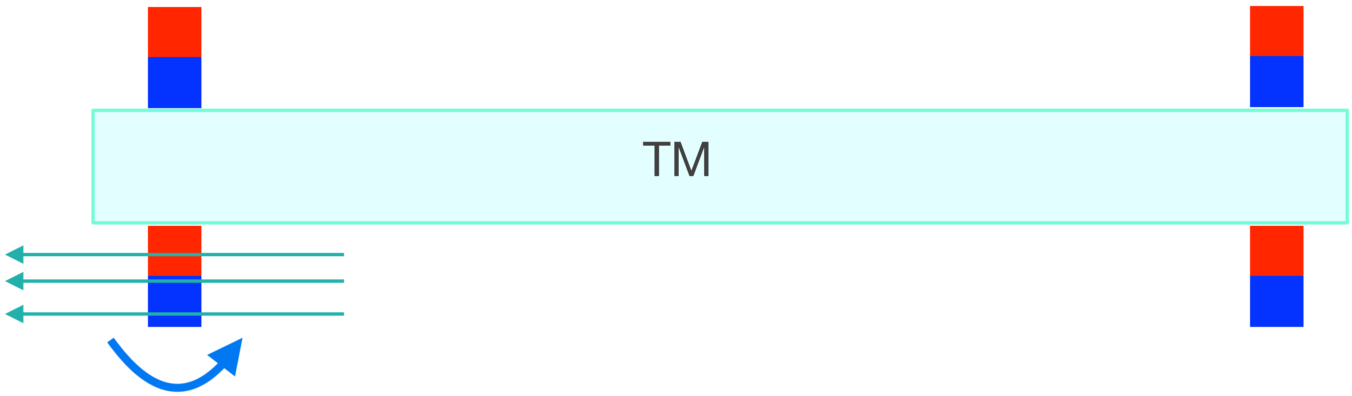
Coupling from ambient magnetic field

$$\tilde{N} = \boldsymbol{m} \times \tilde{B}$$

Torque noise

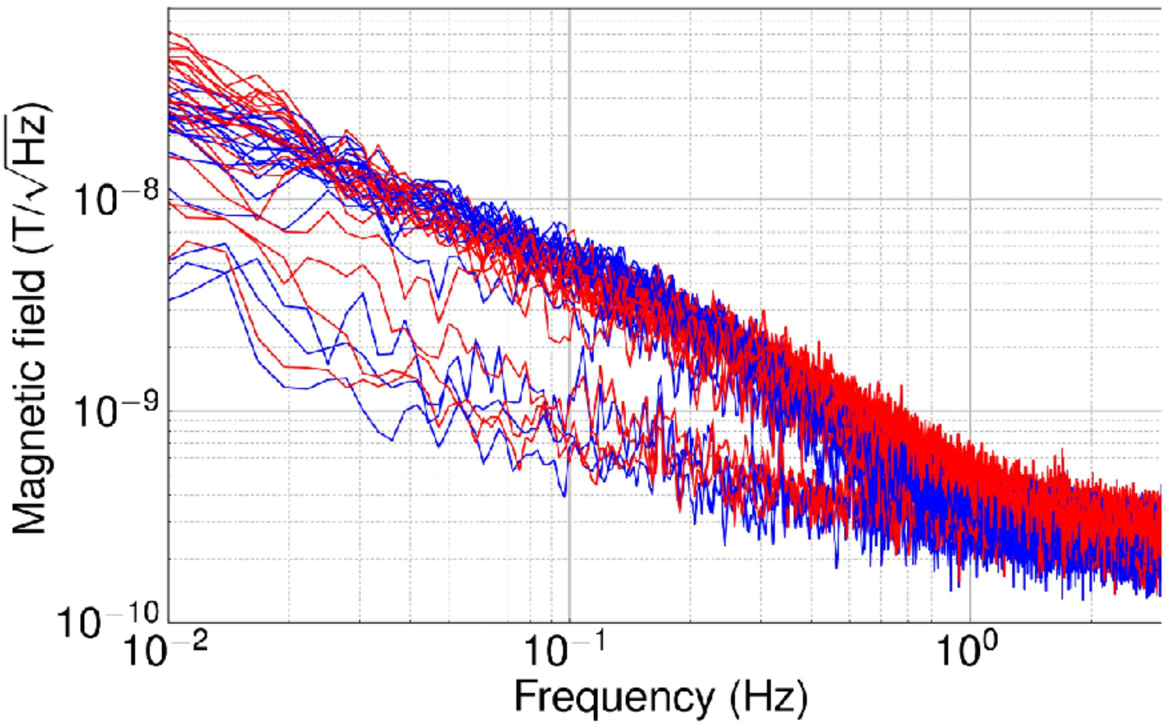
magnetic field fluctuation

magnetic dipole moment = magnets



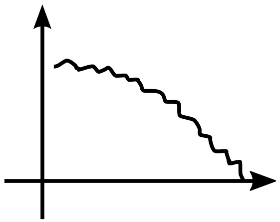
- Magnetic fluctuation directly induces torque noise

Magnetic Field Fluctuation



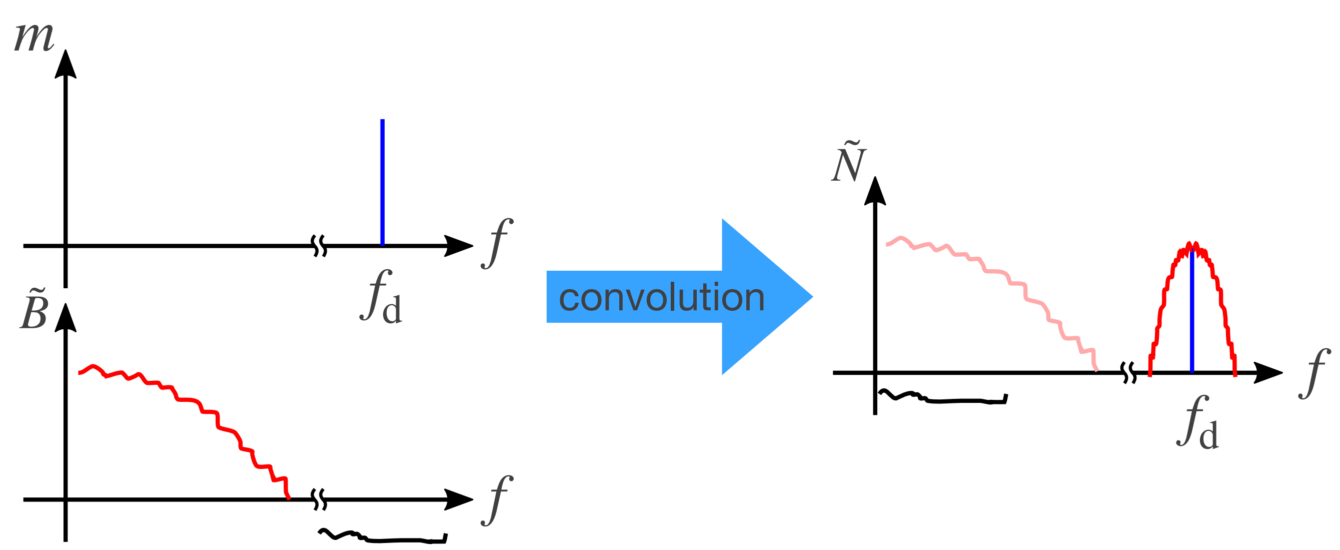
B_x, B_y
measured at B207

- For constant $\boldsymbol{m}$, magnetic fluctuation directly induces torque noise
- What if $\boldsymbol{m}$ varies in time?
  - Frequency conversion



Avoid Magnetic Noise

- When m is oscillating in time: $m \propto \cos 2\pi f_0 t$
- $\tilde{N}(f) = \tilde{m}(f) * \tilde{B}(f) \propto \tilde{B}(f - f_0) + \tilde{B}(f + f_0)$
  - ▸ Magnetic field fluctuation around f_0 contributes torque noise in the observation band!
  - ▸ Oscillation of m = oscillation of current flowing coils



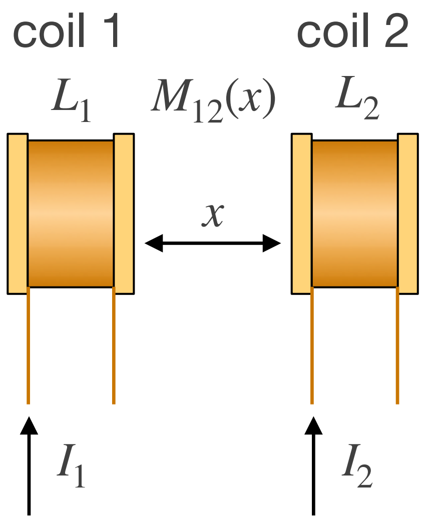
Basic Principle

- Consider 2 coils flowing current I_1, I_2

◉ Energy of that system

$$T = \frac{1}{2}L_1{I_1}^2 + \frac{1}{2}L_2{I_2}^2 + M_{12}I_1I_2$$

- ○ L_i: self inductance of coil i
- ○ M_{12}: mutual inductance of coil 1 and coil 2



◉ Force

$$F_x = \frac{\partial T}{\partial x} = \frac{dM_{12}}{dx}I_1I_2 = \mu I_1I_2 \quad (M_{12} = M_0 + \mu x)$$

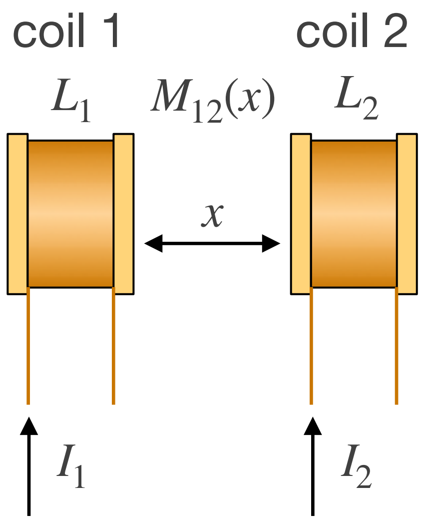
▶ We can control F_x by changing I_1 or I_2

- c.f. the previous definition of 1A

Basic Principle

- Now currents are driving at frequency f_d :

$$I_1 = i_1 \cos 2\pi f_\mathrm{d} t$$
$$I_2 = i_2 \cos(2\pi f_\mathrm{d} t + \phi)$$



- If f_d is high enough, take time average:

$$\bar{F} = \mu i_1 i_2 \cos\phi$$

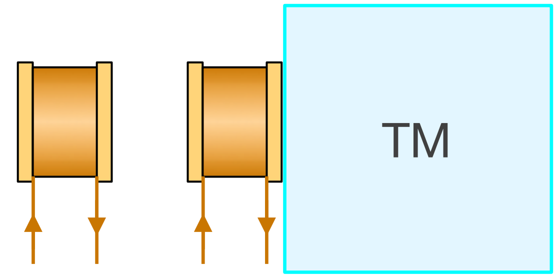
  - We can control force between the coils by:
    - Changing i_1 or i_2 with $\phi = 0$: Amplitude modulation (AM)
    - Changing $\phi = \pi/2 + \delta\phi$: Phase modulation (PM)

- I phase → force
- Q phase → averaged out

Actuator Configuration

3 configurations are proposed:

- 2 driven coils Type I

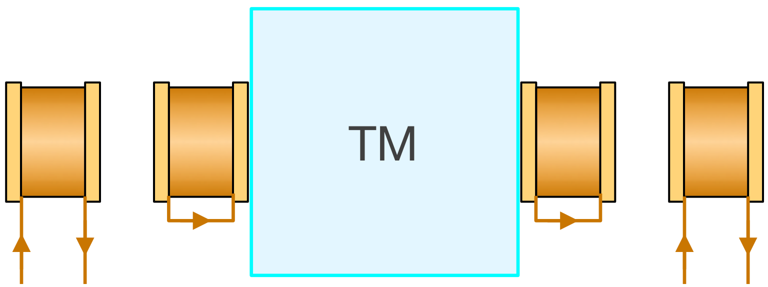


◉ controlled by AM / PM of currents

◉ Attraction / Impulsion

◉ Additional noise / stiffness due to a wire driving a coil on TM

- 2 driven / 2 shorten coils Type II

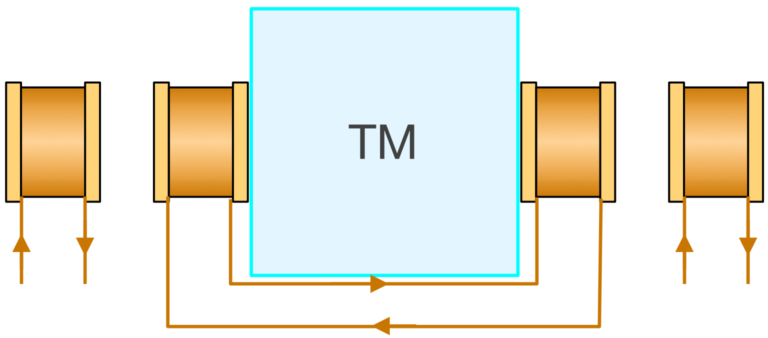


◉ controlled by AM

◉ Impulsion only

◉ Current flowing shorten coils is induced by outer coils

- 2 driven / 1 shorten coils Type III



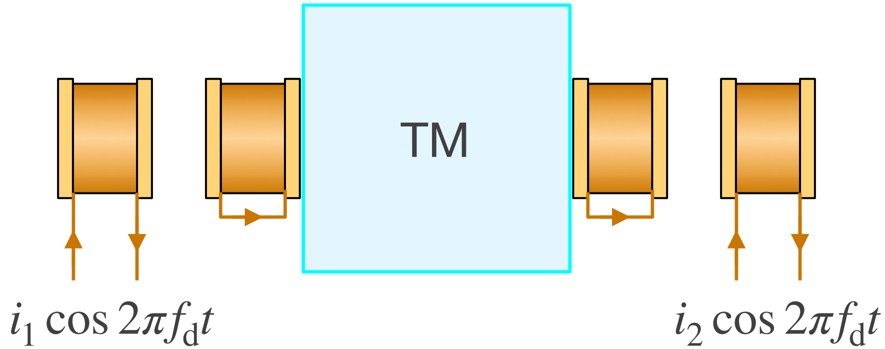
◉ controlled by AM / PM

◉ Attraction / Impulsion

◉ Coils on TM are connected

Induced-Type Actuator

- Type II



R_0: resistance of coils
L_0: inductance of coils
$M_{12} = M_0 + \mu x$

- Actuation Force

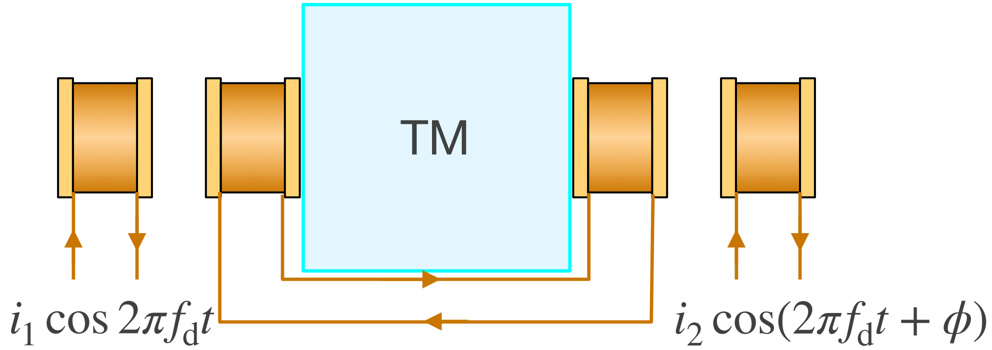
$$F = -\frac{M_0 \mu}{2}({i_1}^2 - {i_2}^2)\frac{(2\pi f_d)^2 L_0}{{R_0}^2 + (2\pi f_d L_0)^2}$$

- Only AM
- Total force: difference of two impulsion
- Additional stiffness

$$K = \frac{\mu^2}{2}({i_1}^2 + {i_2}^2)\frac{(2\pi f_d)^2 L_0}{{R_0}^2 + (2\pi f_d L_0)^2}$$

Induced-Type Actuator

- Type III



◉ Actuation Force

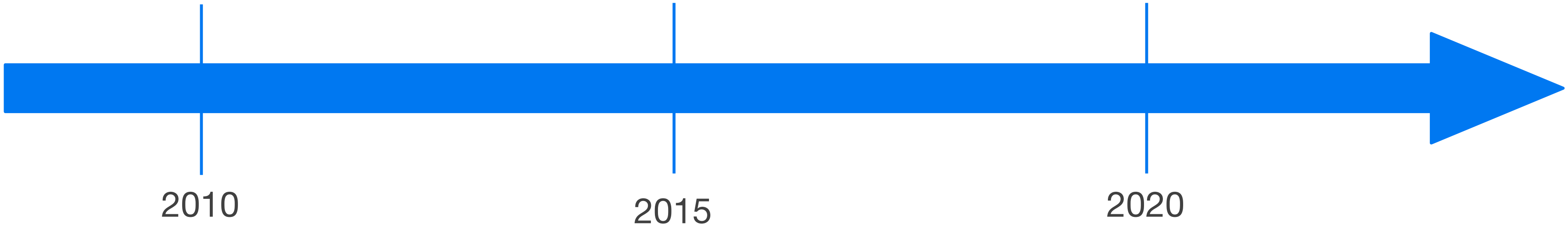
$$F = -\frac{M_0 \mu}{2} \frac{2\pi f_d}{{R_0}^2 + (2\pi f_d L_0)^2} (2\pi f_d L_0 ({i_1}^2 - {i_2}^2) - 2R_0 i_1 i_2 \sin \phi)$$

◉ AM / PM

◉ Additional stiffness

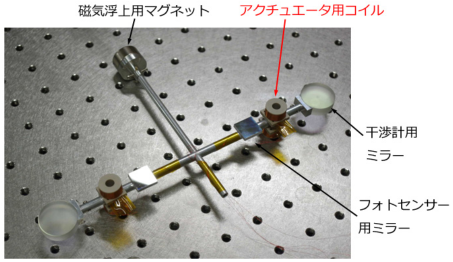
$$K = \frac{\mu^2}{2} \frac{(2\pi f_d)^2 L_0}{{R_0}^2 + (2\pi f_d L_0)^2} |i_1 - i_2 e^{-i\phi}|^2$$

History of Coil-Coil Actuator

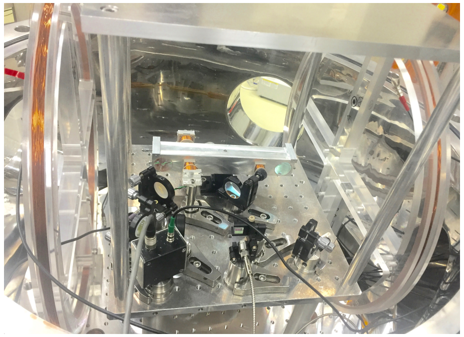


2007:
Proposal
Ando, Lab Seminar

2011:
First Demonstration
Shoda, Master Thesis



2016:
Further Demonstration
Aritomi, Master Thesis
Kawasaki & Arai, B4 Exp.



2016-:
Operation
Shimoda, M&D Thesis

2020:
Calculation, Demonstration
Takano

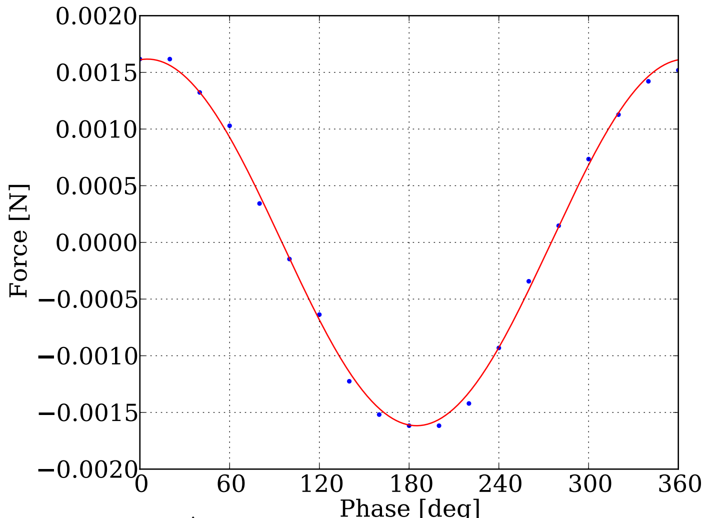
1st Demonstration

- Shoda-san
  - ◉ Actuation force with changing parameters (i_1, f_d, ϕ, …)
  - ◉ Measurement of shift of resonant frequency
  - ◉ Control of Torsion pendulum
- Aritomi-san
  - ◉ Measurement of down-conversion of magnetic field fluctuation
- Kawasaki-Arai pair
  - ◉ Tried to operate higher f_d (~ 100kHz, but failed…)
- Shimoda-san
  - ◉ Operation of torsion pendulum(s) with coil-coil actuators
  - ◉ First time of actuating in phase modulation (master thesis)
  - ◉ Operation under cryogenic temperature (Ph.D thesis)

Demonstration of Basic Principle

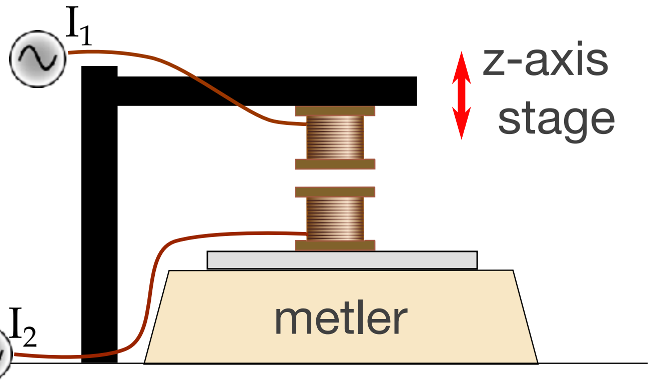
- Test of Type I actuator

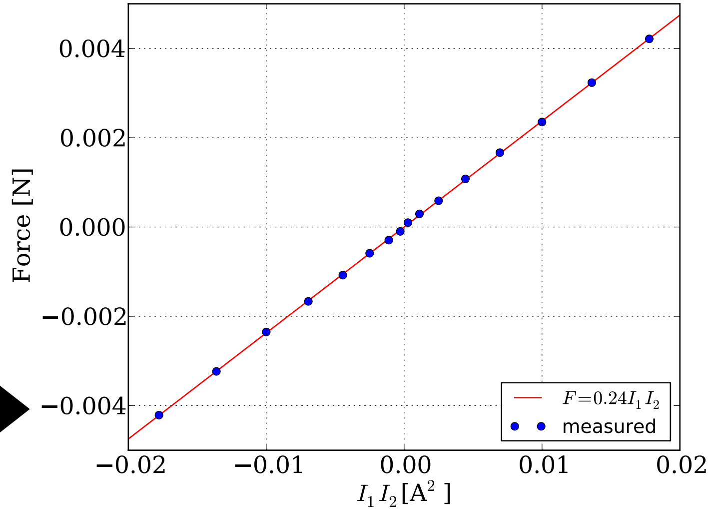
◉ Measure actuation force $\bar{F} = \mu i_1 i_2 \cos\phi$



$i_1 = i_2 = 0.1$ A, changing ϕ

$f_d = 1$ kHz





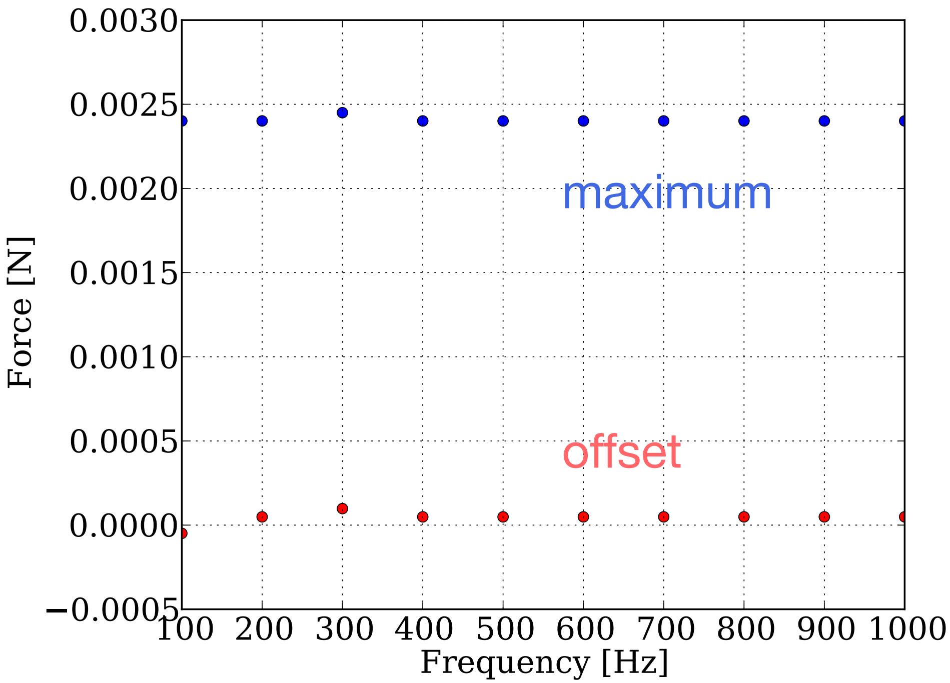
$\phi = 0$ deg, changing $i_1 i_2$

Shoda-san's master thesis

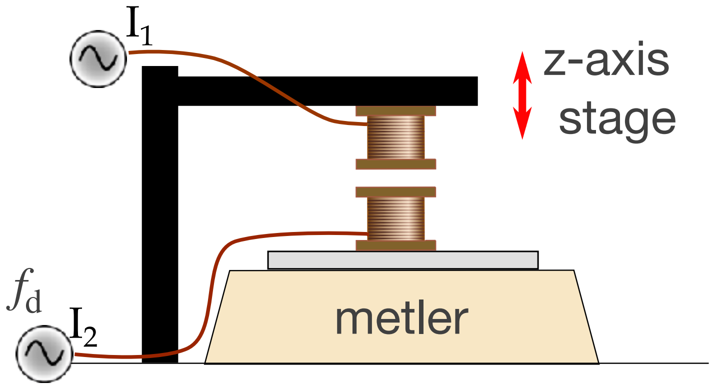
Demonstration of Basic Principle

- Test of Type I actuator

◉ Measure actuation force $\bar{F} = \mu i_1 i_2 \cos\phi$



$i_1 = i_2 = 0.1$ A, $\phi = 0$, changing f_{d}



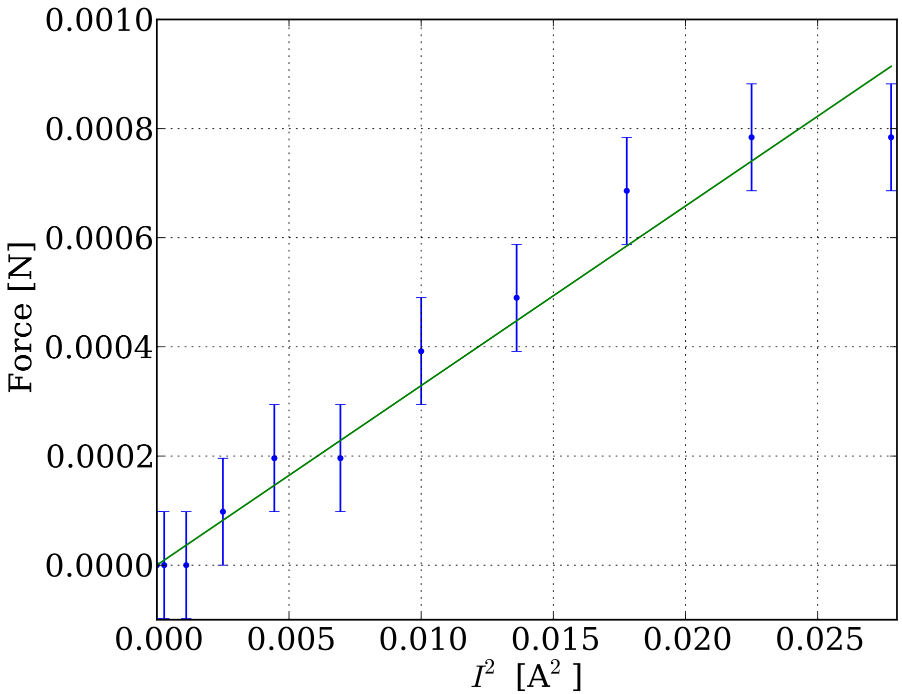
Shoda-san's master thesis

▶ suited well with calculation

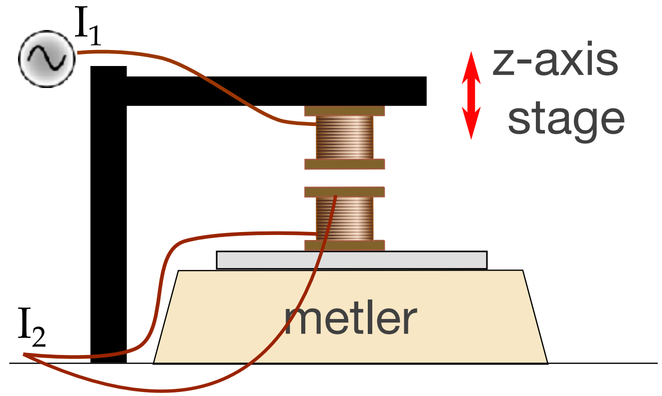
Demonstration of Basic Principle

- Test of Type II actuator

◉ Measure actuation force $\bar{F} = \mu i_1 i_2 \cos\phi$



$f_d = 1\,\mathrm{kHz}$, changing i_1



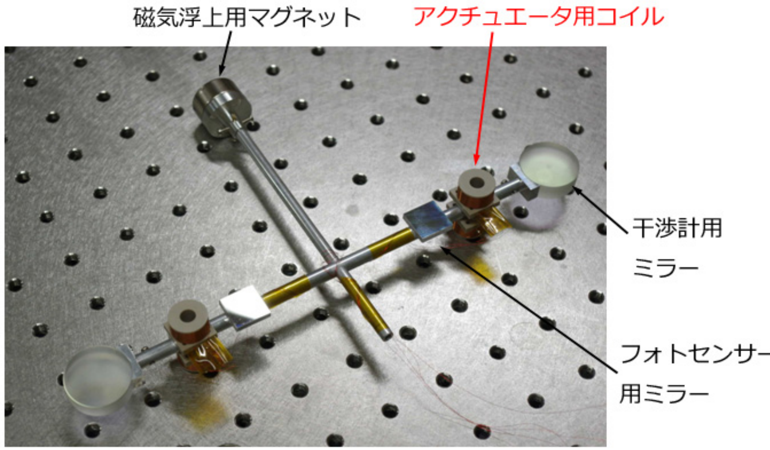
coil2 → shorten

[Shoda-san's master thesis]

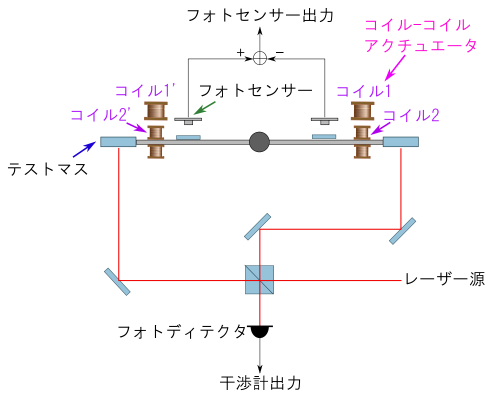
▶ suited well with calculation

Operation of Torsion Pendulum

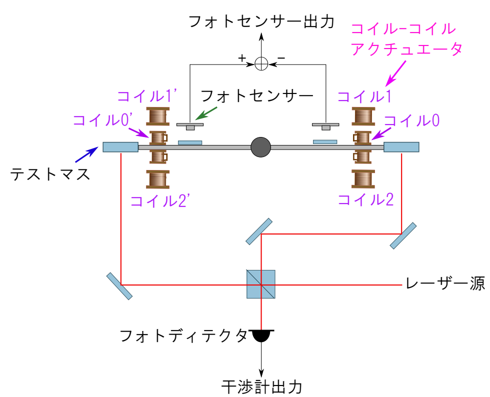
- Control torsion pendulum with CCA by measuring Michelson & PS



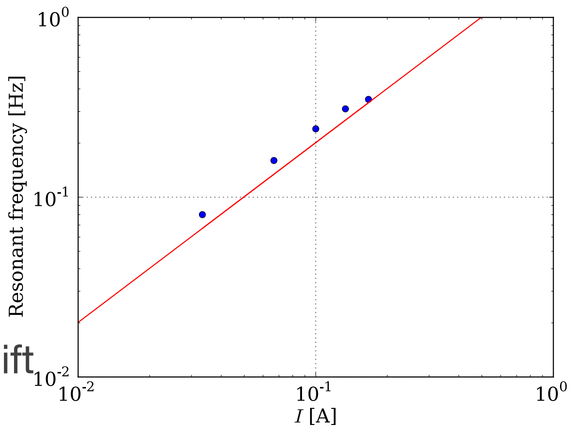
◉ Type I: AM, $\phi = 0$



◉ Type II: AM



◉ Type III: AM, $\phi = 0$



resonant frequency shift depending on i_1, i_2

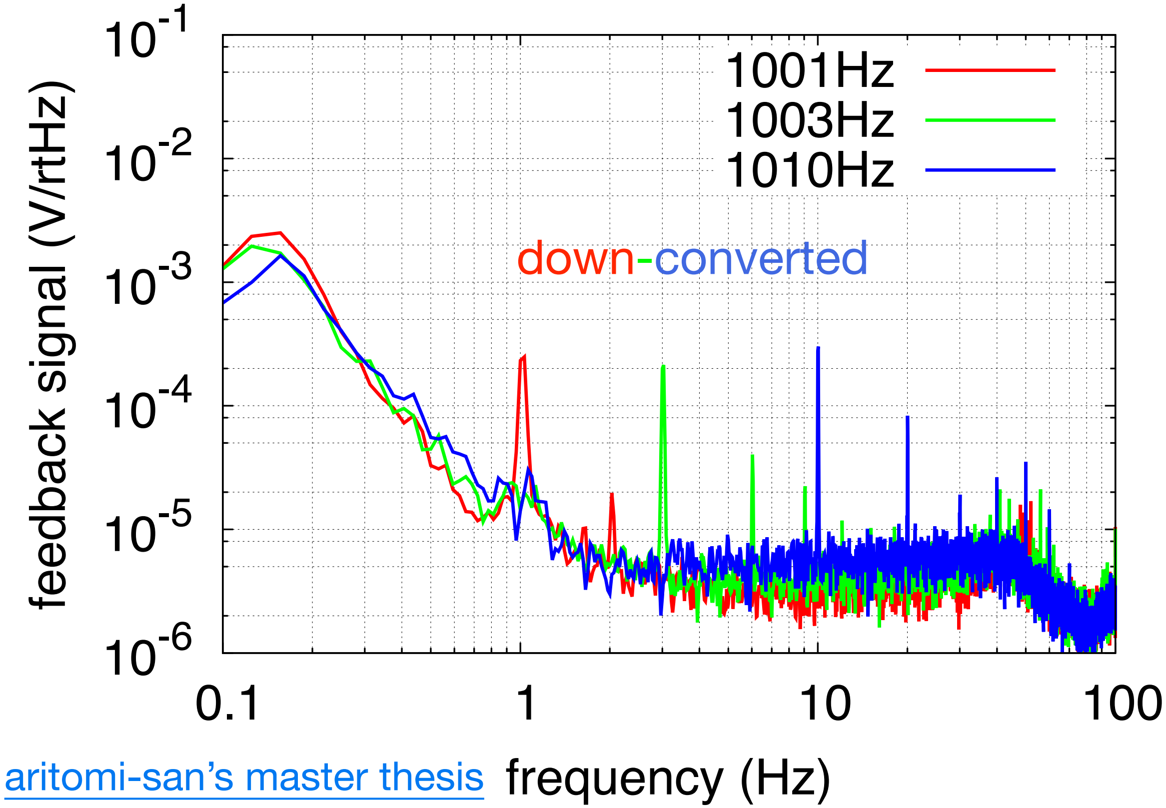
In any case the operation was successful!

Magnetic Noise Measurement

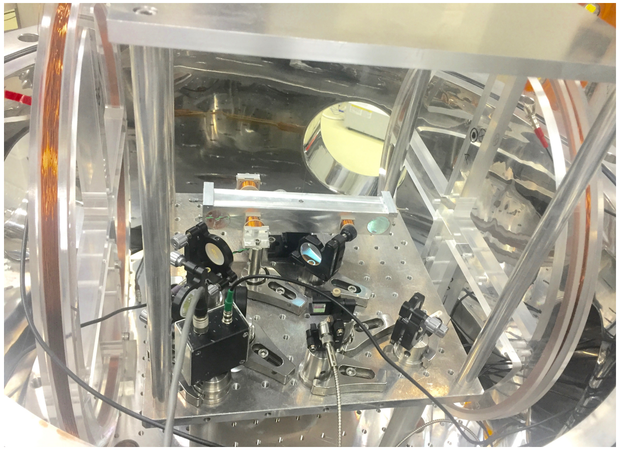
Aritomi-san's master Thesis

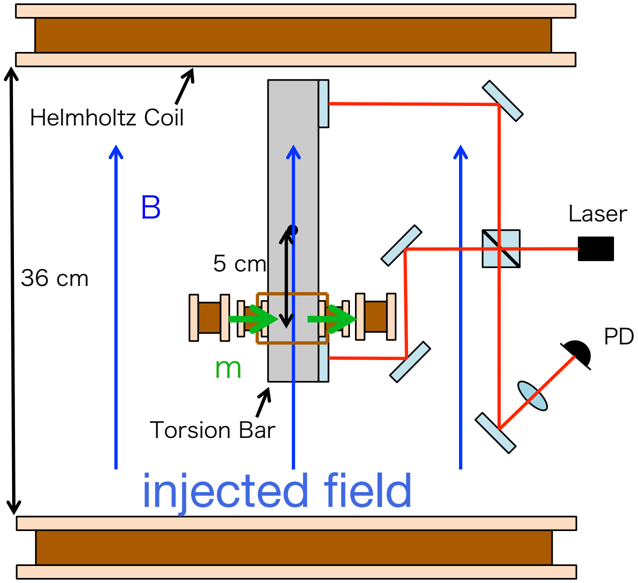
- Measured magnetic noise coupling by injecting magnetic field around f_{d} (= 1 kHz)

◉ Type III AM



aritomi-san's master thesis

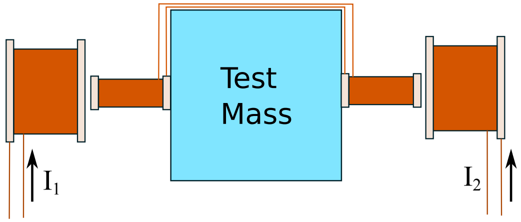


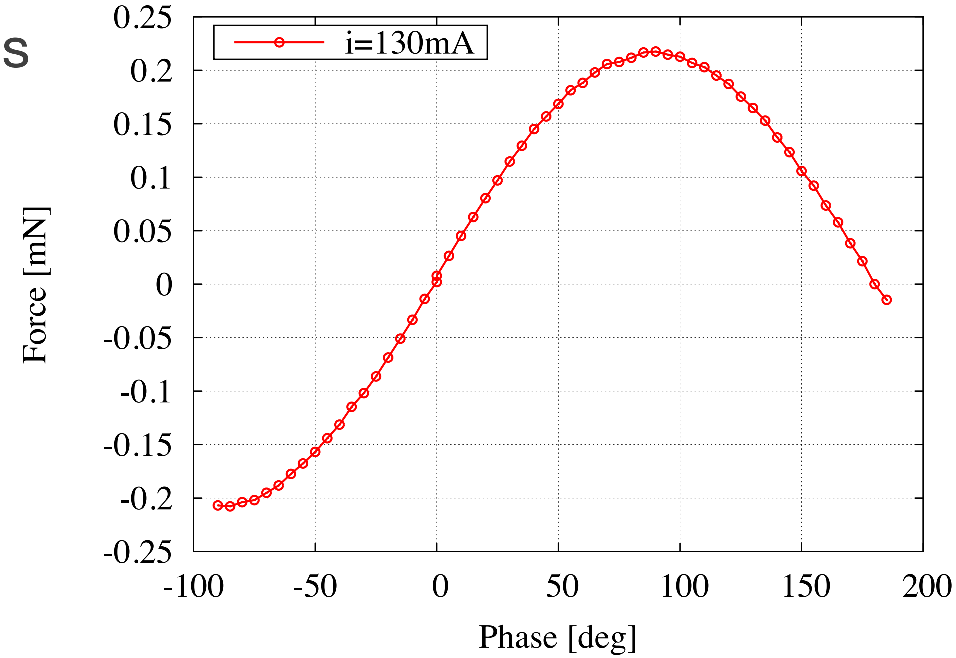


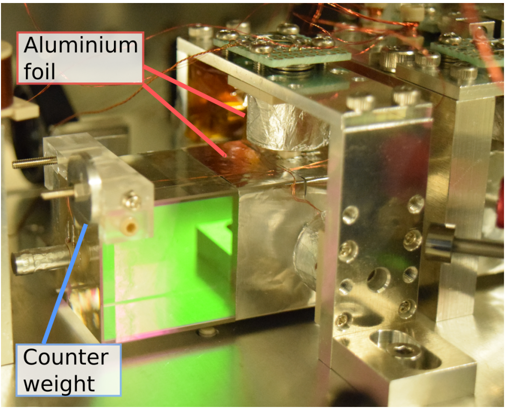
Phase Modulation Operation

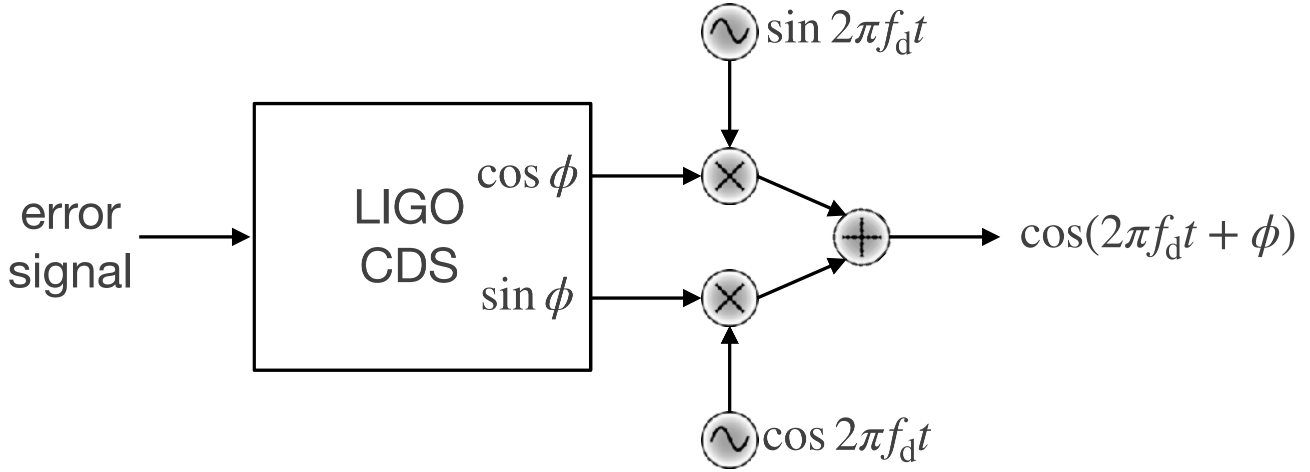
Shimoda-san's master/Ph.D Thesis

- Operating with type III PM









shimoda-san's master thesis

What I did

- Calling
  - ◉ Formulation of thermal noise in type III
  - ◉ Discovery of anti-damping

- Experiment
  - ◉ Magnetic coupling measurement
  - ◉ Resonant frequency shift

Thermal Noise Formulation

- Thermal noise of actuator
  - What is the source?
    - Thermal noise of current flowing coils
    - Fluctuations around f_{d} contributes
  - Type II

$$\sqrt{S_{\mathrm{F}}(f)} = \frac{\mu}{2}\sqrt{{i_1}^2 + {i_2}^2}\frac{\sqrt{2k_{\mathrm{B}}TR_0}}{R_0^2 + (2\pi f_{\mathrm{d}} L_0)^2}$$

  - Type III

$$\sqrt{S_{\mathrm{F}}(f)} = \frac{\mu}{2}\left| i_1 - i_2 e^{i\phi} \right| \frac{\sqrt{2k_{\mathrm{B}}TR_0}}{R_0^2 + (2\pi f_{\mathrm{d}} L_0)^2}$$

Damping Term

- Additional stiffness (Type III)

$$K = \frac{\mu^2}{2} \frac{(2\pi f_\mathrm{d})^2 L_0}{{R_0}^2 + (2\pi f_\mathrm{d} L_0)^2} \, |\, i_1 - i_2 e^{-i\phi} \,|^2$$

- Also introduces damping term

$$D = \frac{\mu^2 R_0}{2} \frac{{R_0}^2 - (2\pi f_\mathrm{d} L_0)^2}{({R_0}^2 + (2\pi f_\mathrm{d} L_0)^2)^2} \, |\, i_1 - i_2 e^{-i\phi} \,|^2$$

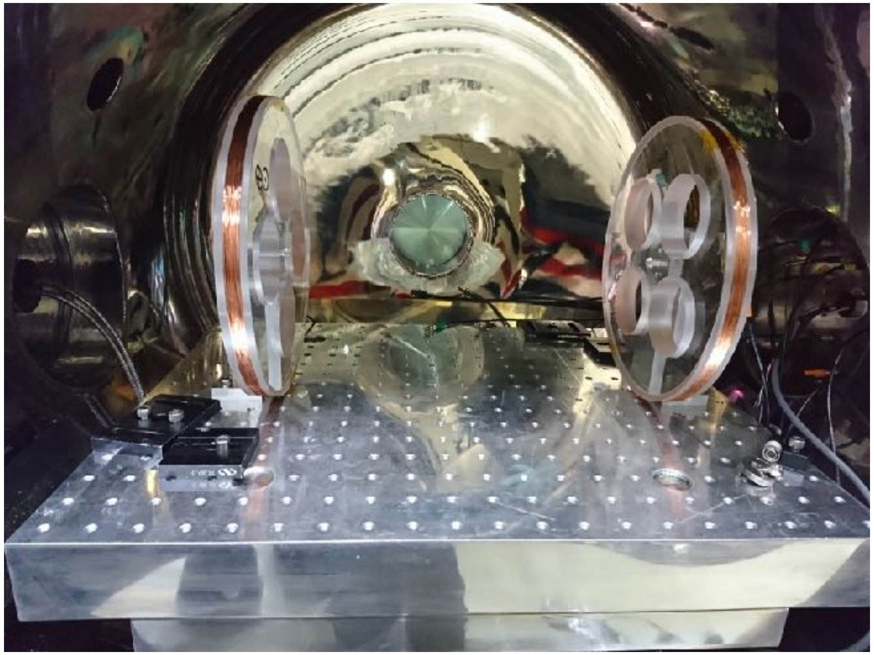
  - Apparently $D < 0$ (anti-damping) when $f_\mathrm{d} > R_0/(2\pi L_0)$
  - Makes the pendulum unstable?

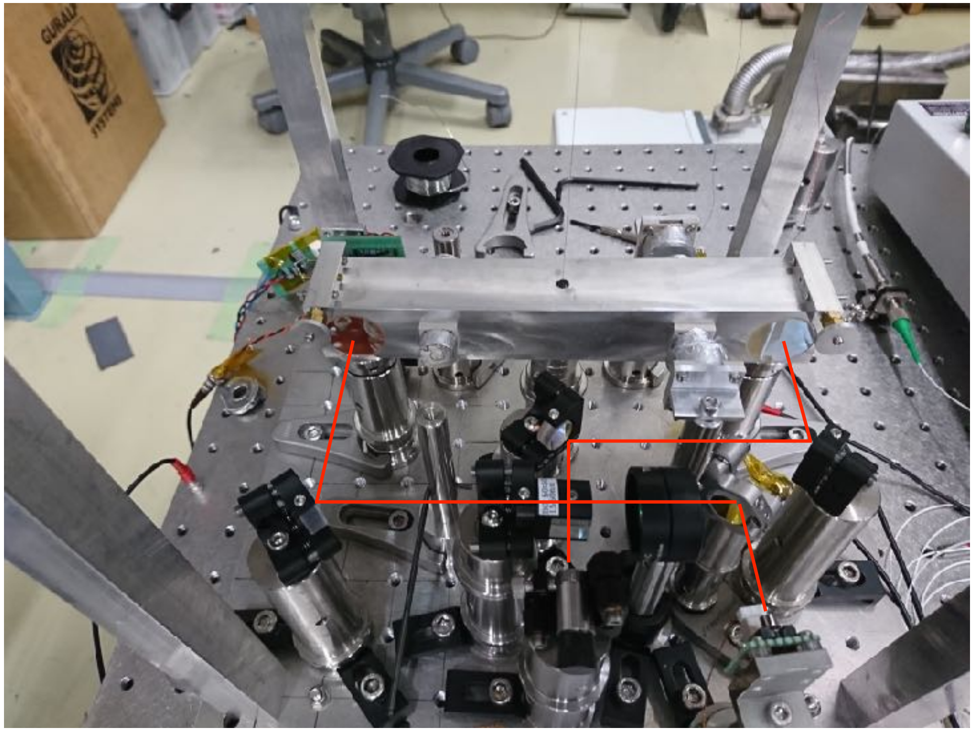
Magnetic Coupling

- Similar setup as Aritomi-san's case (Type III, PM)
- Goal: measurement of

◉ Magnetic coupling from DC/AC field

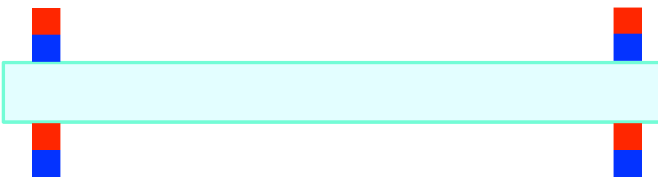
◉ Resonant frequency shift with changing ϕ



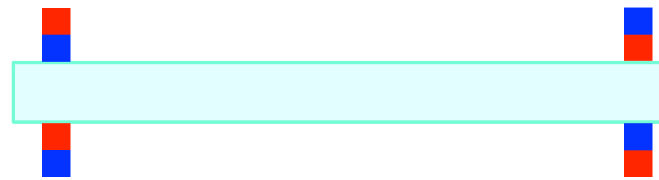


AC Magnetic Coupling

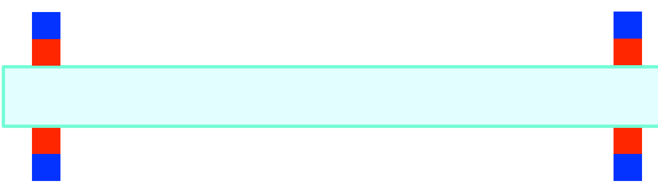
- AC coupling
  - ◉ Injected magnetic field at
    - 1001, 1002, 1003, 1005.5, 1007, 1010, 1020, 1030 Hz (f_d = 1000 Hz)
  - ◉ Direction of dipole moment:
    - Parallel



    - Cross



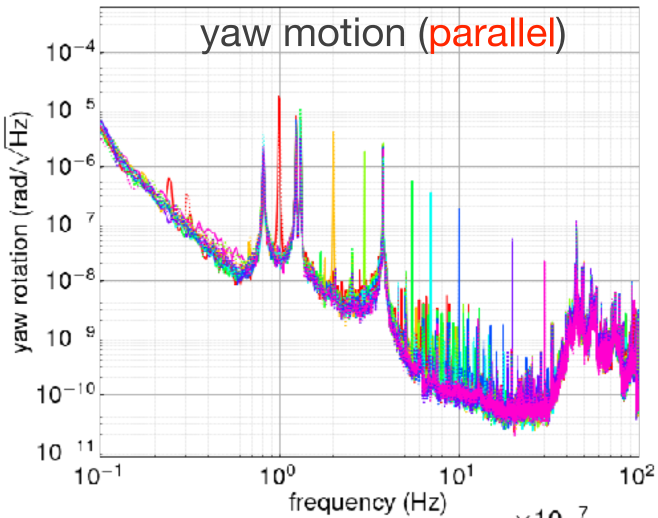
    - Inverse

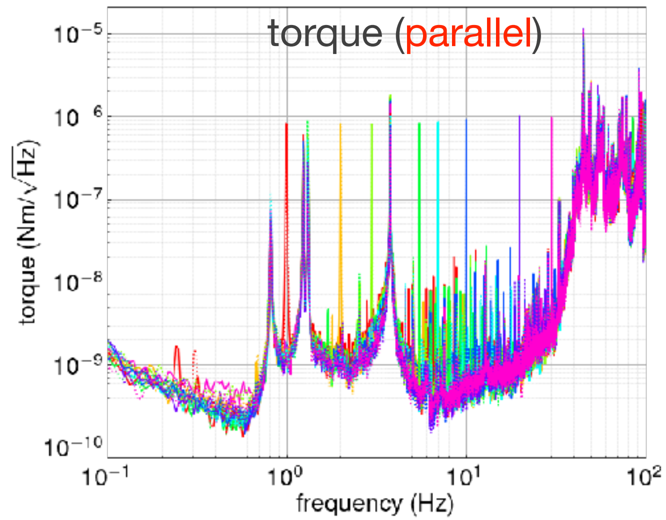


    - Parallel: larger coupling
    - Inverse, Cross: smaller coupling

Down-Conversion

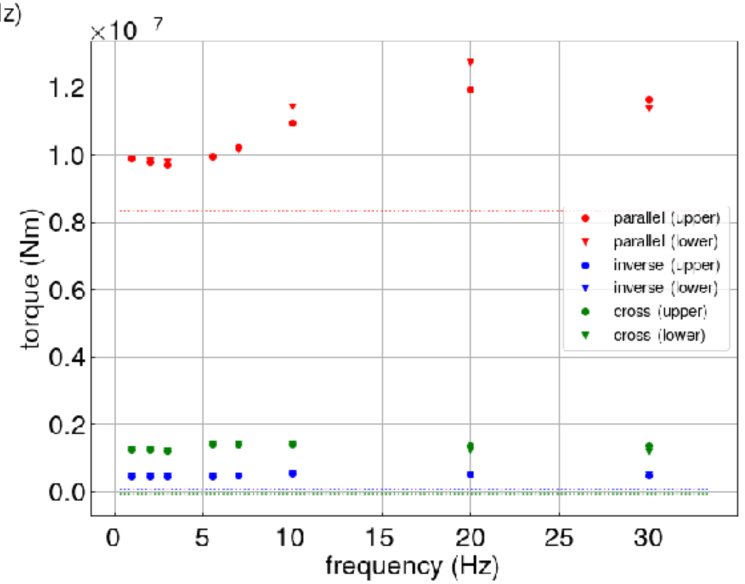
- Power Spectra





- Amplitude

Estimated from
the power spectra
by integrating the peaks

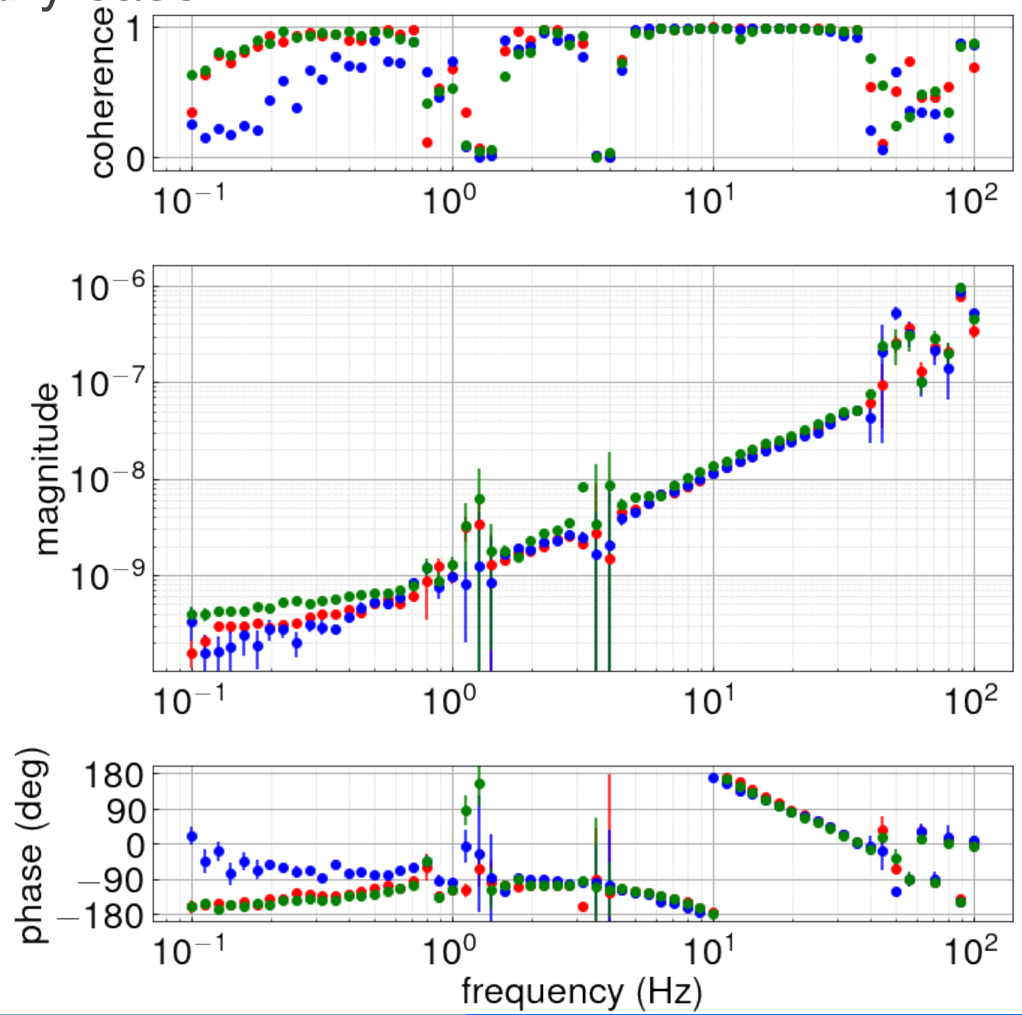


- Looks not so bad
- Error estimation is not enough

Direct Coupling

Measured linear coupling from injected magnetic field

- Looks like no difference in any case
- $\propto f$ dependency
  - Eddy current?
  - No dipole coupling in these frequencies



Resonant Frequency Shift

- Additional stiffness (Type III)

$$K = \frac{\mu^2}{2} \frac{(2\pi f_\mathrm{d})^2 L_0}{{R_0}^2 + (2\pi f_\mathrm{d} L_0)^2} \left| i_1 - i_2 e^{-i\phi} \right|^2$$

- By changing i_1, i_2, ϕ we can control this stiffness
- If we choose $i_1 = i_2$ and $\phi = 0, K = 0$
  - The resonant frequency will be the same as without actuation

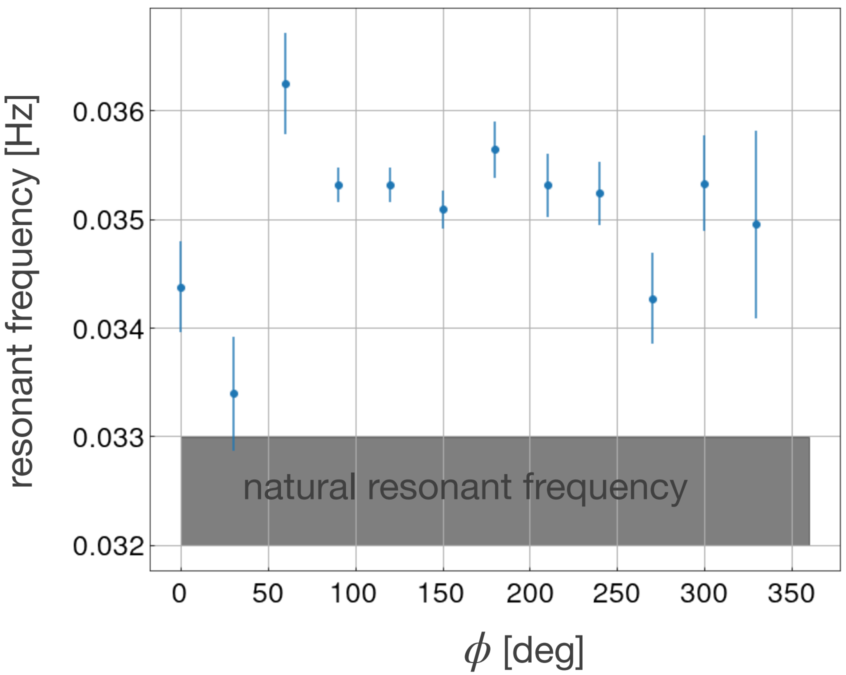
- Measured resonant frequency with driving currents but no feedback control from ringdown measurement

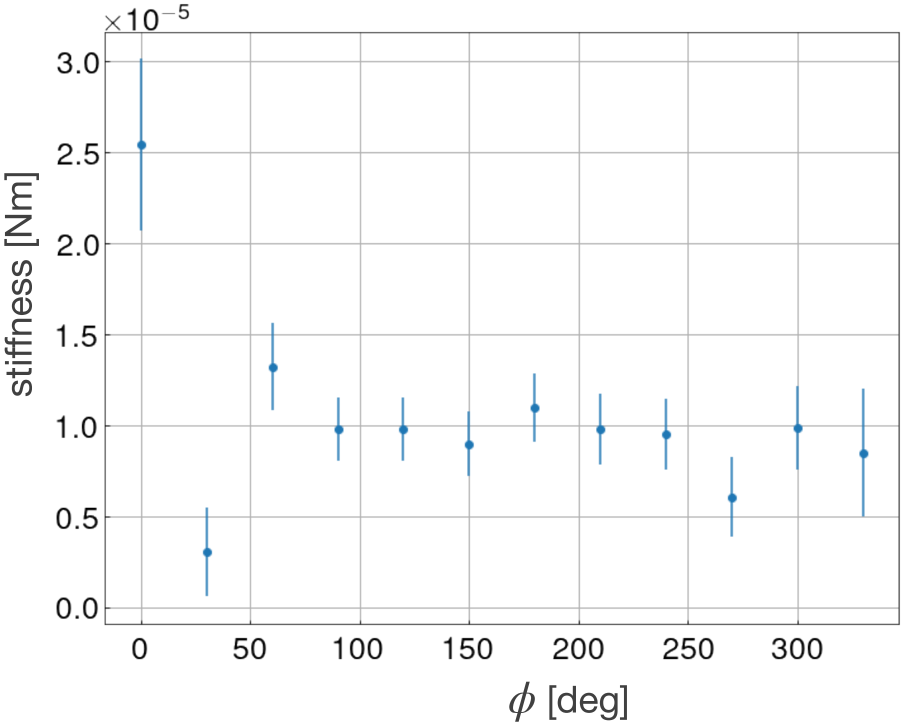
Resonant Frequency Measurement

- Seems independent of ϕ?
- Again, eddy current may affect the dynamics

◉ The effect of eddy current depends on i_1, i_2 (independent of ϕ)

▶ Modification of pendulum is necessary





Summary

- Coil-coil actuator is relatively strong, less magnetic-coupled actuator
- Basic principle was demonstrated
- Already introduced into many experiments in our lab, operated successfully
- Still there are some points we don't understand the actual behavior. Further investigation is welcomed.

- If you interested in it, let's introduce your experiment!