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Loss due to Eddy Current Damping between Magnets and Sensor/Actuator Head Holders in the Small Optics Suspension

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1 ABSTRACT

We measured the loss due to eddy current damping between a small suspended rod with a magnet attached and a sensor/actuator head holder made of aluminum to predict the loss due to eddy current damping in the small optics suspension (SOS) system. The loss was estimated to be $1.8 \pm 0.3 \times 10^{-7}$ at 1 Hz (thus $1.8 \pm 0.3 \times 10^{-5}$ at 100 Hz), which would cause thermal displacement noise of $6.9 \pm 0.6 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$ per mirror (thus $1.2 \pm 0.1 \times 10^{-18} \mathrm{m}/\sqrt{\mathrm{Hz}}$ for three mirrors) at 100 Hz. This is 34 ± 3 % of the total allowable displacement noise of the mode cleaner mirrors ($3.5 \times 10^{-18} \mathrm{m}/\sqrt{\mathrm{Hz}}$).

2 INTRODUCTION

According to the measurement done by B. Lantz in MIT [1], the thermal noise of the mode cleaner mirrors due to eddy current damping in the SOS system was estimated to be 70% of the total allowable displacement noise of the mode cleaner mirrors. Considering the uncertainty of the distance dependence of the effect[1], we decided to measure the loss with the same configuration as the actual SOS system and with more careful set-up.

3 REQUIREMENT

The displacement noise for the quadrature sum of the three mode cleaners is required to be less than $3.5 \times 10^{-18} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz to ensure the required frequency noise of the light coming out of the mode cleaner [2].

4 EDDY CURRENT DAMPING

Since the loss due to eddy current damping is linear to frequency, the spectral density of displacement due to the eddy current damping is expressed as follows:

$$\tilde{x}^2(f) = \frac{4k_B T}{M} \cdot \frac{\omega_0^{\,2}\varphi(f)}{\omega[(\omega_0^{\,2} - \omega^2)^2 - \omega_0^{\,4}\varphi^2(f)]} \tag{1}$$

where $k_B = 1.4 \times 10^{-23}$ J/K, $T = 295$ K, $M = 0.25$ kg, and $\omega_0 = 1 \times 2\pi$ are Boltzman constant, the temperature, the mass, and the resonant angular frequency, respectively [3].

1. The distance between the magnets and the sensor/actuator head holders is slightly larger in the SOS system than the PNI suspension.

5 MEASUREMENT

5.1. Strategy

We used a light suspended mass (5.7 g) and the sensor/actuator head holder made of aluminum whose electric conductivity is lower than that of stainless steel by a factor of 30 (thus eddy current damping is higher by a factor of 30) so that we can clearly distinguish the effect of eddy current damping on the loss in measurement. In the actual SOS system, the mirror weighs 250 g, and stainless steel is used for the holder.

5.2. Experiment Set-Up

5.2.1. Mechanical System

Fig. 1 shows the mechanical set-up to measure the pendulum Q due to eddy current damping.

The suspended mass was constructed with four aluminum rod parts (two $4\mathrm{mmD} \times 25\mathrm{mmL}$ rods and two $4\mathrm{mmD} \times 10\mathrm{mmL}$ rods) as shown in Fig.2 and suspended with two wires. These four rods were connected with each other with screw bolts. These two wires were clamped between a pair of rods in the side of this composed rod, and the upper side of these wires were clamped between aluminum plates to minimize the loss. One magnet ($2\mathrm{mmD} \times 3\mathrm{mmL}$) which was the same one used for the SOS was glued on one edge of this composed rod, and the shading plate was glued on the other edge. The total mass of this pendulum was 5.7 g. The length of the suspension wire is 295 mm. The height of the magnet, that is the height of the center of the holder was 65 mm which was lowered by ~20mm from the formal position.

The whole assembly was put in the vacuum chamber[1] and the pendulum motion was detected by the edge sensor. The He-Ne laser illuminated the shading plate and the unshaded light was detected by the photo-detector.

The relative position of the magnet to the hole was set the same as that for the actual SOS system with the accuracy of ± 0.5 mm in both the longitudinal and transverse directions.[2] The longitudinal distance between the center of the holder hole and the edge of the magnet (denoted by *r*) is 9 mm for the actual SOS system. After evacuation of the chamber, this distance was observed to be shorten maybe due to its change of declination. It was estimated, however, to be ~0.2 mm judging from the photo-detector's output voltage dependence on the suspended mass displacement (~0.1 mm / V).

1. The loss due to air damping was measured to be $\sim 10^{-3}$, which would cover the loss of eddy current damping.
2. It was done by eyes because there was no space to equip micrometers.

5.2.2. Detection System

The pendulum Q was measured by monitoring the decay time of its pendulum swing (0.90 Hz). For convenience, the beat between the pendulum frequency and the reference frequency of 0.91 Hz was plotted as a 0.01 Hz sine curve using a lock-in amplifier.

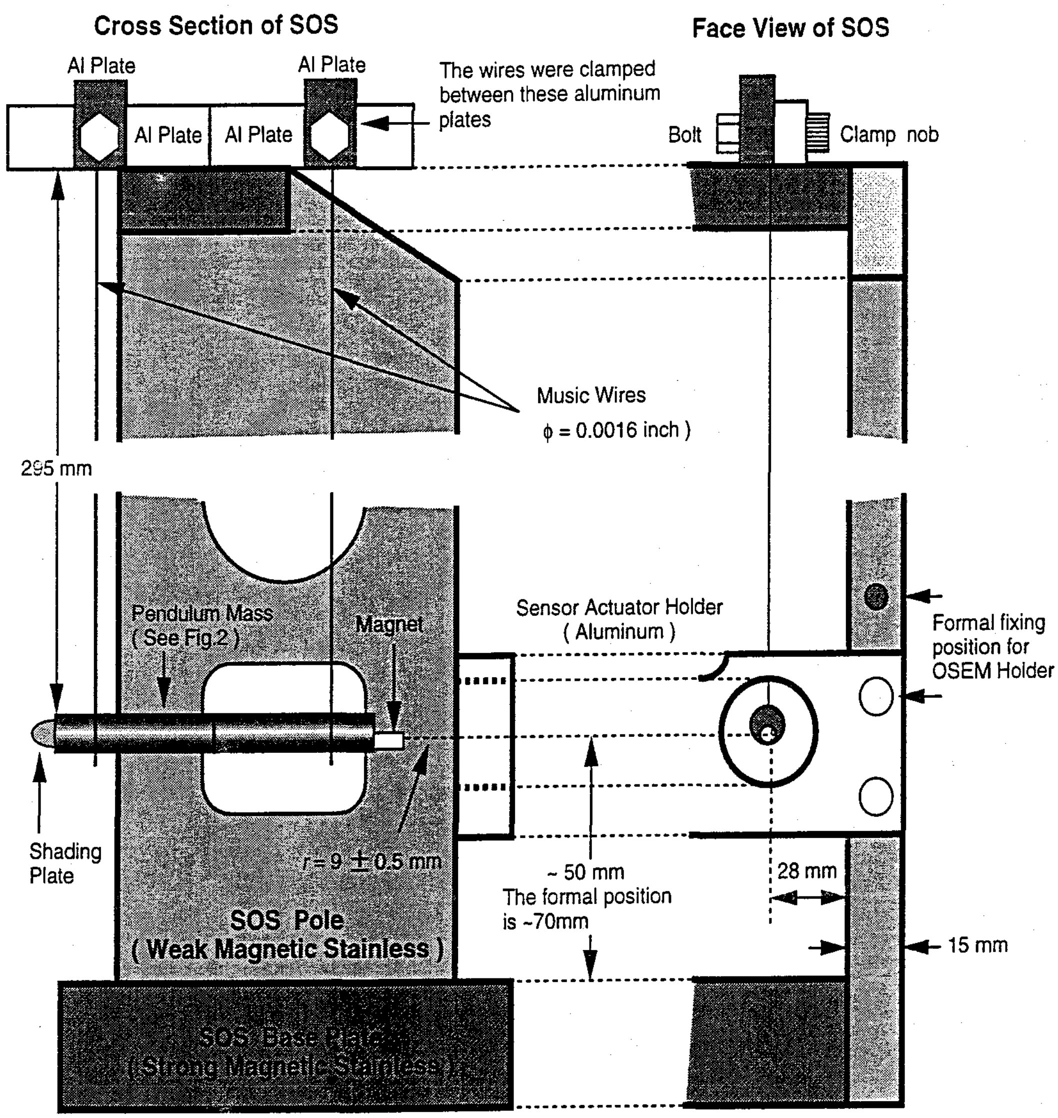

Figure 1: Mechanical set-up to detect the enhanced loss of the eddy current damping

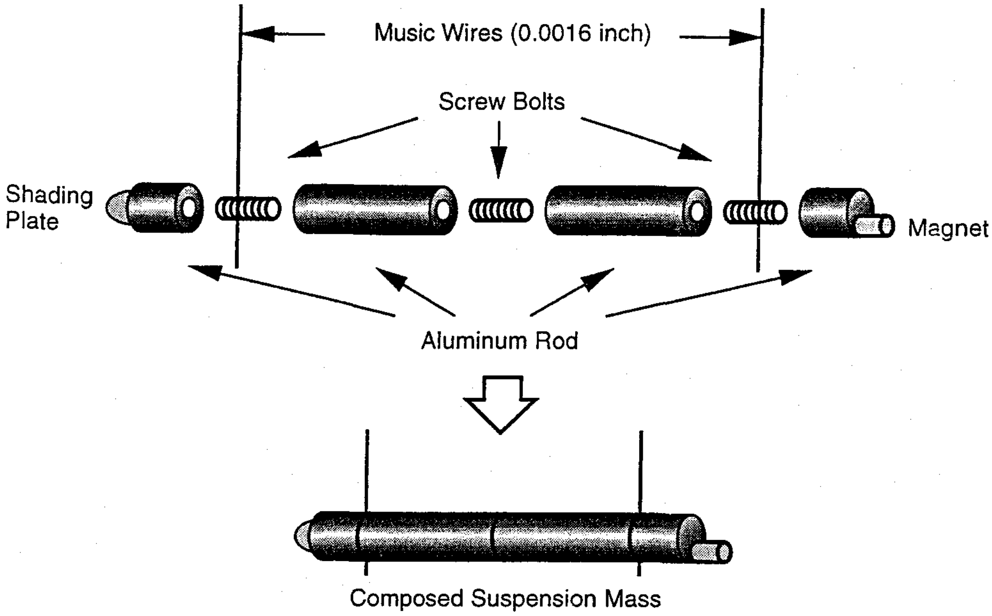

Figure 2: Wire fixing tip to minimize the loss at the suspending points

6 RESULTS

Fig.3 shows the measured Qs of the pendulum with and without the head holder. The Qs without the holder are 6428 ± 43, while Qs with the holder are 4802 ± 204. Calculated from the averaged Qs with and without the holder, the loss due to eddy current damping is estimated to be $5.3 \pm 1.0 \times 10^{-5}$ at 0.9 Hz. This result can be extrapolated to the SOS case by considering the following scaling factor:

- The mass ratio is 5.7 g to 250 g.
- The conductivity of aluminum is a factor of 30 smaller than stainless steel.
- There will be four magnets, whereas only one magnet was used for the measurement.
- The pendulum frequency will be 1.0 Hz, whereas it was 0.9 Hz in the measurement.

The estimated loss due to eddy current damping for the SOS system is $1.8 \pm 0.3 \times 10^{-7}$ at 1 Hz, thus $1.8 \pm 0.3 \times 10^{-5}$ at 100 Hz[1].

1. In this estimation, the error of the distance between the edge of the magnet and the center of the sensor/actuator holder hole was not compensated. If the loss due to the eddy current damping had the dependence of r^{-3}, ± 0.5 mm error of 9 mm corresponded to the 15% error of the estimated loss of $1.8 \pm 0.3 \times 10^{-5}$ at 100Hz

7 CONCLUSIONS

The estimated loss would cause thermal displacement noise of $6.9 \pm 0.6 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$ per mirror (thus $1.2 \pm 0.1 \times 10^{-18} \mathrm{m}/\sqrt{\mathrm{Hz}}$ for three mirrors) at 100 Hz (See Eq. (1)). This is 34% of the total allowable displacement noise of the mode cleaner mirrors ($3.5 \times 10^{-18} \mathrm{m}/\sqrt{\mathrm{Hz}}$).

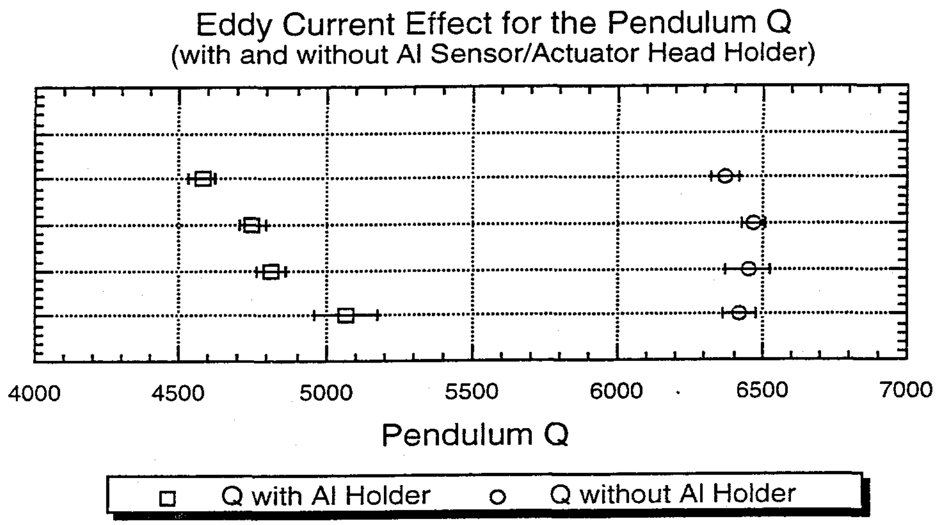

Figure 3: Loss of Q due to the one magnet eddy current damping.

8 REFERENCES

[1] B. Lantz, private communication (1996)

[2] LIGO-T950011-14-D: "Suspension Design Requirements"

[3] LIGO-P940011-00-R: "Suspension Losses in the Pendula of Laser Interferometer Gravitational-Wave Detectors"