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Vibration Suppression of Galvano Mirror Considering Whirling of Shaft

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***Abstract*— Main movement of a galvano mirror is the rolling motion. However, since the structure of galvano mirror is cantilever, this mirror is vertically vibrated to mirror reflective surface. This paper considers the suppression of the above vibration, which is called pitching vibration. Although the galvano mirror is equipped with an encoder to detect the roll angle of mirror, the pitching vibration of mirror cannot be detected. To overcome this problem, the pitching vibration is verified by the frequency response and the time response using two dimensional position sensitive detector. Moreover, three rubbers with different hardness are inserted on the basis of a structure of the motor shaft in order to suppress the vibration.**

Keywords—galvano mirror; vibration suppression; PSD; rubber

I. INTRODUCTION

High speed and precision machining using laser beam greatly contributes to the production of high-performance and small-size portable electronic equipment. A galvano mirror is widely used as a positioning device of the laser beam. In Refs. [1]-[4], a variety of control methods, e.g., feedback and feedforward compensation techniques were proposed in order to suppress vibration at the resonance frequency of this mirror. The structure of galvano mirror can be considered to be the cantilever whose supporting point is the coupling of motor and its shaft. For this reason, the galvano mirror is vertically vibrated to mirror reflective surface. We call this vibration the pitching vibration. Information on the pitching vibration cannot be detected by an encoder. Vibration of the mirror leads to misalignment of the laser beam irradiation position. This causes a deterioration of machining accuracy. In order to cope with this problem, vibration suppression control using piezoelectric elements and a structure to avoid the cantilever were reported. However, since both methods were proposed so as to suppress the vibration caused by the structure of the mirror, the vibration of motor shaft was not sufficiently considered in Refs. [5]-[7]. Therefore, in this paper, we first verify the excitation of the pitching vibration of the galvano mirror by two dimensional position sensitive detector (PSD). Then, the cause of this vibration is explained based on structure of the motor. Finally, we insert rubbers between bearing and motor case in order to suppress the pitching vibration and evaluate the performance of this approach.

II. DETECTION OF PITCHING VIBRATION

Fig. 1 shows outline drawing of the galvano mirror. A mirror which is a load, is attached at the end of the motor. The mirror is rolled by the motor. The galvano mirror is composed of two mirrors. Hereinafter, we call these mirrors X axis and Y axis. By changing the reflection angle of laser beam irradiated to X and Y axis mirrors, laser processing can be performed. Roll angle of the mirror is detected by encoder. The model of the galvano mirror is three-mass system, which consists of the encoder, the motor, and the mirror. However, for simplicity, we consider the encoder and the motor as a rigid body. For this reason, the galvano mirror can be modelled as two-mass system, whose dynamical model is shown in Fig. 2. The model parameters are listed in Table I. From this figure, the dynamical equation of the galvano mirror is expressed as

$$\begin{aligned} T &= J_m\ddot{\theta}_m + D\left(\dot{\theta}_m - \dot{\theta}_l\right) + K\left(\theta_m - \theta_l\right), \\ 0 &= J_l\ddot{\theta}_l + D\left(\dot{\theta}_l - \dot{\theta}_m\right) + K\left(\theta_l - \theta_m\right). \end{aligned} \tag{1}$$

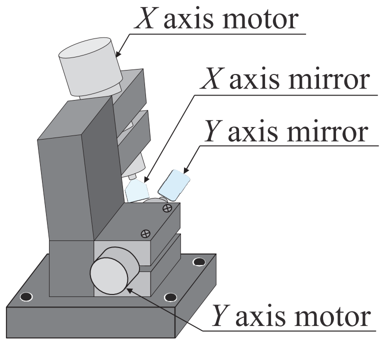

Fig. 1 Galvano mirror.

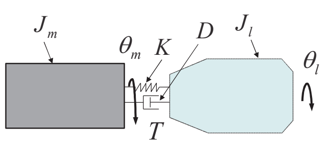

Fig. 2 Two-mass system model.

TABLE I. Model parameters.

Parameters	Description
J_m [kg・m^2]	Motor inertia
J_l [kg・m^2]	Mirror inertia
D [N・m/(rad/s)]	Damping coefficient
K [N・m/rad]	Spring constant
θ_m [rad]	Motor roll angle
θ_l [rad]	Mirror roll angle
T [N・m]	Motor torque

Although the encoder can detect the roll angle, this sensor cannot be used for the detection of pitching displacement of the mirror. For this reason, by evaluating the frequency response, we confirm the pitching vibration of mirror. From (1) and (2), the transfer function from the motor torque T to the mirror roll angle θ_l is written as

$$\frac{\theta_l}{T} = \frac{1}{(J_m + J_l)s^2} \cdot \frac{Ds + K}{\frac{J_m J_l}{J_m + J_l} s^2 + Ds + K}. \tag{2}$$

The simulation result of (2) is shown in Fig. 3.

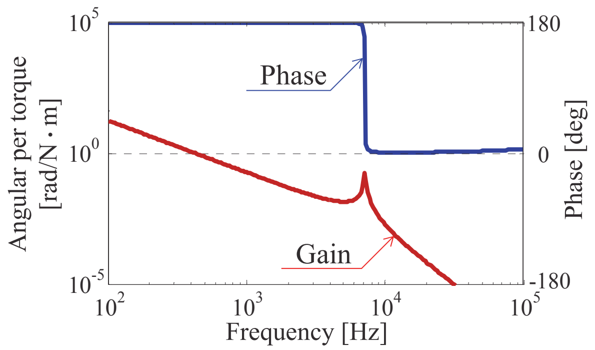

Fig. 3 Bode plots of transfer function from motor torque to mirror roll angle (simulation).

Fig. 4 shows the configuration of the measurement system. In this system, only vibration of Y axis mirror is measured. The center region of the mirror is irradiated with laser beam. The beam reflected by the mirror is shined on the PSD. By using this method, the rolling and pitching displacements are measured. The measurement result on the frequency response of output of the PSD in rolling direction of the mirror is shown in Fig. 5. From Figs. 3 and 5, we can see that the gain observed in this experiment is similar to that obtained by simulation. For example, in both simulation and experiment, the roll-off -40dB/dec is observed until resonance frequency of 7,730 Hz.

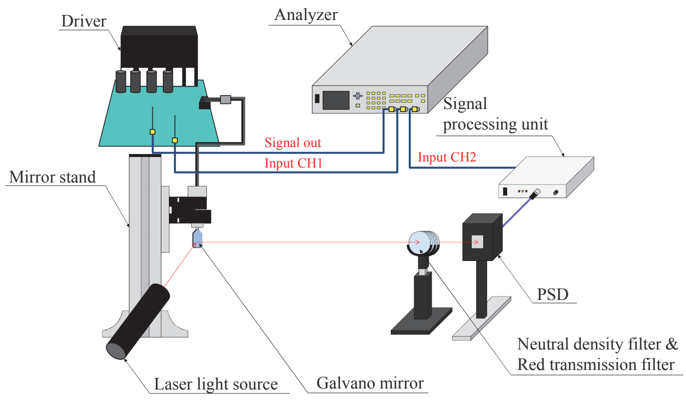

Fig. 4 Experimental setup for measurement of frequency response.

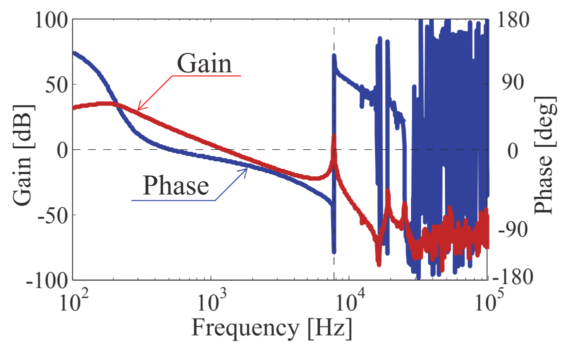

Fig. 5 Bode plots of transfer function from motor torque to mirror roll angle (experiment in rolling direction).

Fig. 6 shows the measurement result on the frequency response of output of the PSD in pitching direction of the mirror. From this figure, we can find that the phase of Fig. 6 is different from that of Fig. 5. Moreover, we can also find that, at 1.45 kHz, the phase changes steeply. From these results, the pitching vibration of the mirror is verified.

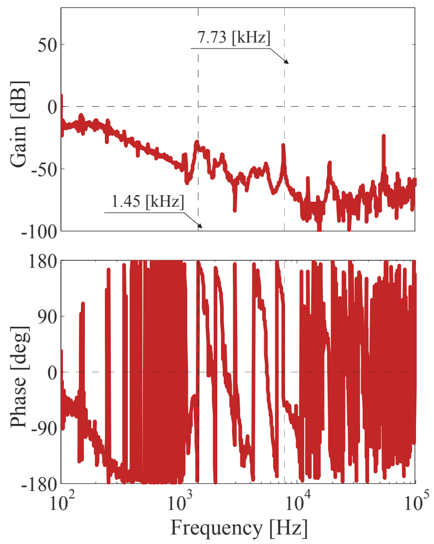

Fig. 6 Bode plots of transfer function from motor torque to mirror roll angle (experiment in pitching direction).

Fig. 7 shows the experimental setup for the measurement of time responses. In this experiment, the motor position signal, deviation signal, PSD output in rolling direction of mirror, and PSD output in pitching direction of mirror are measured by applying a rectangular pulse signal of $0.126V_{p\text{-}p}$ with a frequency of 10 Hz to a driver. The results are shown in Fig. 8. The PSD output in rolling direction of mirror settles in synchronization with the motor position signal. On the other hand, PSD output in pitching direction of mirror does not settle. These results indicate the mirror is vibrated in the pitching direction. The period of the waveform is 1.0 ms, and so the frequency component of 1,000 Hz is appeared.

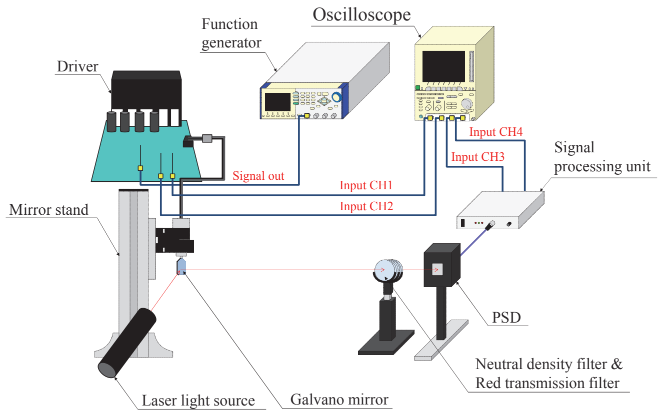

Fig. 7 Experimental setup for measurement of time response.

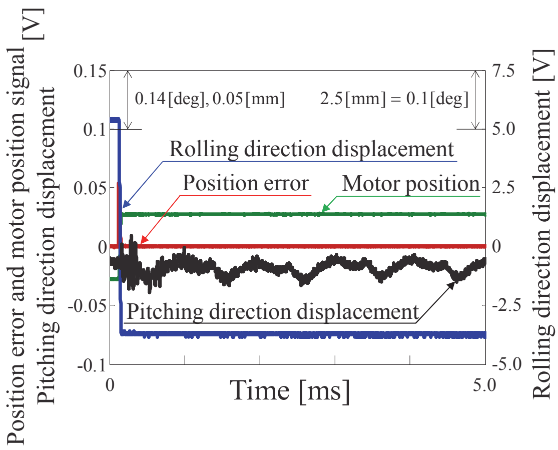

Fig. 8 Time responses.

III. Cause of Vibration and Vibration Suppression Method

In this section, we explain the causes of the pitching vibration and its suppression method. A cause of the pitching vibration is the structure of the mirror is modelled as a cantilever. On the other hand, the whirling of the motor shaft used for driving of the mirror is also the cause of the pitching vibration. The shaft is supported front and rear bearings, though there is a clearance between the bearings and the motor case. It is probable that the whirling of the shaft due to the clearance is the cause of the pitching vibration. For this reason, we suppress the pitching vibration by filling the clearance space. However, since the motor used for the galvano mirror is made with high precision, it is difficult to directly fill objects into the clearance space. For this reason, we suppress the pitching vibration by inserting rubbers between leaf springs. As shown in Fig. 9, the rubbers are inserted on three leaf springs placed on the bearing of the shaft tip. Three rubbers with different hardness are used for the suppression of the pitching vibration. The hardness and the name of each rubber are shown in Table II.

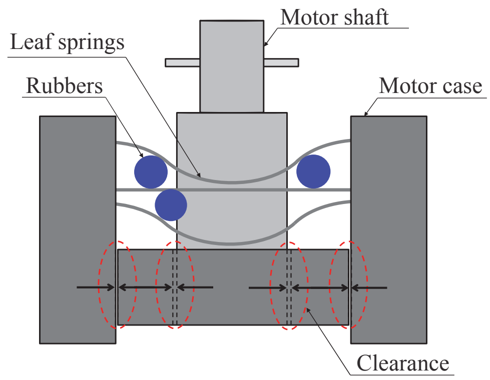

Fig. 9 Outline of suppression method.

TABLE II. Hardness of rubbers [8].

Type	Shore hardness
Soft stiff rubber (Visco-elastic materials)	30
Middle stiff rubber	45
Hard stiff rubber	80

IV. Experimental Evaluation of Vibration Suppression Effects

A. Suppression by Soft Stiff Rubber

The results on the frequency response of PSD output in rolling direction of the mirror are shown in Fig. 10. This figure is the gain diagram for the case with and without the soft stiff rubber. Since the change of characteristics is not observed, the soft stiff rubber does not affect the rolling of the shaft.

Fig.11 shows the results on the frequency response of PSD output in pitching direction of the mirror. This figure is the phase diagram. As shown in Fig. 6, the phase is changed at 1.45 kHz. In order to verify the change of the phase, Fig. 11 is enlarged in the region including this frequency. Although the soft stiff rubber is employed, the phase is changed at several frequencies.

B. Suppression by Middle Stiff Rubber

The results on the frequency response of PSD output in rolling direction of the mirror are shown in Fig. 12. This figure is the gain diagram for case with and without middle stiff rubber. Even in the case, the change of gain characteristics is not observed. Thus, the middle stiff rubber does not affect the rolling of the shaft.

The results on the frequency response of PSD output in pitching direction of the mirror are shown in Fig. 13. The result of this figure is the phase diagram. As well as the case of the soft stiff rubber, phase is changed at several frequencies in the case of the middle stiff rubber.

C. Suppression by Hard Stiff Rubber

The results on the frequency response of PSD output in rolling direction of the mirror are shown in Fig. 14. This figure is the gain diagram in the case with and without the hard stiff rubber. From this figure, even if the hard stiff rubber is used, the change of frequency responses is not observed. For this reasons, the hard stiff rubber does not also affect the rolling of the shaft.

The results on the frequency response of PSD output in pitching direction of the mirror are shown in Fig. 15. This figure, as well as Fig. 14, is the phase diagram. Similar to the case with the soft stiff rubber and the middle stiff rubber, the phase for this case changes steeply at about 1.45 kHz.

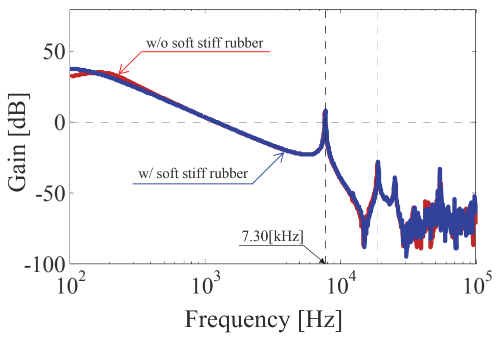

Fig. 10 Bode plots of PSD's rolling output with and without soft stiff rubber.

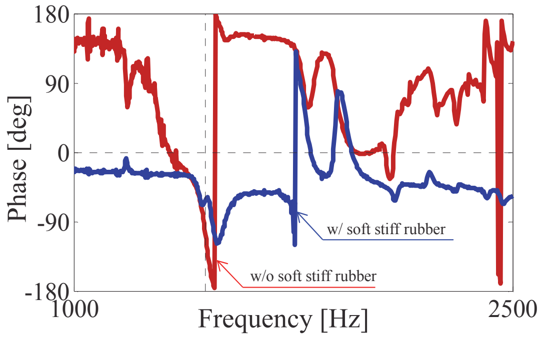

Fig. 11 Bode plots of PSD's pitching output with and without soft stiff rubber.

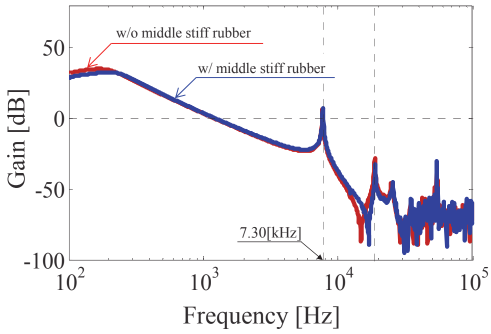

Fig. 12 Bode plots of PSD's rolling output with and without middle stiff rubber.

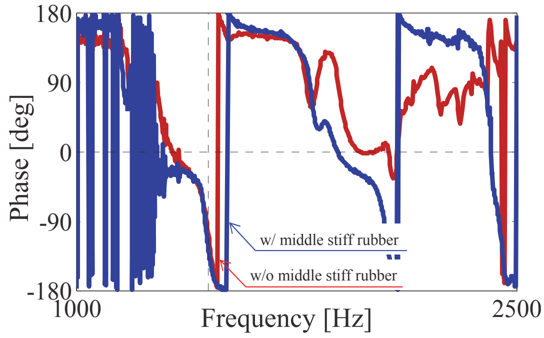

Fig. 13 Bode plots of PSD's pitching output with and without middle stiff rubber.

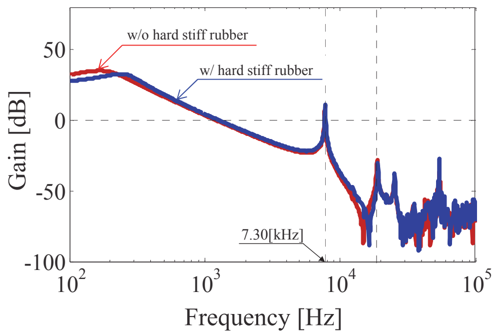

Fig. 14 Bode plots of PSD's rolling output with and without hard stiff rubber.

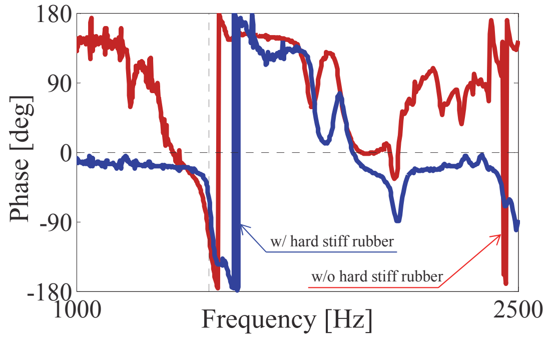

Fig. 15 Bode plots of PSD's pitching output with and without hard stiff rubber.

From frequency responses of Figs. 11, 13, and 15, suppression effects by rubbers are not verified. Therefore, we evaluate suppression effect of pitching motion of the mirror by measuring time responses. The detail is described in the next section.

V. Evaluation of Vibration Suppression Effect by Time Domain

Fig. 16 shows time responses in the case with and without each rubber. The black line denotes the pitching vibration of the mirror. From this figure, we can see that the vibration is damped by using each rubber. For this reason, the suppression effect is verified in the time domain. Moreover, we can also see that the rolling of the mirror is not changed. Therefore, each rubber does not affect the rolling of shaft, and the waveform of PSD output in the rolling direction of mirror synchronizes the motor position signal detected by the encoder.

VI. Correspondence Between The Frequency Responses And Time Responses

As mentioned in section V, in vibration suppression using rubbers, the frequency responses do not correspond with the time responses. This is because the pitching vibration has two kinds of vibrations due to backlash of the shaft and elastic vibration of the mirror. Since the frequency responses was measured by irradiating a laser beam to the mirror center, the elastic vibration of the mirror due to the structure of cantilever was observed in the results. On the other hand, vibration component due to backlash of the shaft is dominant on time response waveforms. Then, the suppression effect is verified from the time responses because the vibration of shaft is suppressed by the rubbers. For these reasons, the frequency responses do not correspond with the time responses.

In order to verify vibration suppression effects in frequency domain, we measure frequency responses again by irradiating laser light at the neighborhood of shaft junction of the mirror because this measurement point is not significantly affected by the elastic vibration of the mirror. In this experiment, the middle stiff rubber is mounted.

Fig. 17 shows phase diagrams on the frequency response of PSD output in pitching direction of the mirror measured at the neighborhood of shaft junction of the mirror. This results show the case with and without middle stiff rubber. From Fig. 17, we can see that when the middle stiff rubber is used, the change of the phase becomes small. Since the effect of elastic vibration is not observed, the change of the phase at 1.45 kHz is also small. Thus, the vibration suppression by middle stiff rubber is verified in frequency domain.

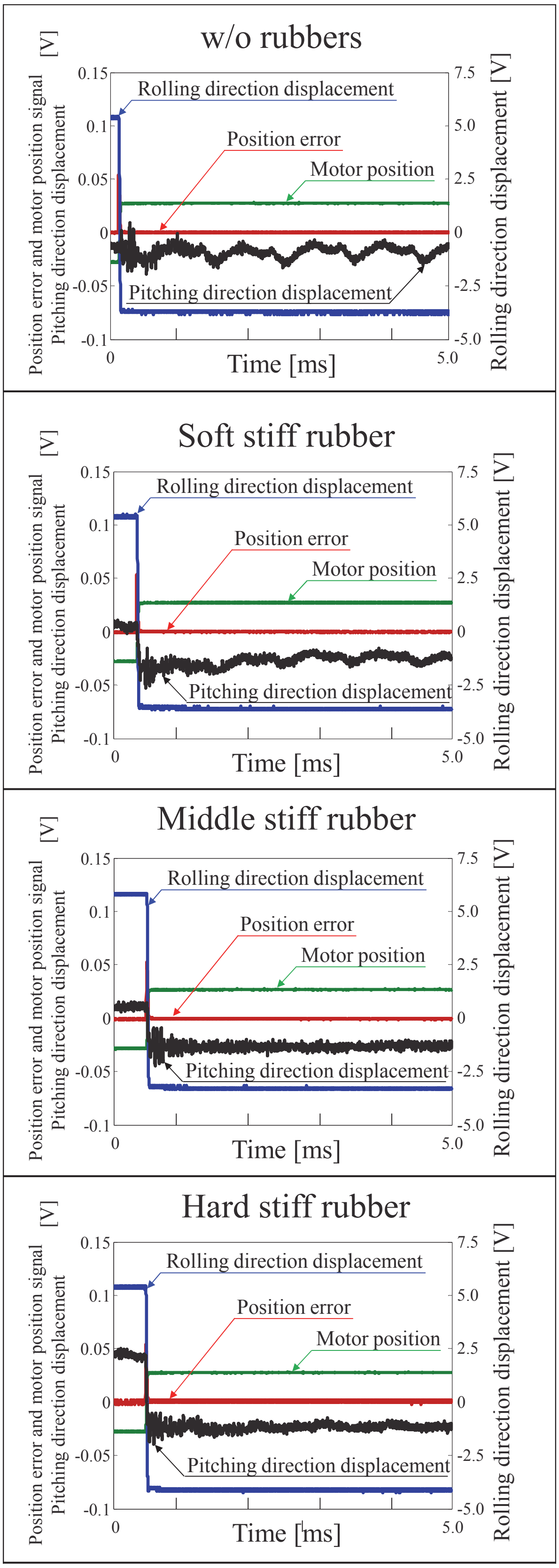

Fig. 16 Time responses under each condition.

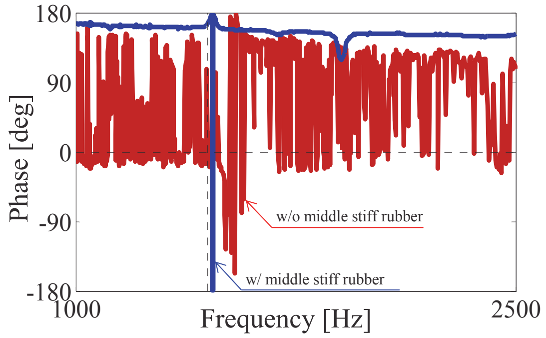

Fig. 17 Bode plots of PSD's pitching output with and without middle stiff rubber.

VII. Conclusion

In this paper, the pitching vibration of the mirror was verified by using the two dimensional PSD. Since we assumed the vibration was caused by backlash of the shaft, three kind of rubbers were inserted so as to suppress the vibration. From experimental results on time responses, we found that the vibration of the shaft backlash was suppressed without effects on the rotational motion of the shaft. Moreover, from the experimental results on measurement at the neighborhood of shaft junction of the mirror, we verified that the suppression effects are observed also in frequency domain.

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