Improvement of Bending Vibration Suppression Performance for Galvano Mirror by Self-Sensing Actuation

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This paper presents a method for suppressing the bending vibration of galvano mirrors used in laser positioning systems. Fast and highly precise positioning of the mirror is vitally important for these systems. Thus, the flatness of the mirror should be maintained to ensure highly precise laser positioning. However, mechanical resonant vibrations of the mirror, which are excited by the moment force during positioning, lead to residual vibrations after positioning; these vibrations degrade the flatness of the mirror and the laser manufacturing accuracy. In this paper, therefore, a vibration suppression method is proposed in which a piezoelectric element is mounted on the mirror so as to utilize the multifunctionality of the piezoelectric element by applying it as both actuator and sensor in the vibration suppression controller design. The applicability of the proposed approach to industrial galvano scanners has been verified by performing experiments with a prototype.

**Keywords:** vibration suppression, self-sensing actuation, piezoelectric element, galvano mirror, decoupling compensation

1. Introduction

A variety of technologies for high packaging density and miniaturization of circuit patterns in printed wired boards (PWBs) have been rapidly developing in recent decades, in order to provide, e.g. small and high quality mobile electronic devices. In the production process of the PWBs, laser-drilling machines are especially in practical use to make a large amount of via holes with high precision accuracy (1)(2).

Laser-drilling machine is one of typical machine tools, that scans laser beams to the arbitrary position using galvano scanners and drills via holes on the PWBs. The galvano scanner is composed of a servo motor and a galvano mirror to reflect the laser beam (3). That is, the fast and precise positioning of the galvano mirror should be an inherent key technique to achieve higher production performances of the laser-drilling machine. In order to provide the requirements, a variety of control approaches have been practically proposed and implemented to the actual systems (4)–(7). Among the researches, however, since the mirror is indirectly controlled by an angular sensor on the motor shaft as a semi-closed control manner, behaviors of the mirror and/or irradiated position of laser beam on the PWBs cannot be directly controlled and evaluated.

The mirror used in galvano scanners is generally a flat plate whose mechanical structure is a cantilever beam supported on the motor shaft edge. Therefore, the mirror is essentially distorted by a force of moment during positioning, resulting in the vibration of mirror according to bending vibration modes, under the mechanical conditions such as rotational unbalance and moment. As a result, the drilling accuracy of via holes may be deteriorated as laser irradiation positions shift. In order to solve the problem, authors have already proposed the basic approach to suppress the bending vibration (8). In the approach, the vibrations were suppressed by mounting a piezoelectric element (PZT)(9)–(11) on the mirror, where a multi-function of both sensor and actuator of the piezoelectric element was simultaneously applied to design the vibration suppression controller (called SSA: self-sensing actuation) (12)–(15). However, since the suppression performance was insufficient for the mirror positioning time, the improvement of suppression performance have been required as a remaining work.

In this paper, a PZT is directly mounted on back of the mirror to improve the vibratory behaviors. In the SSA, control states in the signal can be generally separated by using an electrical bridge circuit, where a virtual bridge circuit (16) can be applied to reduce the analog devices, e.g. capacitor and resistor, considering an easy tuning of the bridge balance. In order to improve the vibration suppression performance of the mirror, a decoupling compensation signal is generated on the basis of the mathematical model to cancel the vibration source. A feedback compensator based on the detected signal through the bridge circuit, on the other hand, can be designed to reduce effects of modeling errors in the decoupling compensator and parameter variations of the plant, where the compensator for the SSA is appropriately designed by paying attention to the relationship between open-loop transfer function and sensitivity function (17)(18). Effectiveness of the proposed approach has been verified by experiments using a prototype of galvano scanners.

2. Positioning Mechanism and Performance of Galvano Scanner

2.1 Configuration of Positioning System

Fig. 1 shows a structure of moving part of galvano scanner as a prototype. The moving part is composed of a mirror, a servo motor, and a galvano scanner.
motor (rotor), and an angle sensor, where a shaft of the rotor is supported by bearings. Fig. 2 shows a configuration of positioning device for galvano scanner as an experimental setup. The galvano scanner is composed of a servo motor with a mirror, where motor angular position $y_r$ (in the dimension of angle [rad]) is detected by a sensor and is transferred into a digital signal processor (DSP) controller through an interface with the sampling period of 20 $\mu s$. The servo motor is driven by a current controlled amplifier with control input $u$ generated by the position controller. In the actual system, since the laser irradiation position cannot be directly detected by the angle sensor, the direction of two dimensions, i.e., rotational $y_r$ and vertical $y_v$, is measured and evaluated by a position sensitive detector (PSD) using a semiconductor laser for detection use in the experimental setup.

### 2.2 Plant Characteristic

The galvano scanner can be mathematically modeled by a multi-degrees of freedom vibration system whose frequency characteristic of $y_r$ for $n$ is plotted by solid lines in Fig. 3. From the figure, the mechanism includes the primary vibration mode (1300 Hz), the 2nd vibration mode (4400 Hz), and a dead time component due to the current control delay, affecting the positioning performance. These vibration modes are caused by twist of the shaft. Fig. 4 shows deformation shapes of mechanical twist vibration modes by a finite element method (FEM) analysis for the moving part of galvano scanner. From the result, the primary twist vibration mode is generated by the axial twist between rotor and mirror, while the 2nd vibration mode is generated by the axial twist among mirror, motor, and angle sensor. In these vibration modes, a rotation moment by the twist vibration greatly deforms a mirror.

By considering these two vibration modes, the following non-parametric model can be formulated as a plant mathematical model $P_s$, consisting of a rigid mode, twist vibration modes up to $n = 2$, and a dead time component:

$$P_s = \frac{y_r}{u} = \frac{K_p}{J} \left( 1 + \sum_{n=1}^{2} \frac{k_n}{s^2 + 2ζ_nω_n s + ω_n^2} \right) e^{-L_s} \cdot \cdots \cdot (1)$$

where $K_p$: gain which includes torque constant of motor and current control gain, $J$: moment of inertia, $ω_n$: natural angular frequency of $n$th twist vibration mode, $ζ_n$: damping coefficient of $n$th twist vibration mode, $k_n$: modal constant of $n$th twist vibration mode, and $L$: equivalent dead time, respectively. These parameters are identified by curve-fitting on the basis of experimental data. The broken lines in Fig. 3 indicate the frequency characteristic of the mathematical model $P_s$, while parameters of (1) are listed in Table 1.

### 2.3 Positioning Control System

Since the galvano scanner detects the angular position only on the motor side as stated in Fig. 2, a semi-closed positioning controller is generally designed by using the detected motor angle $y_r$. Fig. 5 shows a block diagram of a 2-degree-of-freedom (2DOF) positioning control system based on the final-state control (FSC) method, where $P_r$ and $P_v$: plant systems of laser irradiation positions (mirror rotational and vertical direction displacements $y_r$ and $y_v$ as shown in Fig. 2, both in the dimension of displacement converted into [m]) for control input $u$, $C$: feedback compensator consisting of a phase lead-lag filter and notch filters, $P_s$: nominal discrete transfer function for $P_r$, including the primary and 2nd twist vibration modes (1300 and 4400 Hz), $r$: motor angle reference corresponding to laser irradiation position (rotational direction displacement...
Fig. 5. Block diagram of 2DOF positioning control system

Fig. 6. Experimental waveforms of positioning. Top: motor position error. Middle: laser irradiation position error for rotational direction $y_r$. Bottom: laser irradiation position for vertical direction $y_v$.

$y_v, u^*$: feedforward control input based on the FSC. In the following, the motor angular position $y_s$ is converted into the corresponding laser irradiation displacement $y_r$.

The desired control specification for the positioning system is given as a point-to-point positioning within the settling time of 2.0 ms for a typical positioning stroke $R$ (laser irradiation position) of 1.5 mm. The settling time means the time from when a motion starts till when the positioning error falls within the target settling accuracy $\pm 1\, \mu m$.

### 2.4 Positioning Performance

Fig. 6 shows an experimental waveform of positioning for a target positioning stroke of $R = 1.5$ mm, where top figure indicates the motor position error ($R - y_s$), middle figure indicates the laser irradiation position error ($R - y_r$), and bottom figure indicates the vertical direction displacement $y_v$. In the figure, two waveforms are presented. In the figures, solid lines indicate waveforms under a good mechanical condition of rotational balance in the galvano scanner and, on the other hand, broken lines indicate ones under small unbalance in the rotational axis due to e.g. attachment errors in shaft and mirror. From the result, $y_s$ and $y_r$ can achieve the required target settling time (indicated in vertical dotted lines) without residual vibration, where $y_s$ and $y_r$ provide the same positioning performance regardless of the rotational balance and unbalance. In the waveforms of $y_v$, on the other hand, the solid line settles to zero immediately at the corresponding settling time, while the broken line includes a large amount of residual vibration with the frequency of 500 Hz after the settling time. This result under the rotational unbalance supposes the deterioration in laser processing accuracy although the motor and mirror rotational displacements can be appropriately controlled.

### 3. Analyses of Vibration in Vertical Direction

The vibration in the vertical direction is analyzed by frequency responses of the laser irradiation position for control input and FEM analyses.

Solid lines in Figs. 7 and 8 show the frequency characteristics of rotational direction displacement $y_r$ and vertical direction displacement $y_v$ for control input $u$. In Fig. 7, the vibration modes at 1300 and 4400 Hz as same as in Fig. 3 exist due to the twist of shaft. Therefore, the transfer function $P_r$ of $y_r$ for $u$ can be formulated as follows:

$$P_r = \frac{y_r}{u} = \frac{K_p}{J} \left( \frac{1}{s^2} + \sum_{n=1}^{2} \frac{k_n}{s^2 + 2\xi_n\omega_n s + \omega_n^2} \right) e^{-Ls}, \cdots (2)$$

where $K_p$, $J$, $\omega_n$, $\xi_n$ and $L$ are the same parameters as in (1). The broken lines in Fig. 7 show the frequency characteristic of the mathematical model $P_r$, while parameters of $k_n$ are listed in Table 2. In Fig. 8, on the other hand, another vibration modes indicated by vertical chained lines exist at 500 and 3100 Hz, which cannot be detected in the rotational direction.

Fig. 9 shows shapes of the vibration modes (500 and 3100 Hz) of the mirror by FEM analyses. From Fig. 9, the vibration modes of 500 and 3100 Hz are generated as bending
vibration modes that are caused by the support of fixed end of the mirror as a fulcrum. Since motor torque acts only in the rotational direction of the galvano scanner, these bending vibration modes are not generally excited. However, force of the vertical direction to the mirror surface caused by the vibration modes are not generally excited. However, force of the vertical direction to the mirror surface caused by the support of fixed end may generate and excite the bending vibration mode. Since motor torque acts only in the rotational direction of the galvano scanner, these bending vibration mode is lower than the primary twist vibration mode (1300 Hz) and it exists within the servo band-width, the bending vibration mode might be excited even in the normal positioning. Since the galvano scanner has no sensor to detect the bending vibration components as well as no actuator to suppress the components, an alternative approach should be introduced to suppress the bending vibration modes.

4. Bending Vibration Suppression Using Self-Sensing Actuation

4.1 SSA Using PZT In this research, a PZT is directly mounted on the mirror to effectively suppress the bending vibration modes, where a SSA plays roles of both sensor and actuator simultaneously. Fig. 11 indicates a schematic configuration of the experimental setup with a PZT as the SSA. From the FEM analyses shown in Fig. 9, since the bending vibration modes excite the vertical direction vibration on the surface of the mirror, the PZT should be mounted on the axis of rotation as shown by broken lines in Figs. 9 and 11 to realize the efficient detection and the vibration suppression.

Fig. 12 shows a piezoelectric property as frequency characteristic of output voltage \( V_p \) of PZT for control input \( u \). From Fig. 12, the primary and 2nd bending vibration modes can be successfully detected by the PZT. However, the deformation of the mirror caused by the twist vibration modes as shown in Fig. 4 is inherently detected simultaneously. Fig. 13, on the other hand, shows an inverse piezoelectric property which corresponds to the frequency characteristic of laser irradiation position (vertical direction displacement \( y_v \)) for input voltage \( v_p \) of the PZT. From Fig. 13, only the bending vibration modes can be excited by supplying voltage to the PZT. This means that it is possible to detect and actuate the bending vibration modes by installing the PZT on the mirror.

4.2 Signal Isolation Using Bridge Circuit In the SSA, since the PZT can be operated as both sensor and actuator, the voltage applying to the PZT includes both sensing and actuating signals. The voltage, therefore, should be separated by a bridge circuit as shown in Fig. 11. Fig. 14 shows a CC bridge circuit to separate the signals in the voltage. In the figure, the PZT can be expressed by the output voltage \( V_p \) caused by the deformation of mirror and an equivalent ca-

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**Table 2. Parameters of plant for laser position**

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**Fig. 9. Mode shapes of mirror by FEM analyses**

(a) 500 Hz  (b) 3100 Hz

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**Fig. 10. Block diagram of bending vibration model**

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**Fig. 11. Schematic configuration of experimental setup with PZT as SSA**

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**Fig. 12. Frequency characteristic as piezoelectric property of PZT**
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Fig. 13. Frequency characteristic as inverse piezoelectric property of PZT

Fig. 14. CC bridge circuit for separation of signals in PZT voltage

Fig. 15. Virtual CC bridge circuit for separation of signals in voltage

4.3 Controller Design for SSA System

4.3.1 Positioning System with SSA Control System

By using the bending vibration mode model $P_{\text{res}}$, (8), and (9) acquired through the balanced bridge circuit, a positioning control system with SSA control system can be designed as a block diagram of Fig. 16, where $K_s'$: coefficient of transformation from mechanical energy to electrical energy, $K_f'$: coefficient of transformation from electrical energy to mechanical energy, $H$: feedback compensator of SSA control system, $C_f$ and $C_f'$: decoupling compensators, $\hat{f}$: estimated $f$, and $u_2$: decoupling compensation signal, respectively. In the SSA control system, since the mirror is bent by the force of vertical direction $f$, the vertical displacement $y_v$ occurs. Then, the output voltage $v_p$ is generated by a piezoelectric effect of the PZT, while the sensor voltage $v_i$ is detected by the bridge circuit. By supplying the voltage $v_i$ through the compensators $C_f$, $C_f'$, and $H$ to the bridge circuit, the actuation voltage $v_a$ is given to the PZT. As a result, the excitation force by the inverse piezoelectric effect can suppress the bending vibration of mirror.

4.3.2 Plant Characteristic for SSA Control System

Fig. 17 indicates frequency characteristics of sensor voltage $v_i$ for supplied voltage $v_i$ to the virtual CC bridge circuit shown in Fig. 15, solid lines indicate results in experiment, and broken lines indicate ones by the simulation model. From the figure, both sensing and actuating of the bending vibration modes can be separated by the bridge circuit. Especially, the primary bending vibration mode 500 Hz can be precisely expressed by the simulation model. The feedback compensator $H$, therefore, can be designed on the basis of the characteristics in Fig. 17 because the characteristic at around the primary bending vibration frequency 500 Hz is especially important to suppress the residual vibration.
4.3.3 Controller Design

In this approach, a decoupling compensation signal $u_d$ is calculated to cancel the force of vertical direction $f$ by the mathematical model, where the dead time component $L$ can be ignored within the control bandwidth about 1 kHz. From the block diagram of Fig. 16, $C_{f1}$ and $C_{f2}$ are designed as follows:

$$C_{f1} = K_p K_{pr}$$  \hspace{1cm} (11)

$$C_{f2} = \frac{1}{K_p K_{pr}}$$  \hspace{1cm} (12)

The feedback compensator $H$, on the other hand, can be designed to suppress the effect of modeling errors and parameter variations in (11) and (12). From Fig. 16, a sensitivity function $f'/f$ can be calculated as follows:

$$f' = \frac{1}{1 + P_{am} \cdot \frac{K_p K_{pr}}{K_p K_{pr} + C_{pr}}} H = \frac{1}{1 + G_o} \quad \cdots \cdots \cdots (13)$$

Here, $G_o$ is an open-loop transfer function of the SSA feedback loop. From (13), the sensitivity function $f'/f$ can be shaped by the open-loop transfer function $G_o$, that can be arbitrarily shaped by the feedback compensator $H$. As a relationship between the open-loop transfer function and the sensitivity function, it is known that the sensitivity of control system decreases by receding the vector locus of the open-loop transfer function in the complex plane from the critical point of $(-1, j0)^{17(18)}$. Therefore, the vector locus of the primary bending vibration mode should be considered to draw a larger mode circle in the right side of the complex plane. In addition, in order to avoid the spillover of higher vibration modes, the feedback gains should be decreased in the high frequency range. The compensator $H$, therefore, can be designed as the following bandpass filter:

$$H = K_p \frac{s^2}{s^2 + 2\zeta_1 \omega_1 s + \omega_1^2} \frac{s^2 + 2\zeta_2 \omega_2 s + \omega_2^2}{s^2 + 2\zeta_1 \omega_1 s + \omega_1^2} \quad \cdots \cdots \cdots (14)$$

where $K_p = 40$, $\omega_1 = 2\pi \times 100$ rad/s, $\omega_2 = 2\pi \times 500$ rad/s, $\zeta_1 = 0.7$, and $\zeta_2 = 0.7$. These parameters are designed by considering parameter variations such as bridge circuit and plant characteristics. Fig. 18 indicates Nyquist diagrams of the SSA control system with the designed compensator $H$, where (a) indicates the case of variation in $C_{pr}$, (b) indicates the case of variation in $C_2$, solid lines represent the nominal condition without parameter variation, broken lines represent the cases with $+5\%$ variation in each capacitance, and dotted lines represent the cases with $-5\%$ variation in each capacitance, respectively. In the variations, the bridge unbalance is simulated by changing the parameters of virtual bridge circuit. Fig. 19, on the other hand, indicates the sensitivity gains at around the primary bending vibration mode frequency. From Fig. 18, the desired loci due to the primary bending vibration mode can be drawn in the right side in the complex plane. As a result, the gain can be reduced in the primary bending vibration mode as shown in the sensitivity gain of Fig. 19. In addition, the SSA system can ensure the stability under the $\pm 5\%$ variations of capacitance.
5. Experimental Verifications

The proposed approach has been verified by experiments using the galvano scanner, where the 2DOF positioning control framework has been applied with the proposed SSA system as shown in Fig. 16. The compensators are implemented as discrete transfer functions by a bilinear transformation with the sampling time $20\mu s$. Fig. 20 shows experimental results for the target position of 1.5 mm, where the upper waveforms are positioning errors of laser irradiation position (rotation) $y_r$, and the bottom waveforms are the vertical direction displacements $y_v$. In the figure, the light solid lines represent responses without SSA, the broken lines represent ones with SSA feedback compensator $H$, the dotted lines represent ones with decoupling compensators, and the dark solid lines represent ones with SSA feedback compensator and decoupling compensators. From Fig. 20, the waveforms of rotational direction displacement show the same performance in both with and without SSA system. Although the bending vibration can be attenuated by applying SSA as indicated in the bottom of Fig. 20, the performance of vibration suppression is insufficient concerning the settling time. In addition, the residual vibration occurs after the settling in the decoupling compensation without SSA feedback compensator due to the modeling errors between the compensators and the actual parameters ($K_p$, $K_r$, $K_p\phi$, $C_p$, $C_1$). On the other hand, the bending vibration after positioning can be completely suppressed by applying the decoupling compensators and the SSA feedback compensator.

Fig. 21 shows experimental results in the cases with the parameter variations, where the waveforms of vertical direction displacement are indicated. Top figure shows waveforms under the parameter variation, where the gain of decoupling compensators is set with 10% variation. Middle and bottom figures show the waveforms under the bridge unbalance, where $C_r$ and $C_2$ are changed $\pm 5\%$ by software. From these results, sufficient suppression performance of bending vibration can be achieved under the conditions. However, since the SSA system becomes unstable under the capacitance variation over 10%, a parameter identification approach in offline or online manner should be developed by applying the advantage of virtual bridge circuit as the future works.

6. Conclusions

This paper presented a vibration suppression approach of the mirror for galvano scanners, where the SSA using PZT was applied to improve the bending vibration suppression performance. The FEM analyses showed that the residual vibration caused by bending vibration of the mirror on the laser irradiation position was excited during positioning. In order to suppress the bending vibration of mirror, a PZT was directly mounted on the mirror as a SSA device. The signals of both sensor and actuator included in the voltage of the PZT were separated by the virtual CC bridge circuit to implement the SSA control system. In order to sufficiently suppress the vibration, decoupling compensators were designed on the basis of the mathematical model. The feedback compensator of SSA system, on the other hand, was designed paying attention to the relationship between the sensitivity function and the open-loop transfer function to reduce the sensitivity gain at around the primary bending vibration frequency. As a
result, the attenuation of bending vibrations could be sufficiently achieved. The effectiveness of the proposed approach has been verified by experiments using the galvano scanner positioning system.

References


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