Investigation of Super-Finishing Process Control Using a Fine Diamond Stone with a Five-Bar Planar Parallel Robot

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***Abstract*—In this study, the existing super-finishing method used for polishing glass surfaces was refined using a five-bar planar parallel robot with fixed abrasive grains. In previous studies, a voice coil motor had been used to control the constant-pressure pressing force while maintaining the polishing force for a relatively short time period. To achieve a high-quality polished surface, however, it is important to maintain the polishing force for a long period of time. Thus, in this study, a strain gauge load cell was adopted in addition to the conventional piezoelectric force sensor to maintain the polishing force for a long time period. First, the amounts of DC drift of the piezoelectric force sensor and the strain gauge load cell were compared to confirm the necessity of signal processing. Next, the measurement system was subjected to a hammering test, and the gain of the Proportional-Integral-Differential (PID) control was determined by obtaining the transfer function. Finally, a long-time polishing experiment using two sensors with PID control was conducted to confirm the stability of the polishing. It was found that the system was able to maintain a preset low pressure and perform stable polishing for a long time. It was also able to detect high-frequency vibrations simultaneously.**

***Index Terms*—Force control, PID control, polishing, automation, robot**

I. Introduction

In recent years, environmental issues, such as acid rain and global warming, have become a cause for concern. Consequently, it has become important to discover ways of achieving a sustainable development, which is a principle that enables the present generation to use the environmental resources to satisfy their requirements without compromising the ability of the future generations to satisfy their own needs. To achieve this, it is necessary to downsize machine tools, such that small machines are used for small parts, to reduce the amount of waste during production in consideration of the environment [1].

Generally, the quality of a surface finish is highly dependent on the skill of the operator. Finishing is a difficult task that requires dexterity and skill; however, due to the declining birthrate and aging population, it is becoming difficult to train workers and maintain their skills for a long period of time [2, 3]. Thus, from the perspective of quality stabilization and traceability, the automation of finishing operations is necessary [4].

In this study, we used a compact and small size robot, which is composed of a five-bar planar parallel mechanism, to perform fixed abrasive processing with low environmental impact for polishing borosilicate glass. The robot was equipped with a fine powder super polishing stone; by combining its motion in the horizontal plane with a force control technology, we aim to achieve high precision in the polishing of small objects in the next generation [5, 6]. In a previous study, the polishing force was also maintained for approximately 40 min by introducing feedback control using a piezoelectric force sensor to prevent the stick-slip vibration [7]. In the present report, we developed a novel technology that the polishing force was maintained for several hours by applying a polishing force control method using both a piezoelectric force sensor and a strain gauge load cell. First, the effect of the DC drift was investigated, and the transfer function was obtained from the hammering test of the measurement system. The gain of PID control was determined from the transfer function, and the polishing force was verified in a polishing experiment using PID control. By applying the results of the verification experiment, it was possible to maintain a constant control over the polishing force in a 3-hour polishing experiment.

II. Experimental Equipment

A. Five-bar Planar Parallel Robot and Control Devices

For this experiment, a five-joint closed-link compact and small robot, shown in Fig. 1(a), is employed, which is composed of a five-bar planar parallel mechanism. A tool was attached to the end-effector of the robot, which consisted of a voice coil motor with an ultra-fine polishing stone attached to its tip. This tool, shown in Fig. 1(b), was used for low-pressure machining. The pressing force in Z direction was controlled by adjusting the current of the voice coil motor. The workpiece was mounted on a table, along with two types of force sensors in the present report. A charge amplifier (KISTLER, type5015A) and a dynamic

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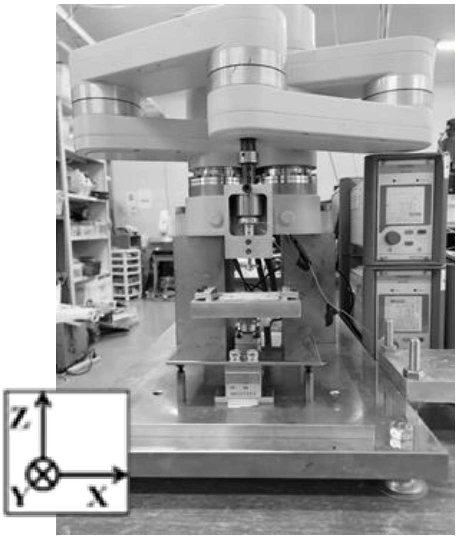
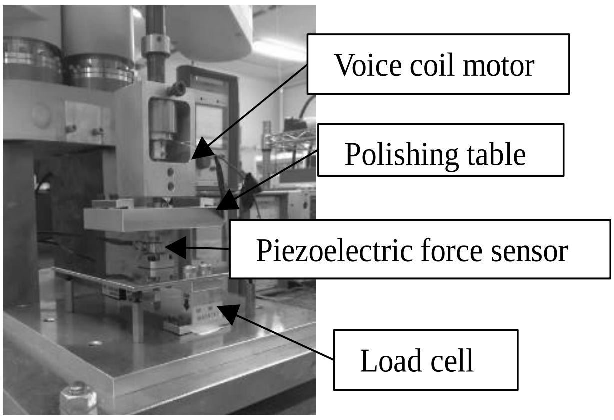
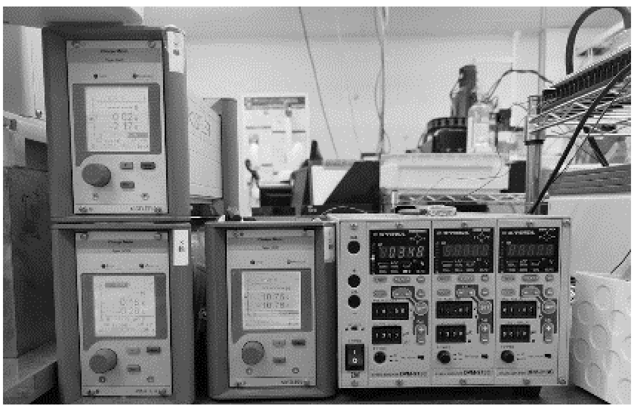
strain amplifier (KYOWA, DPM-900), shown in Fig. 1(c), were used. A digital signal processing system (MTT, SEAGULL mini), shown in Fig. 1(d), was used to control the output of the force sensor. The current output of the coil was controlled using a stabilized power supply.



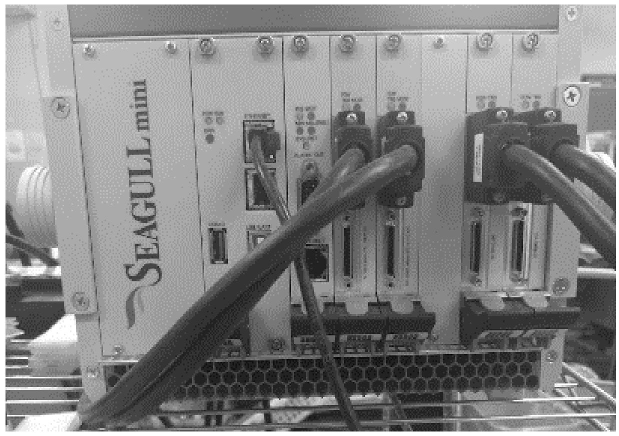
(a) Five-bar planar parallel robot



(b) Low-pressure machining tool



(c) Force sensor amplifiers



(d)Digital signal processing system

Figure 1. Experimental equipment.

The basic devices that comprised the experimental equipment were connected as shown in Fig. 2, and the workpiece was polished using a pressing force feedback control mechanism with a piezoelectric force sensor in the previous report [7].

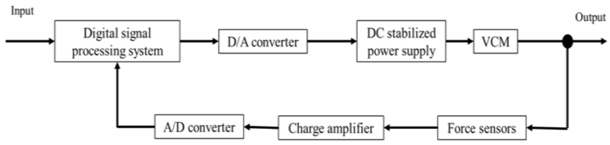


Figure 2. Basic equipment connection to control pressing force in Z direction.

B. *Workpiece and Polishing Stones*

Table I shows the details of the workpiece, and Table II shows the details of the polishing stones.

TABLE I. BOROSILICATE GLASS

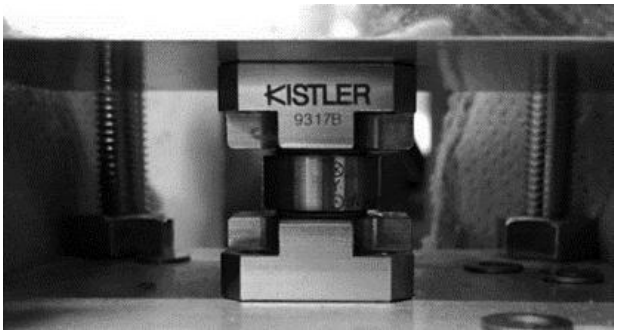
Material	Borosilicate glass
Main component	SiO_2
Size [mm × mm]	26×76
Thickness [mm]	1
Vickers hardness [HV]	630
Surface Roughness R_a [nm]	670

TABLE II. POLISHING STONES

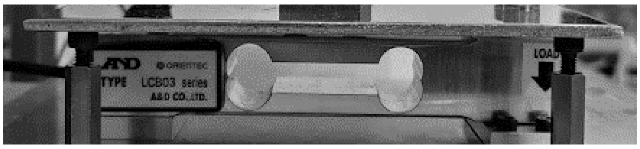
Grain mesh number	#8000
Volumetric grain percentage	27.5
Mean grain diameter [μm]	1
Abrasive grain	Diamond
Bond material	Vitrified
Size [mm × mm]	3×3
Height [mm]	4

C. *Force Sensors*

In the present report, a strain gauge load cell in Z direction was introduced to keep a DC polishing force stable during long time, in addition to the piezoelectric sensor used in the previous study, and both sensors were installed under the workpiece to measure the force applied on it during polishing, as shown in Fig. 1 (b). The details of two sensors are shown in Fig. 3. A three-axis force sensor (Kistler's type 9317 B), which could simultaneously measure the forces acting in the X, Y, and Z directions, was used as the electric sensor to prevent the stick-slip vibration. The electric charge output from the force sensor was converted to a voltage output by a charge amplifier, and this voltage was processed by a digital signal processing system to visualize the force applied on the workpiece. The strain gauge load cell (A&D LCB03K003M) used in this experiment was a beam-type, single-point load cell with a rating of 30 N, wihch was mounted on the piezoelectric sensor. The voltage output from the load cell was amplified using a dynamic strain amplifier and was transmitted to the digital signal processing system. The natural frequency of the piezoelectric force sensor was 20 kHz in the Z direction, approximately 14 times higher than that of the load cell, which was 142.5 Hz. Therefore, piezoelectric force sensors could measure higher frequencies of vibrations than those measured by the load cells. gain of the PID control was also obtained. Fig. 6 shows the striking point of the hammering test to estimate the relationship between input force and measured one and the time and frequency responses of the load cell recorded at that point.



(a)Piezoelectric force sensors



(b) Strain gauge load cell to measure pressing force

Figure 3. Details of force sensors in developed system.

III. Experimental Methods

The Lissajous curve was employed as the polishing path in this experiment and is given as:

$$\begin{cases} x = A\cos(\alpha\omega t). \\ y = B\sin(\beta\omega t+\delta). \end{cases} \tag{1}$$

In this case, the constants were given as: A = 10, B = 10, δ = 0, α = 14, and β = 13. Fig. 4 shows the polishing path and the positions at which the surface roughness of the workpiece was measured. Table III lists the polishing conditions.

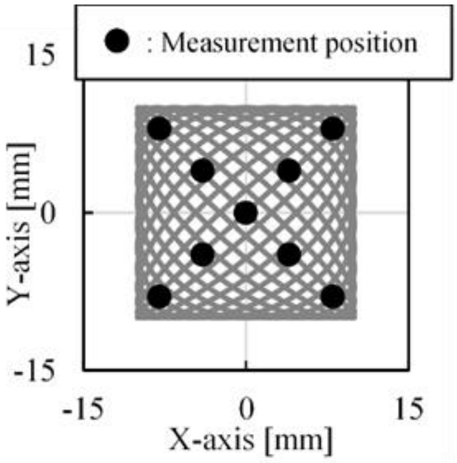


Figure 4. Polishing path.

TABLE III. Polishing Conditions.

Polishing force F [N]	2.0
Polishing speed v [mm/s]	15
Polishing time t [min]	30,60,120,180
Lubrication condition	Water

The surface roughness of the workpiece was measured at 9 points on the polishing path, using a laser microscope (KEYENCE, VK-210). The coordinates of these points were: (0,0), (-8,8), (8,-8), (8,8), (-8,-8), (-4,4), (4,-4), (4,4), and (-4,-4); their average values were used. In order to reduce the bias of the surface roughness at each position, measurements were taken at nine points and averaged.

IV. Results and Discussion

A. DC Drift

The long-term stable force control was investigated by incorporating a strain gauge load cell. To compare the drift characteristics of the piezoelectric force sensor with that of the strain gauge load cell, no polishing experiment was conducted, but the values of the two force sensors were recorded. The applied force, F, was measured at 0 N for 5 min. To reduce the influence of temperature increase of the strain gauge load cell and piezoelectric force sensor on the output, we ensured that the power supply connected to each sensor and the amplifier were turned on for more than 24 h during the experiment. Fig. 5 shows the outputs of the force sensors recorded at 0 N for 5 min.

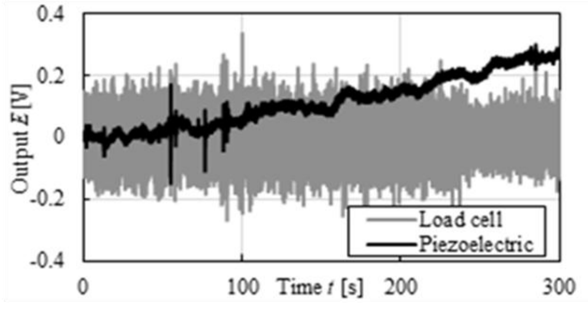


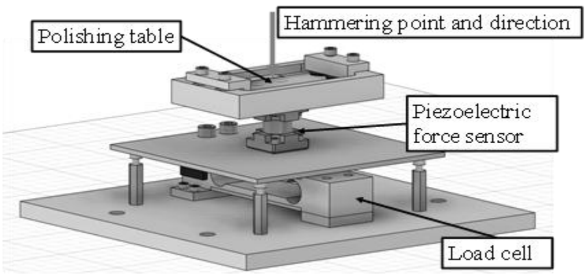
Figure 5. Drifting comparison.

From Fig. 5, the DC drift, which is related to the stability of the measurement over a long period of time, was smaller for the strain gauge load cell than for the piezoelectric type force sensor. This implies that the strain gauge load cell is more suitable for long-term stable force measurement.

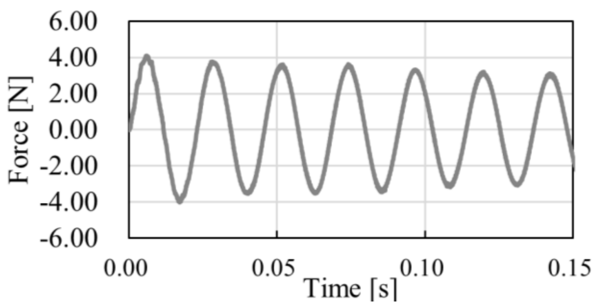
However, the output noise of the piezoelectric force sensor was smaller than that of the strain gauge load cell. The load cell generated an output noise of approximately ±0.2 V, almost 10 times higher than that generated by the piezoelectric force sensor, which was ±0.02 V. This demonstrates the necessity of signal processing for strain gauge load cells.

B. *Transfer Function and Developed System*

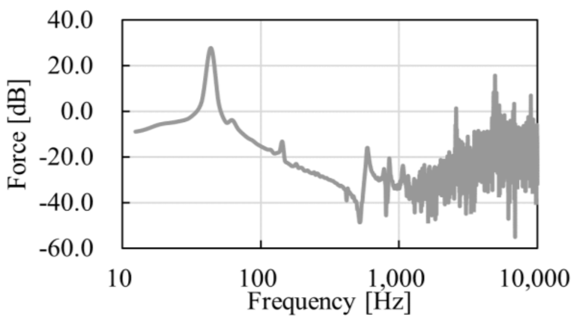
The transfer function of a second-order delay system was assumed to be the transfer function of the measurement system used in this experiment and was obtained through a hammering test. Consequently, the gain of the PID control was also obtained. Fig. 6 shows the striking point of the hammering test to estimate the relationship between input force and measured one and the time and frequency responses of the load cell recorded at that point.



(a) Hammering point



(b) Time response



(c) Frequency response

Figure 6. Hammering test for developed sensor system

The transfer function of the second-order delay system is given as: (2)

$$G(s) = \frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}. \quad (2)$$

Where ω_n is the natural angular frequency and ζ is the damping ratio. The natural angular frequency was set to 275 rad/s, obtained from the peak frequency response of 43.8 Hz from Fig. 6(c). Next, the damping ratio was calculated. The logarithmic damping ratio, δ, is expressed as:

$$\delta = \ln\left(\frac{a_n}{a_{n+1}}\right). \quad (3)$$

Where a_n is the nth amplitude. The damping ratio, ζ, is given by:

$$\zeta = \frac{\delta}{2\pi}. \quad (4)$$

Using Equation (3) and (4), the damping ratio of the load cell was determined to be 0.04.

The transfer function of the voice coil motor is given as follows:

$$G_0(s) = \frac{0.53}{0.004s+1}. \quad (5)$$

A strain gauge load cell with a low DC drift and a piezoelectric force sensor with high temporal resolution were combined to maintain the polishing force for several hours and to detect high-frequency vibrations of several hundred hertz. The voice coil motor, used to control the polishing force, was regulated by the PID control using the outputs of the strain gauge load cell and piezoelectric force sensor. Fig. 7 shows a block diagram of the developed control system with both a strain gauge load cell to control DC static pressing force and a piezoelectric force sensor to control AC dynamic chatter force.

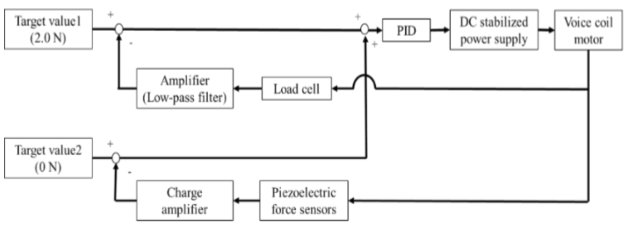
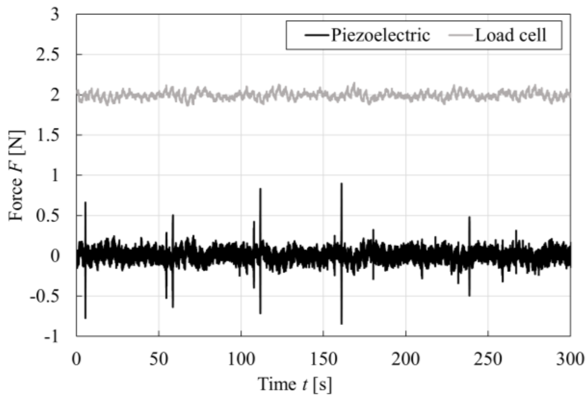


Figure 7. PID block diagram with both a strain gauge load cell and a piezoelectric force sensor.

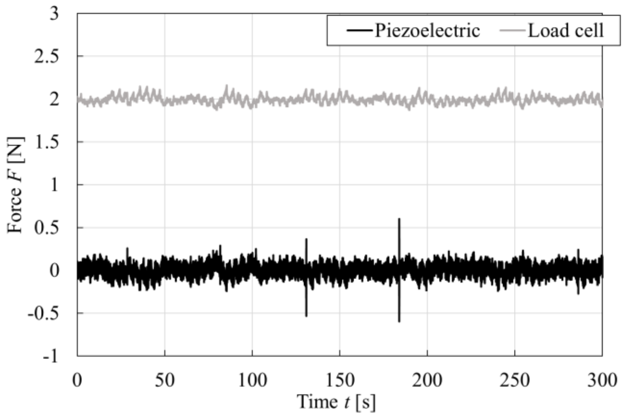
The polishing force was regulated by the PID control for each target value, such that the sum of the target values of the load cell output and the piezoelectric sensor output were 2.0 N and 0 N, respectively. To reduce the effect of DC drift on the piezoelectric sensor output and to estimate AC dynamic component due to stick-slip vibration, the charge amplifier was re-zeroed every five seconds by receiving an external signal from the digital signal processing system. That is, the targe value 2 is set 0N in a piezoelectric force sensor feedback loop, as shown in Fig. 7. The low-pass filter of the load cell was a 10 Hz, analog, low-pass filter with the Butterworth characteristics of a dynamic strain amplifier. The proportional, integral, and derivative gains of the PID control were obtained from the transfer function of the voice coil motor and the measurement system described above using the automatic PID gain adjustment tool in MATLAB/Simulink. The values obtained were: Kp = 2.1, Ki = 69, and Kd = 0.006.

C. Long-time Polishing

A polishing experiment was conducted using PID control, and the measurement force and surface roughness were recorded. Fig. 8(a) and (b) depict the outputs of the force sensors in the first five minutes and last five minutes, respectively, of a three-hour polishing experiment with PID control.



(a) Start



(b) Finish

Figure 8. Measurement force.

From the output of the load cells, shown in Fig. 8(a) and (b), it is evident that the target polishing force of 2.0 N (pressing pressure 0.2 MPa) was maintained for five minutes after the start of polishing and for five minutes before the end of polishing. In contrast, for the piezoelectric force sensor, there were some points of time at which the force changed significantly. This vibration was considered to be a chattering vibration caused by a stick-slip. The frequency of this chattering vibration was relatively high immediately after the start of polishing and immediately before the end of polishing; if a vibration with an amplitude of 0.4 N or higher were considered as the chattering vibration, then it is evident from Fig. 8 that the chattering vibration occurred seven times immediately after the start of polishing and two times immediately before the end of polishing. Additionally, the maximum value of the chattering vibration was greater immediately after the start of polishing than that of the chattering vibration immediately before the end of polishing. This indicates that the chattering vibration due to stick-slip is more likely to occur immediately after the start of polishing than before the end of polishing in a three-hour glass polishing process, and the magnitude of the vibration would be greater immediately after the start of polishing than the magnitude immediately before the end because of the poor surface roughness initially.

The surface roughness was measured with and without PID control during the polishing experiment. Fig. 9 shows the average surface roughness measured at nine points for each time interval.

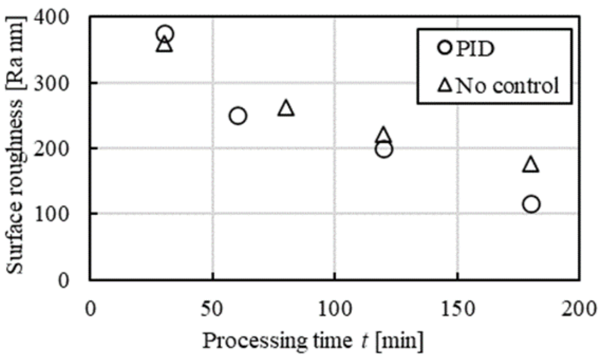


Figure 9. Measurement force

It is evident from the figure that the surface roughness was better without PID control than with PID control during the initial 30 minutes of polishing; thereafter, the surface roughness was better with PID control than without it. This might be because there were no significant long-term effects of force maintenance on surface roughness during the initial stage of polishing; however, the effects became apparent after polishing for more than one hour.

V. Conclusion

In this study, a system that could polish at a constant pressure for a long period of time was realized using both a strain gauge load cell and a piezoelectric force sensor with a five-bar planar parallel mechanism robot. The system utilized the low DC drift of the strain gauge load cell for keeping a static polishing force and the high time resolution of the piezoelectric force sensor for prevent the stick-slip vibration. The effectiveness of the system was confirmed in a polishing experiment using a voice coil motor for the force feedback and PID control of the output of the strain gauge load cell. As a result, we successfully maintained the polishing force during a 180-minute polishing test. Although we were able to measure the high-frequency vibrations, we were unable to suppress them. Thus, our future research may be targeted at discovering ways to reduce the vibrations during polishing to achieve a better surface finish.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Taichi Yamamoto conducted the research, analyzed the data and wrote the paper; all authors had approved the final version.

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