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REGULAR PAPER

Vibration-Damped Tool Holders in Industrial Robotic Machining Systems

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Abstract
Since the introduction of automation systems has begun to be applied to most industries with the development of technology, the utilization of industrial robots is increasing every year. However, the processing field a such as milling and Rough Cutting processing process occurs vibration from large processing load. Since industrial robots basically have low stiffness, they are vulnerable to vibration generated from processing loads when processing. In this paper, multi-axis active spindle holder of high stiffness was developed to improve precision and quality deterioration due to vibration generated from a processing load. If an active spindle holder of high stiffness is applied, it can increase the dynamic stiffness of the robot by blocking vibrations in the low-frequency range at the end effector before they are transmitted from the spindle to the robot, and as a result, it is expected to improve precision and quality. The performance evaluation of the active spindle holder manufactured based on the design was proceeded, and it was verified that the active spindle holder developed to compensate for the shortcomings of industrial robots was made with moving range and high stiffness of 200 Hz more. Furthermore, machining experiments confirmed an improvement in quality of more than 10%.

Keywords Vibration-damped tool holder · Flexure · Piezo actuator · Robot machining

1 Introduction

Multi-axis industrial robots are designed for use in manufacturing and industrial environments and are used in a variety of manufacturing and industrial applications that require precision, speed and repeatability. Multi-axis industrial robots are widely used in the fields of handling field for transporting raw materials or workpieces, assembly field for inserting and assembling parts, welding field for arc welding and spot welding, painting field for painting and coating parts, inspection field for dimension measurement and parts defect analysis used. Overall, multi-axis industrial robots are used for repetitive or high-risk tasks. However, there are problems to be solved in order to use it effectively and safely in an industrial environment. First, multi-axis industrial robots must be able to work with high accuracy and repeatability, so each joint must be precisely controlled and calibrated for each posture [1–4]. Second, because multi-axis industrial robots have more moving parts than single-axis robots, the risk of mechanical failure is higher. Mechanical failures can be particularly problematic in harsh or demanding industrial environments. Overall, while multi-axis industrial robots offer many benefits, they also require careful planning, design, and operation to ensure that they perform optimally and safely in industrial settings. Today, the use of industrial robots is increasing to introduce automation systems in various industries. Currently, the stiffness of robots is higher than in the past, but it is not enough to apply them to milling machining, which requires a lot of processing load, so many studies are conducted to reinforce the stiffness of robots [5–10]. In this research, an active spindle holder was developed to reduce vibration by increasing dynamic stiffness during processing, regardless of the external environment and robot poses during milling processing. For the development of active spindle holders,

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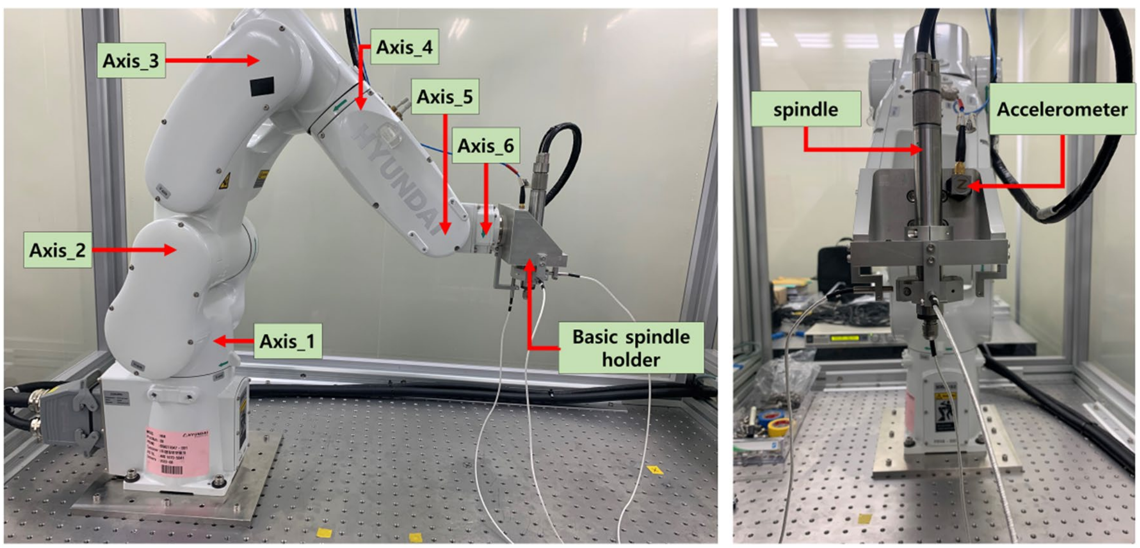
optimal design was verified through modeling verification with mathematical modeling and simulation modeling, and product manufacturing and performance evaluation will be described based on this.

2 Industrial Robot Processing System

2.1 Natural Frequency of Industrial Robot

According to existing research cases, since multi-axis industrial robots have low stiffness, there are problems in that resonance due to vibration generated from processing loads is easily generated. In this study, a small industrial robot from Hyundai Robotics was utilized, and the stiffness of a multi-axis industrial robot system equipped with a basic spindle holder was confirmed for the development of an active spindle holder. To confirm the stiffness of the system, an impact test was conducted using the impact hammer and trial axis accelerometer of PCB PIEZOTRONICS. Figure 1 (a) shows an industrial robot equipped with a basic spindle holder, and (b) is a list of measurement equipment consisting of impact hammer, measurement and control equipment, and accelerometer for impact test. As a result of the impact test measurement, it was confirmed that all the x, y, and z axes had low stiffness. As shown in Fig. 2, the stiffness of the current robot system confirmed the natural frequencies of 18 Hz, 31 Hz, and 51 Hz in the low range. The mode shapes of an industrial robot, according to its natural vibration frequencies, are observed in



(a)

(b)

Fig. 1 Multi-axis industrial robot system **a** industrial robot system assembled basic spindle holder **b** units for measurement impact test

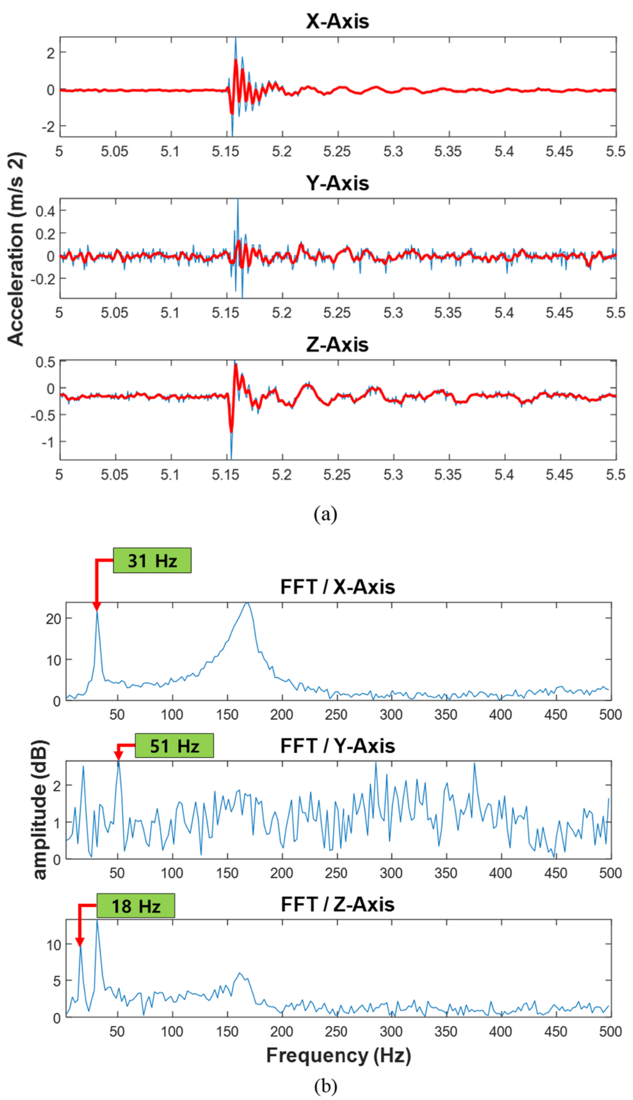


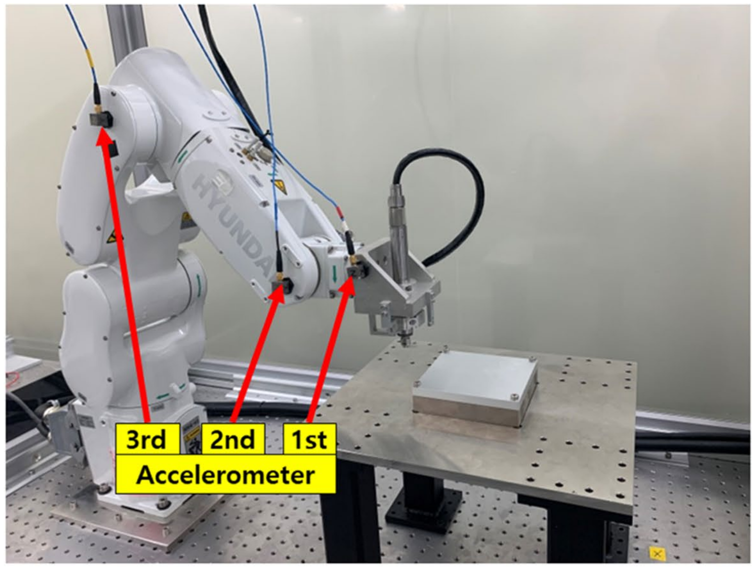
Fig. 2 Impact test measurement **a** impact test **b** impact Test FFT result

the ZXY. The first mode occurs at 18 Hz, and the mode shape is in the z-direction with Axis 2 as the reference. The second mode occurs at 31 Hz, and the mode shape is in the x-direction with Axis 2 as the reference. The third mode occurs at 51 Hz, and the mode shape is in the y-direction with Axis 3 as the reference.

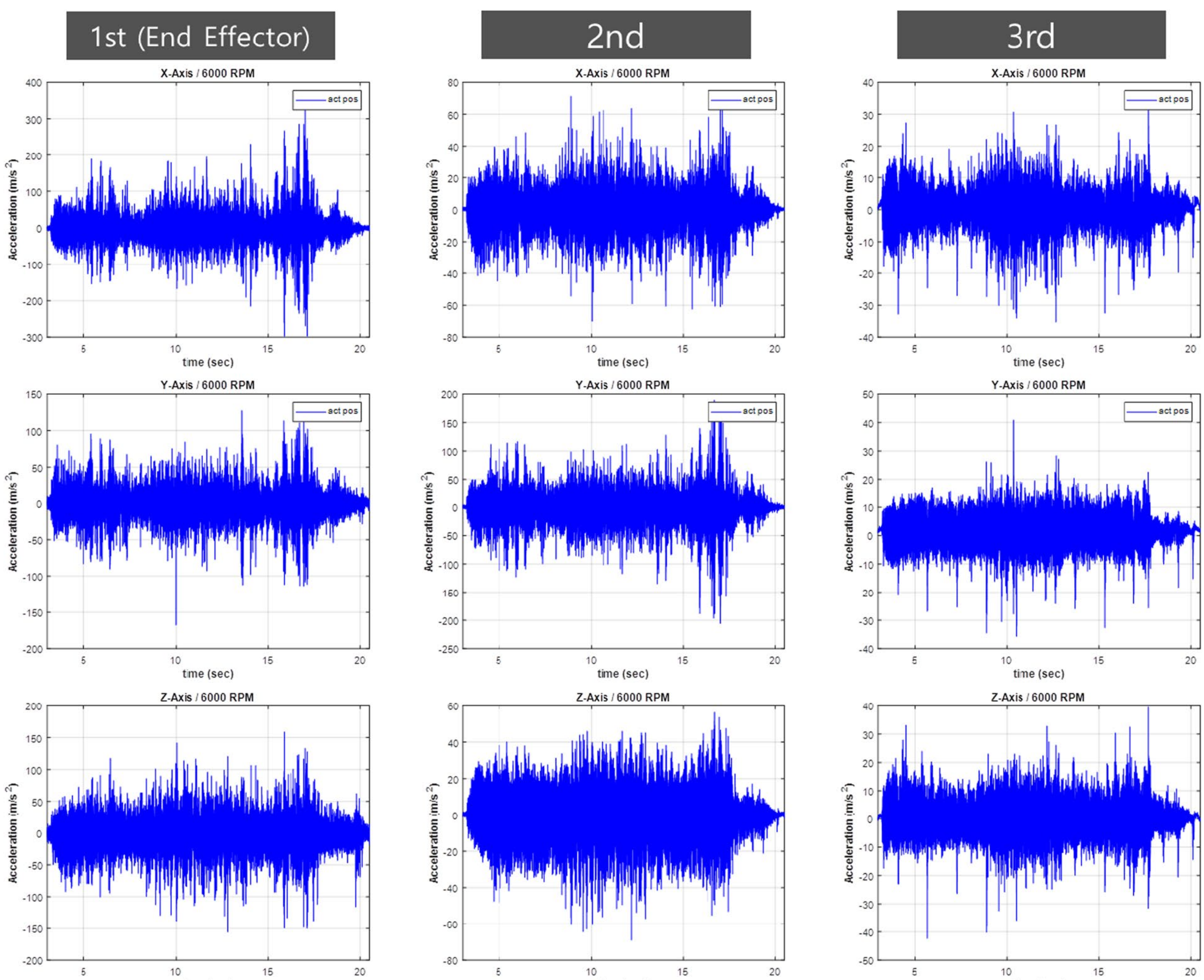
It was confirmed that the stiffness of the current robot system was low, and based on this, it was decided to develop a high-stiffness active spindle holder to increase the dynamic stiffness of the robot by removing frequency in the low range.

2.2 Fundamental Experiment of Basic Holder

Performance tests of basic spindle holder were conducted for the design of the active spindle holder. The performance test was conducted with the basic spindle holder installed, and a total of three acceleration sensors were attached for performance evaluation. The first acceleration sensor was attached to the basic spindle holder, and two acceleration sensors were attached to each link part as a weak point of the multi-axis industrial robot. Before the experiment, we conducted experiments for each condition according to the experimental design method to select the worst case of this system. The experimental conditions were selected as Feed rate, Depth of Cut, and spindle speed. Among them, the Feed rate was selected as 1 mm/s, 0.5 mm/s, and 0.1 mm/s for 3 conditions, and the Depth of cut was selected as a total of 6 conditions from 1 to 0.5 mm per 0.1 mm. According to these conditions, we conducted machining experiments for each spindle speed, and selected the possible machining conditions and the worst case. The selected conditions were Depth of cut 0.5 mm, feed rate 1 mm/s, and spindle speed 6000 rpm, which was selected as the worst case where the largest vibration occurs among the possible machining conditions. Experimental conditions were the cutting depth and feed rate were fixed at 0.5 mm and 1 mm/s, and the machining experiments were conducted with spindle rotation speeds of 6000 rpm as shown in Fig. 3, it was confirmed that a large vibration was transmitted to the robot due to the machining load. Did As a result of the experiment with the standard spindle holder installed, it was confirmed that the processing quality deterioration problem occurred seriously as shown in Fig. 4. As shown in Fig. 2, the system's low stiffness is vulnerable to vibrations that occur during processing. This can be confirmed by the large vibrations that occur during the machining experiment of the system with the basic spindle holder applied, as shown in Fig. 3. The quality degradation and precision degradation problems that occur as a result can be seen in the machining experiment results, as shown in Fig. 4. It was confirmed that the low stiffness of the system with the basic spindle holder installed causes serious machining quality degradation problems. To solve these problems, it is necessary to mount a high- stiffness holder on the spindle mounted on the end effect of the industrial robot so that resonance does not occur at the low natural frequency of the industrial robot, and to block the low-frequency vibrations that occur from the machining load.



(a)



(b)

Fig. 3 Fundamental experiment measurement result of basic holder **a** accelerometer position for measurement, **b** 6000 rpm measurement data

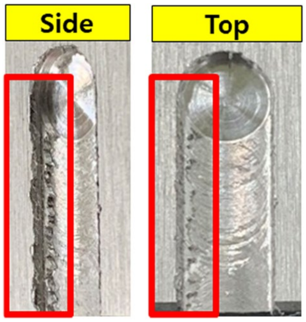


Fig. 4 Fundamental experiment processing result of basic holder

3 Modeling

Multi-axis industrial robots have their own repetitive precision according to size and type, and the repetitive precision shown in each robot's specification is the repetitive precision for simple robot movements. Depending on the field and method of use of industrial robots, the repetition accuracy defined in the specification is bound to be greater than the existing value [11–13]. Active spindle holders can reduce the precision of the machining system using multi-axis industrial robots. In addition, a high stiffness piezo actuator was applied as the driving system of the active spindle holder, and in order to meet the payload of the industrial robot, the reverse bridge type was applied to all axial directions as shown in Fig. 5a. The configuration of the active spindle holder designed as in the corresponding conceptual design is as shown in Fig. 5b. The performance goal of the active spindle holder for this purpose is configured with 3 degrees of freedom to increase machining precision as shown in Table 1, and it is set to have a driving range larger than the repeatability precision of ± 20 um of the industrial robot. Also, the stiffness of the active spindle holder is set to high stiffness of 200 Hz or more to block low-frequency vibrations.

The configuration of the active spindle holder is largely divided into XY-Stage and Z-Stage for driving to three axes. One amplification mechanism was designed in a Parallel structure on the X-axis and Y-axis, and two amplification mechanisms were mounted on both sides of the XY-Stage to implement motion in the Z-direction. Due to the nature of the Parallel structure, a guide was additionally designed to the amplification mechanism to prevent motion in the parasitic direction when driven in each axial direction of the XY-Stage.

4 FEM Simulation

As shown in Fig. 6, FEM Simulation was confirmed for modeling designed using Ansys workbench, and results meeting the design goals were confirmed. Table 2 shows the results of static and dynamic characteristics through FEM Simulation.

5 Active Spindle Holder

The active spindle holder manufactured with modeling is largely divided into two parts. It consists of an active spindle holder that combines xy-stage and z-stage for each axial motion, along with a holder cover for mounting each sensor jig and the robot's end effector. The manufactured active spindle holder is shown in Fig. 7. The total size of the active spindle holder is 190 × 205 × 64 mm, and the material is made of aluminum 6061-T5. A piezo actuator is installed for each stage, and one actuator is installed for x-axis and y-axis motion. For z-axis motion, a total of two actuators are installed, one each in both directions of the xy-stage. Components of Active spindle holder show in Table 3

The Fig. 8 shows the control algorithm for evaluating the performance of the active spindle holder. A PID control system based on a feedback position control system was constructed to compare input signals and output signals and compensate for errors. The input/output signal for controlling the active spindle holder is driven to correct the position of the X, Y, and Z axes by applying a voltage from the controller and voltage amplifier to the actuator from the measurements output from the capacitive sensors.

6 Performance Evaluation of Active Spindle Holder

The system configuration for evaluating the performance of the active spindle holder is as shown in Fig. 9. Capacitive sensors were used for feedback control of the active spindle holder. Six capacitive sensors and drivers were applied to measure in each axial direction. The controller for measurement and control from each sensor was composed of dSPACE's Micro LabBox. PI's P.844 series Piezo Actuator was applied as a driver for performance

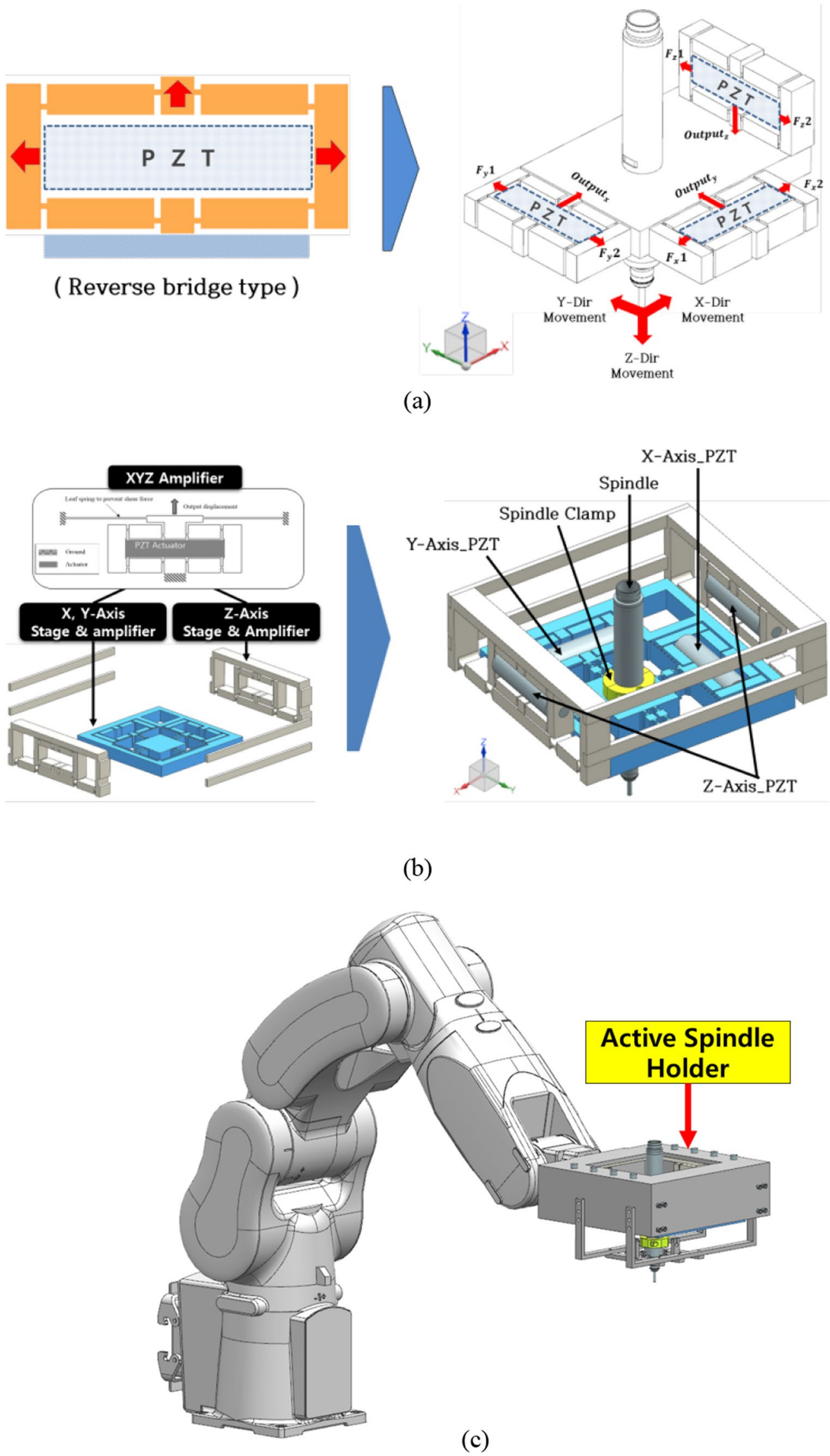


Fig. 5 Active spindle holder **a** conceptual design **b** Active Spindle Holder 3D Modeling **c** Assembly View

Table 1 Design target to develop active spindle holder

Design target	
DOF	3DOF
Moving range	> 20 μm(X, Y, Z)
Natural frequency	> 200 Hz

Table 2 Active spindle holder FEM simulation result value

Design target	
Moving range	
X-axis	104.4 μm
Y-axis	105.2 μm
Z-axis	46.7 μm
Mode 1	255.94 Hz
Mode 2	260.98 Hz
Mode 3	284.24 Hz

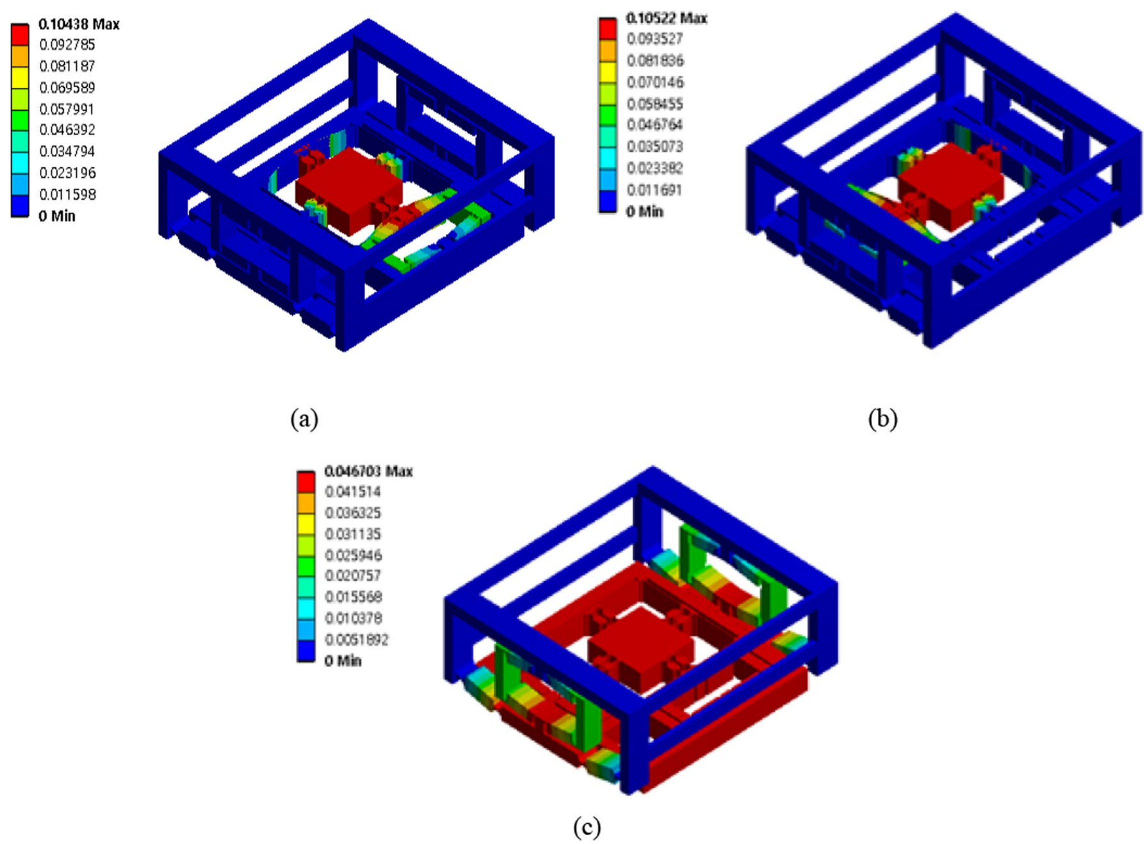


Fig. 6 Active spindle Holder FEM simulation result **a** y-axis motion **b** x-axis motion **c** z-axis motion

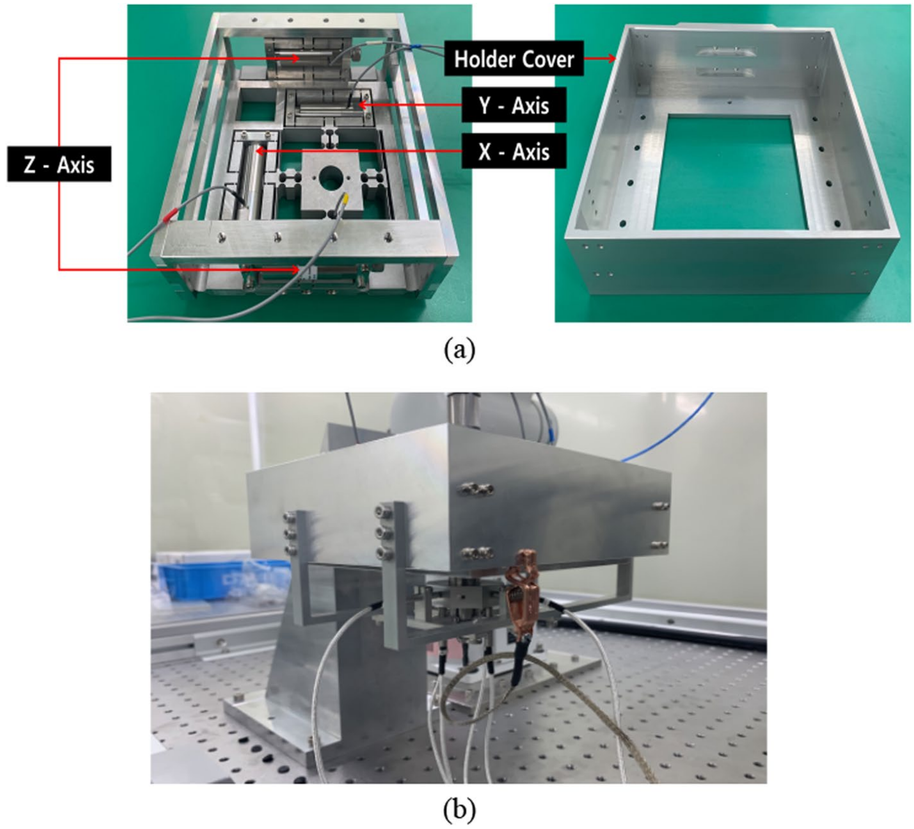


Fig. 7 Active spindle holder **a** explode view **b** assembly view

Table 3 Components of active spindle holder

Parts	Company	Reference
Spindle	Nakanishi	1000–60,000 rpm
Piezo actuator	PI	p.844.20
Capacitive sensor	Lion	6 axis

evaluation. The piezo amplifier of the E-500 and E-505 series as low voltage controller of − 30 to 130 V was configured as a dedicated amplifier for LVPZT to drive by applying voltage to four actuators.

The performance evaluation of the active spindle holder have evaluated for Moving range, In-Position, Resolution, and Setting Time. The performance evaluation for Moving range, which was the design goal, was shown in Fig. 10. It was confirmed that it has a driving range of 100 μm in the XY direction and 45 μm in the Z direction and is satisfied with the target performance. The positional stability of the system is as shown in Fig. 11, and the positional stability of a minimum of 23.3 μm and a maximum of 28.8 μm was confirmed. The resolution of the active spindle holder is from a minimum of 25.4 μm to a maximum of 27.3 μm, as shown in Fig. 12. The setting time of the system was set based on 20 μm, which is the repetition precision of the industrial robot, as shown in Fig. 13, and the measurement to the reference position confirmed that the X-axis has 103 ms, the Y-axis 108 ms, and the Z-axis 199 ms. All measurement results were expressed as 3sigma standard deviation values.

An impact test was conducted to verify the system stiffness of the active spindle holder designed and manufactured with high stiffness as the goal, and the FFT results are as shown in Table 4. Figure 14a conducted an impact test after mounting on a fix JIG, and it was confirmed from the measurement results that there were no frequency components in the low-frequency region, and it was confirmed that it satisfies the target performance of 200 Hz or more. Next, after mounting on an industrial robot and conducting an impact test, it was confirmed that the low-frequency region that was targeted is blocked differently from when the basic spindle holder was mounted. In addition, to evaluate the performance of the active spindle holder, the machining performance of the active spindle holder and the basic spindle holder was compared and evaluated, and it was possible to obtain a quality improved by more than 10% as shown in Table 4.

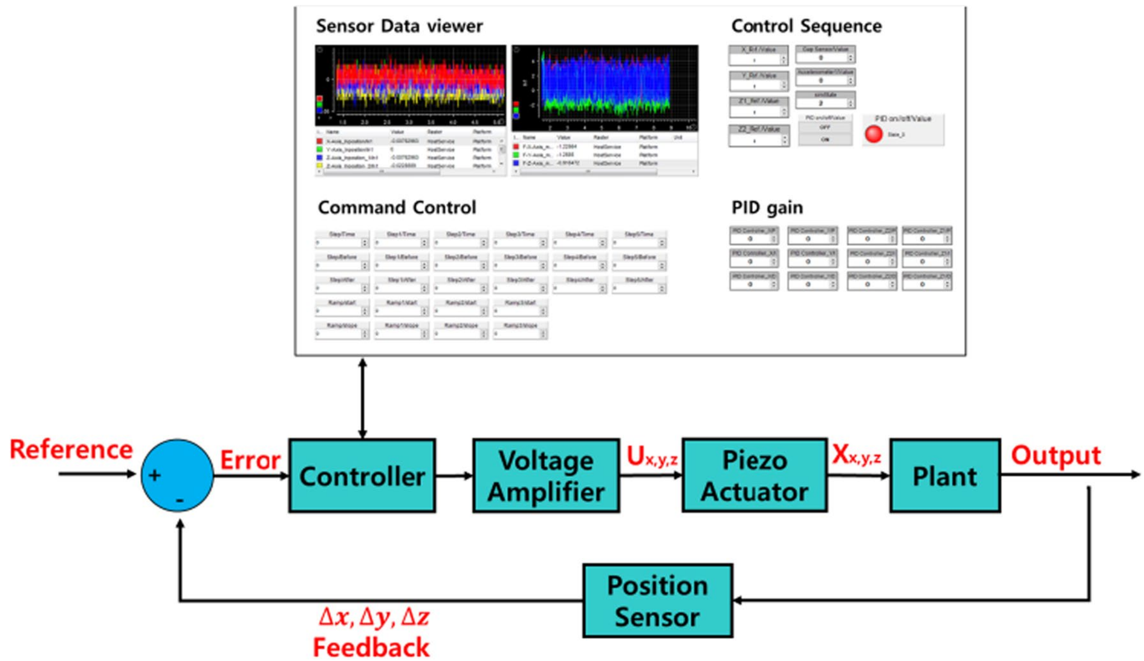


Fig. 8 Feedback control system composition for control active spindle holder

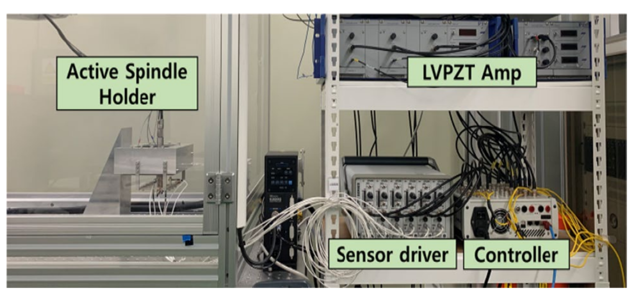


Fig. 9 System configuration of active spindle holder for performance evaluation

Fig. 10 Moving range performance evaluation **a** X-axis **b** Y-axis **c** Z-axis

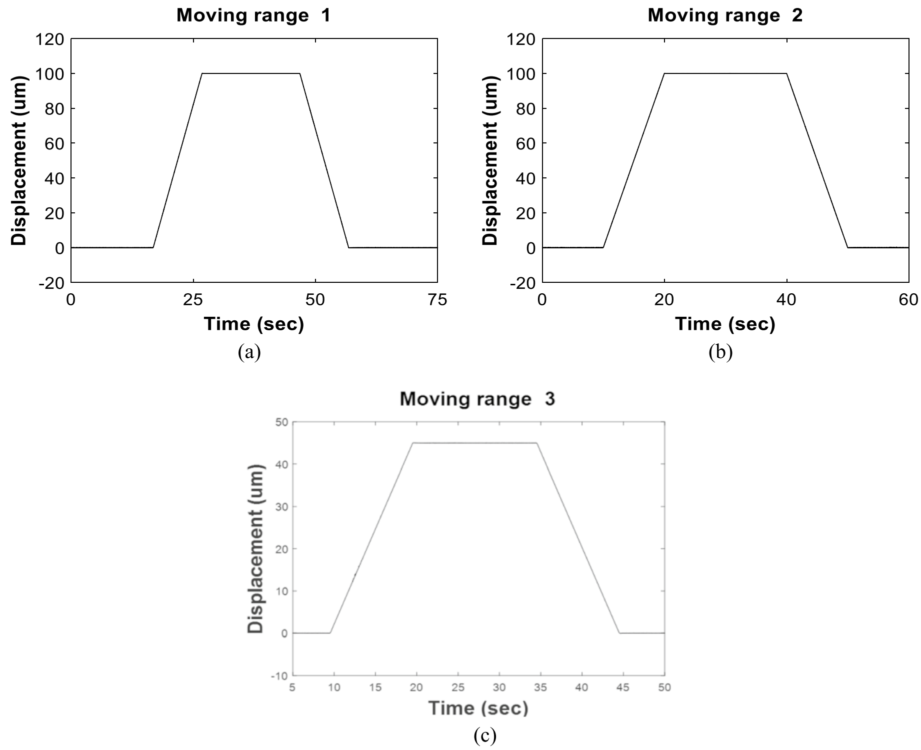
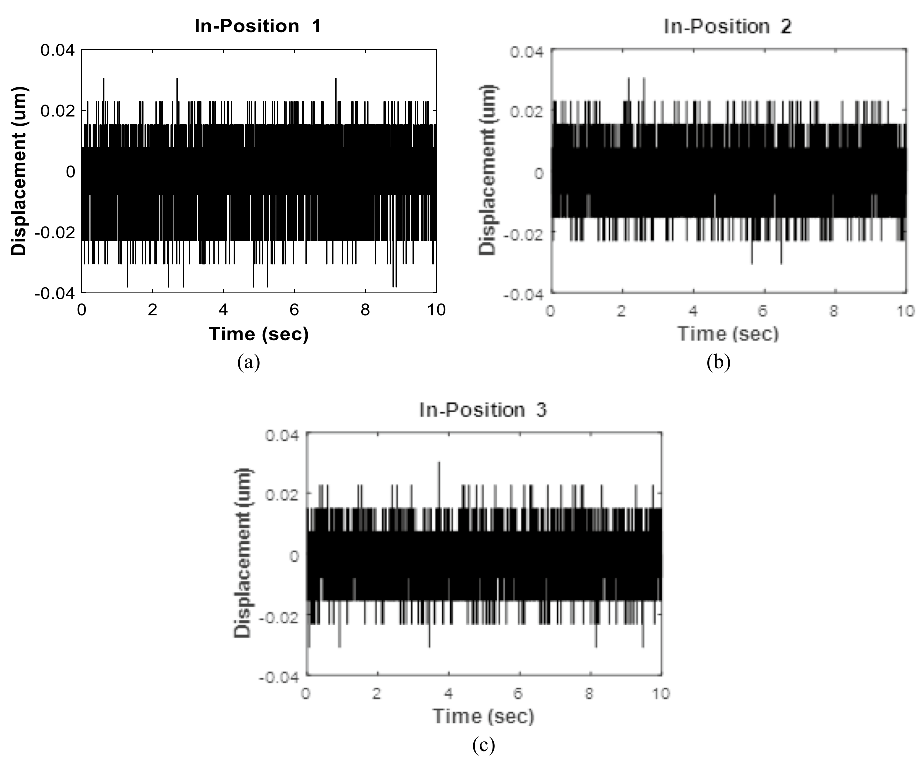


Fig. 11 In-position performance evaluation **a** X-axis **b** Y-axis **c** Z-axis



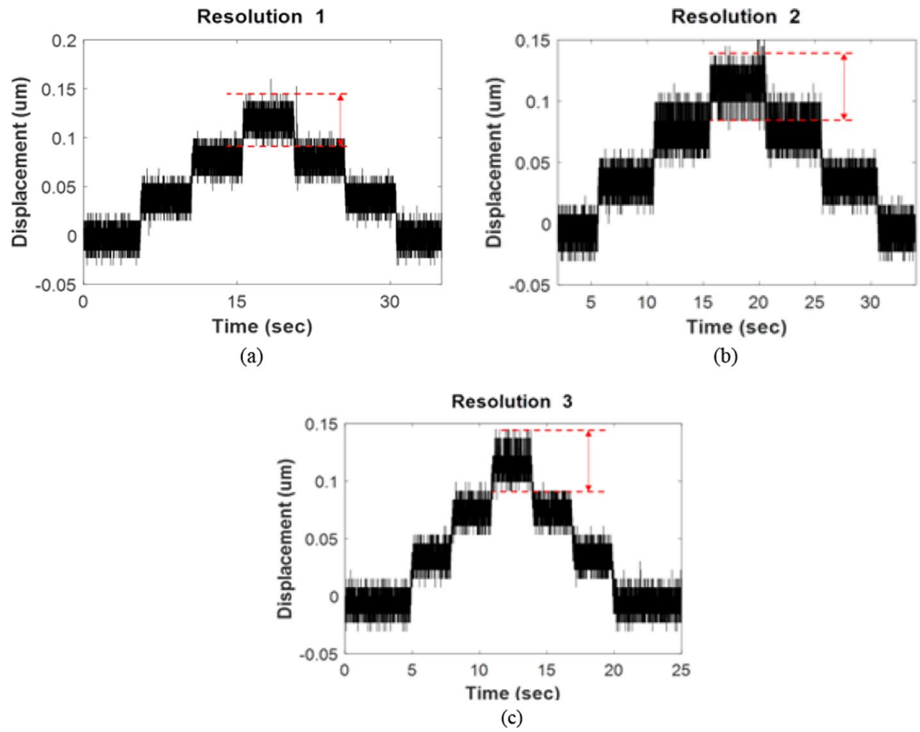


Fig. 12 Resolution performance evaluation **a** X-axis **b** Y-axis **c** Z-axis

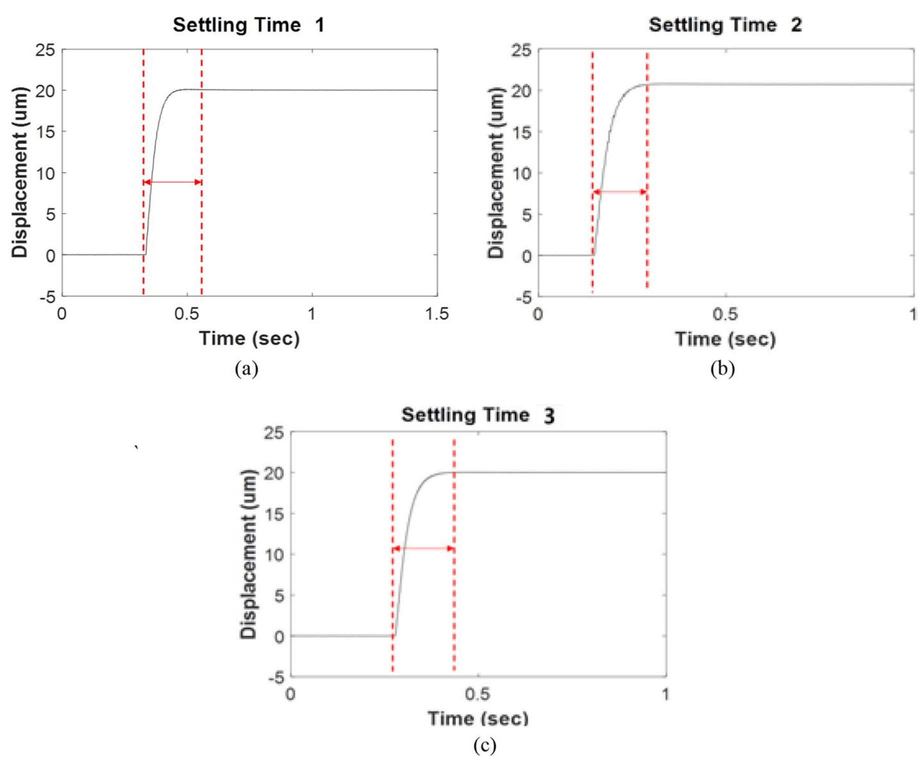
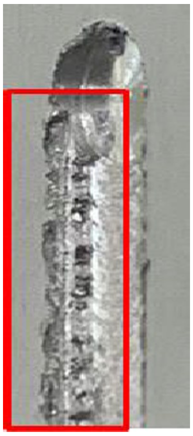
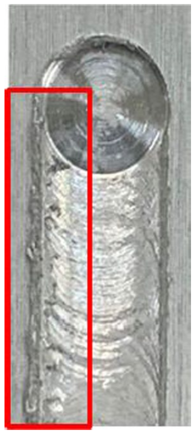
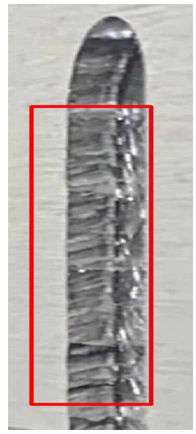


Fig. 13 Settling time performance evaluation **a** X-axis **b** Y-axis **c** Z-axis

Table 4 Machining performance comparison evaluation

Basic spindle holder		Active spindle holder	
Side	Front	Side	Front
			
–	Ra: 2.54 µm	–	Ra: 2.08 µm
Quality deterioration		Quality improvement: 18%	

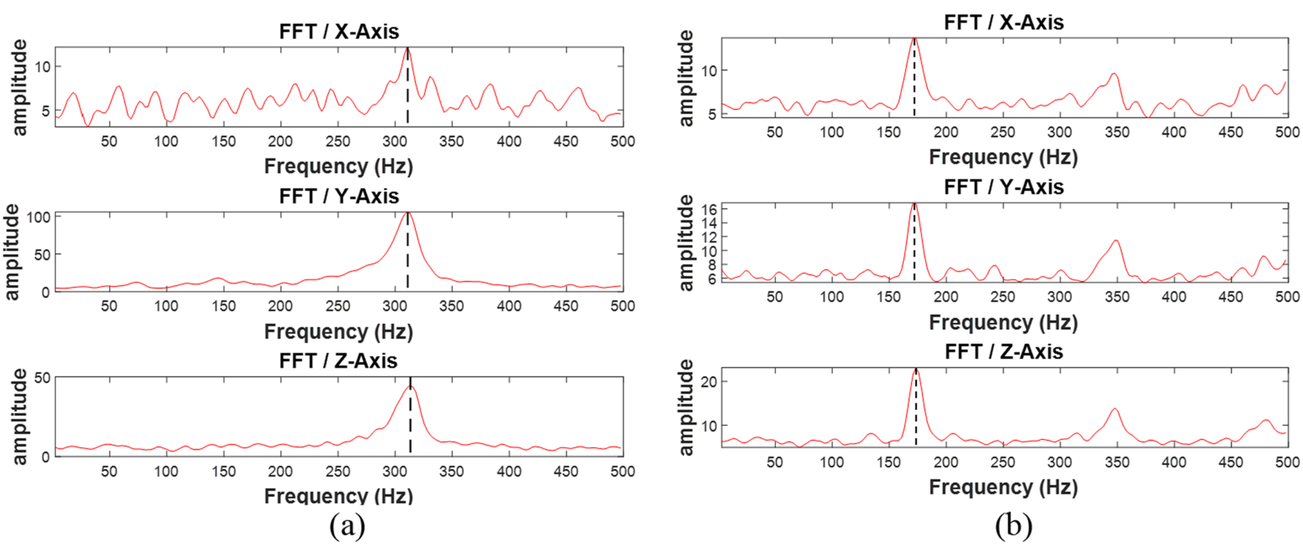


Fig. 14 Impact test FFT result **a** active spindle holder mounted on the JIG **b** active spindle holder mounted on industrial robot

7 Conclusion

In this paper, an active spindle holder for vibration reduction of a multi-axis industrial robot processing system was proposed. The active spindle holder built based on modeling can implement 3 freedom of motion using a flexible mechanism with piezo actuator and amplification mechanism, and the performance evaluation of active spindle holder with PID control through feedback control system confirmed that it meets the design goal. In addition, the weight of the basic spindle holder is 1 kg, and the weight of the active spindle holder is 2.3 kg. Although there is a weight difference of more than 1 kg, it has been confirmed that it does not affect the dynamic performance at weights less than 4 kg, which is the payload of the industrial robot. In the future, we plan to verify the machining performance and vibration reduction performance of the industrial robot according to more conditions and machining methods of the high stiffness active spindle holder with the feedback control system applied.

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