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Design of Piezo-Flexure stage for machining error compensation

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Abstract
Recently, there is an increasing demand for a machining technology capable of improving productivity in a machining industry that requires large-sized products such as aircraft and automobiles. In particular, robot-based machining technology has been studied in the field of cutting-edge materials machining and aviation parts because of its flexibility and high space efficiency compared to conventional machining equipment. However, the machining equipment using robots is vulnerable to vibrations generated during machining due to the low rigidity of the robot and has a large machining error compared to conventional machining equipment. As the machining error degrades the machining quality and degrades the durability of the machine, there is a need for a technology that can improve the machining error. In this study, we propose a flexure stage with piezo actuator to compensate for the low rigidity of the robot. Piezo-flexure stage is a high rigidity and high precision stage that can actuate spindles. It is a system for compensating for machining errors in robot machining.

Keywords: Machining error, Piezo actuator, Flexure guide, Precision stage

1. Introduction

Precision stages consist of piezo actuators and flexure mechanisms are widely used in industrial fields [1-3]. Piezo actuators and flexure-guided mechanisms that produce specified motions are widely utilized in precision-positioning stages. A piezoelectric actuator is capable of generating large forces and is characterized by fast response, no wear, and sub-nano resolution. A flexure mechanism has the particular advantages of no friction, no backlash, and good repeatability for guide mechanism.

In this research, a piezo-flexure stage is proposed with sufficient natural frequency and moving ranges for compensating machining errors. The stage is designed with piezo actuators and flexure-guided mechanisms. The optimal design is conducted using analytical modeling of the flexure guide for optimization of the design variables. The stage performance is evaluated using testbed. Moving range tests are also described in this research.

2. System Configuration

The stage proposed in this research is a high stiffness stage that moves the spindle to compensate for machining errors in robot machining. The stage consists of piezo actuators that can exert a large force to withstand the machining load during machining, and flexure guides to move the spindle in the desired direction. The basic structure of the stage according to the conceptual design is as follows in Figure 1.

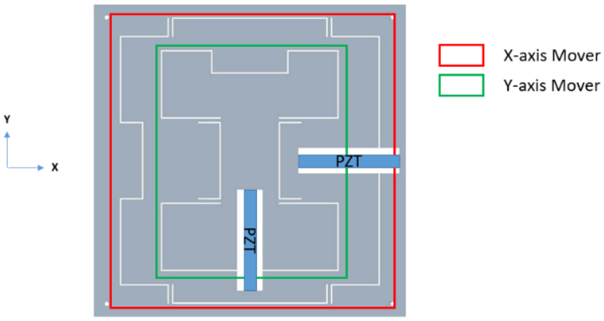

Figure 1. System configuration

The stage is a two-axis (XY) stage which one actuator actuates the X axis and the other actuator actuates the Y axis. The stage is serial type which the Y-axis moving body is located inside the X-axis moving body. The structure of the stage is symmetric for the convenience of control and rigidity of thermal deformation. The entire system is a stage capable of actuating a spindle and is sized at 480x480x40 mm^3.

3. Optimal design of Stage

Optimal design is needed to satisfy the desired moving range and natural frequency. Accurate modeling of the stage must be the basis for optimal design for the desired purpose.

3.1. Modelling of Stage

Stage modeling can be obtained based on the equations of motion of the flexure mechanism. The kinetic and potential energy of the flexure mechanism can be calculated and applied by Lagrange's equation. For optimal design, the number of movable bodies, the mass and moment of inertia of the rigid bodies, the mechanical properties of the flexure mechanism, and the connection information between the rigid bodies and the flexure mechanisms are required.

Modeling is conducted based on conceptual design of stage. The modeling of the stage can be performed through the equations of motion of the leaf spring mechanism. Looking at the stage in the previous figure, two moving bodies (X-axis, Y-axis) and eight leaf springs are connected to each other. Based on the leaf spring modeling, the stiffness of the whole stage is calculated using the axis transformation matrix and the stiffness of whole stage is 6x6 matrix. The whole stage can be assumed to be one elastic body and can be represented by applying Hook's law. Based on this equation, the moving range and natural frequency of the system can be calculated.

3.2. Optimal design result

Optimal design is based on objective function and constraints function using design variables. Figure 2 shows the design variables for optimal design of the stage. The design variables consist of the thickness (t), the length (l) and the width (b) of the leaf spring, and each axis has design variables. The objective function of the optimal design is to set the natural frequency of the stage to the maximum within the constraints. In this research, the moving range is set to 15um or more and the structural frequency is 200Hz or more. In addition, the range for the design variables was specified considering the size of the stage. The optimal design results are selected from the design variable values that converge within the objective function and constraints and are shown in Table 1.

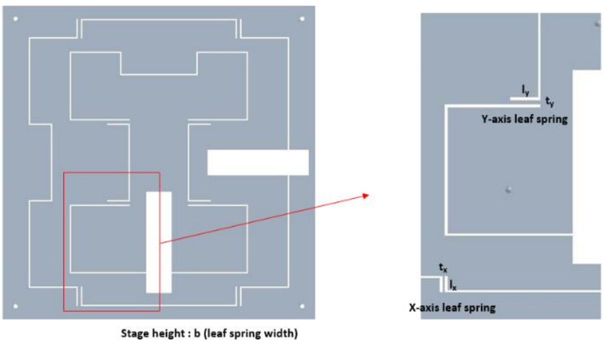

Figure 2. Design variables

Table 1 Optimal design results

Design variables (X-axis)	l_x=13mm, t_x=2.3mm
Design variables (Y-axis)	l_y=24mm, t_y=3.2mm, b=38mm

4. Experiment Results

The stage was manufactured based on the optimal design results. The testbed for performance evaluation was constructed and it is shown in Figure 3. Two piezo actuators for two-axis actuation are combined with fabricated stage and a preload was applied to the piezo actuators for continuous compression. Capacitive sensor for measuring the moving range was coupled to the stage using a sensor jig.

For stage performance evaluation, position control based on control algorithm is required. The position signals can be measured using two position sensors and the desired position information can be obtained through the sensor kinematics.

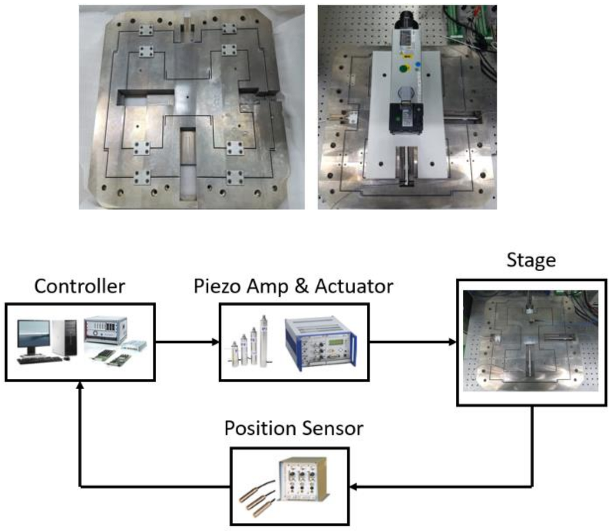

Figure 3. The stage and testbed for performance evaluation

When the error occurs compared to the desired position value (command), the feedback control algorithm is used. The moving range was checked on the x and y axes through position control. We confirmed that the x axis and the y axis follow the command well and are over 15um. (X axis 20um, Y axis 30um)

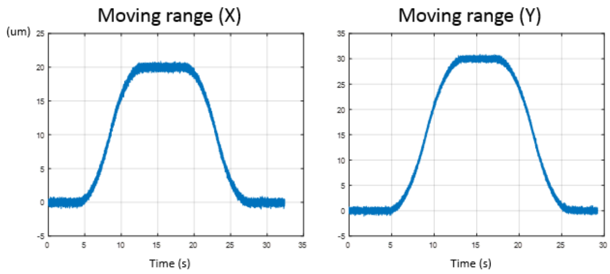

Figure 4. Moving range test

5. Conclusion

In this research, a piezo-flexure precision stage is proposed. The stage consists of a piezo actuator and a flexure guide mechanism. Piezo actuator can transport the spindle and exert a large force to withstand the processing load. Flexure guide is a frictionless, wear-free guide mechanism using elastic deformation of the elastomer. The stage is optimally designed according to the objective function and constraints. Based on the optimal design, the stage was manufactured. The testbed for performance evaluation was constructed and the proposed stage is verified with performance evaluation.

Acknowledgement

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