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EVALUATION OF CUTTING DEVICE WITH STROKE ENLARGEMNET MECHANISM

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Abstract – A new cutting device driven by an enlargement mechanism with a PZT drive has been developed to realize positioning the cutting tool from nm to mm. In this study, the mechanical principal of a newly developed enlargement mechanism consisting of fluid chamber, a PZT device, and cutting tool stage is reported. The basic performances of the developed mechanism are also evaluated. This developed device demonstrates that the magnitude of enlargement reaches 4 times of stroke than the original one of the PZT. The dynamic characteristics show DC to 50 Hz which is enough frequency response to realize the non-circle cutting. The non-circle profile is machined by the developed mechanism. The profile accuracy obtained settles in ±1.3μm by the repetitive control method.

Keywords: PZT Enlargement mechanism, Thrust force, Positioning accuracy

1. INTRODUCTION

The author has developed the cutting tool holder that enlarges the stroke of tool by using the resonant vibration. This holder enlarges 50 times of stroke than the one of PZT. However, the driving frequency is limited only in the resonant frequency of cutting tool holder.

On the other hand, some cutting devices with displacement enlargement mechanism by the elasticity hinge are not always enough rigid as a machining tool. The rigidity is the essential and needed for the machine tool. The application of the elasticity hinge has another serious problem. There exists the resonant vibration at each elasticity beam. The local resonant vibration often causes the chatter vibration during cutting.

We propose a new enlargement mechanism consisting of a fluid chamber, a PZT device, and cutting tool holder to break the stroke limitation caused by the one of PZT. In addition, the rigidity to overcome the conventional enlargement mechanisms is guaranteed.

As a typical application of the developed new device, we try to realize the non-circle cutting for machining of an internal-combustion piston. The profile of the piston is designed as the ellipse one and its error has to be less than 10μm. In this case, the high response of the cutting tool holder is strictly required for not only the surface quality but also the productivity.

In this study, the fundamental mechanical principle of the enlargement mechanism is described and the basic performances as a cutting tool holder are examined by the non-circle cutting.

2. PRINCIPLE OF DEVELOED MECHANISM

To realize the high frequency response and orbital accuracy, the simple mechanism is required. PZT as a drive device is efficient from technical perspective. A newly developed positioning system consists of two fluid chambers and a PZT device. The principle of the enlargement mechanism is so simple that the various capabilities as a positioning device and a cutting tool device are expected to come into practical use. The principal of our developed mechanism is shown as the cross-section drawing in Fig.1.

In Fig.1, the fluid chamber consists of two different cross sectional areas. The chamber is filled with machine oil. A PZT is connected to the wall of the fluid chamber by a hemisphere. The displacement of horizontal direction is almost in proportion to the ratio between the area A_1 of this wall and the area A_2 of bellows. The elongation ratio depends strongly on the designed cross sectional area of A_1. The additional elongation ratio would be obtained by filling the inner rod into the bellows.

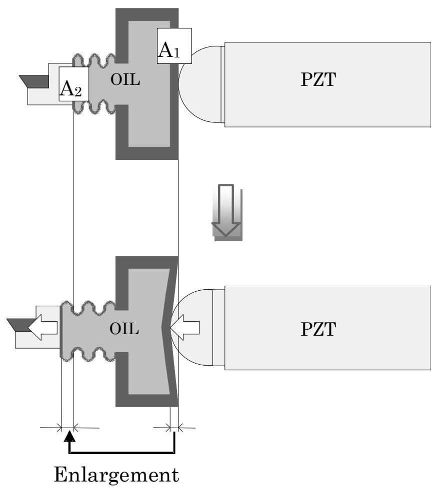

Fig.1. Principle of enlargement mechanism.

3. BASIC PERFORMANCE OF DEVELOPED MECHANISM

3.1 Mechanical layout of non-circle cutting tool holder

Figure 2 shows the schematic diagram of developed cutting tool holder. This cutting tool holder consists of a PZT, an enlargement mechanism, a tool tip, a linear guide, a linear position encoder and a laser displacement sensor. The rigidity of the cutting tool holder depends on the linear guide set between the tool holder and tool base. This linear guide supports the cutting tool to endure the cutting force in spite of reducing the frequency response.

3.2 Positioning system of non-circle cutting tool holder

The PI control is applied to position the tool holder by feeding the analogue current to the PZT drive amplifier as shown in Fig. 3. The feedback control is realized by detecting the position of the cutting tool with a linear position encoder that has the resolution of 1.22nm. The target value prepared previously in the PC is fed to the PZT drive amplifier by means of D/A converter. The PZT expands from the original length by this operation. In this case, the preload by the hemisphere contacted to the right side wall is adjusted previously as shown in Fig.2. When the displacement of PZT is enlarged, the enlargement mechanism positions the cutting tool to the desired position. The displacement of the PZT is measured by the laser displacement sensor and the position of the tool is measured by the linear position encoder simultaneously.

The positioning control is executed by the control program synchronizing with the spindle rotation of the NC lathe. The rotary encoder is attached to the spindle and the "A" phase signal is used for the synchronization between D/A converter for the cutting tool and spindle. The depth of cut is controlled according to the rotation of spindle. Therefore, non-circle cutting is realized.

3.3 Experimental setup

Figure 3 shows the schematic illustration of the control system including the cutting tool holder. The manipulate signal is fed from PC to the PZT drive amplifier. The displacement of the tool is fed back to the PC from the linear position coder. The manipulate signal is calculated by the PI control program in PC as shown in Fig.4. This cutting tool holder is able to realize the non-circle cutting

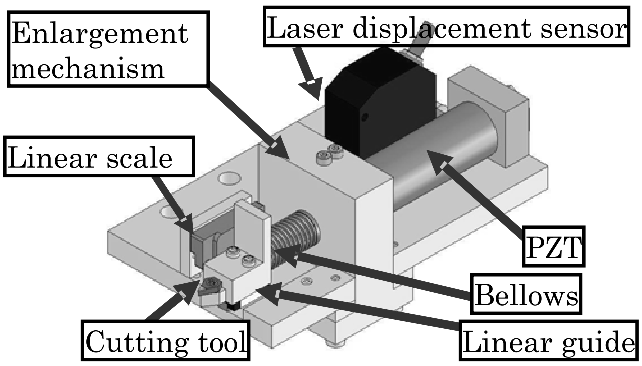

Fig.2. Developed cutting device.

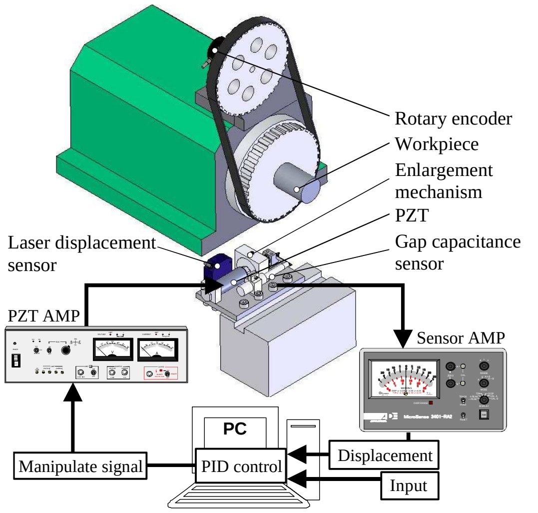

Fig.3. Schematic illustration of cutting holder system.

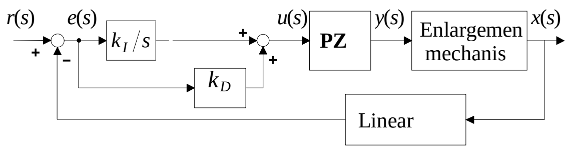

Fig.4. Block diagram of PI control.

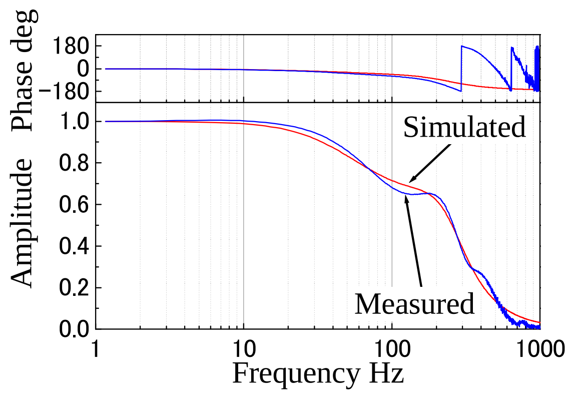

Fig.5. Frequency response analysis.

synchronized with the spindle rotation of NC lathe by the rotary encoder equipped on the spindle. The resolution of the rotary encoder is 360 pulses per revolution. The "A" phase is used for the synchronous with the developed device. The "Z" phase is used for the external start trigger.

3.4 Dynamic characteristics

Figure 5 shows the frequency response by the Bode diagram when the step input of 1μm is fed to the amplifier of PZT from D/A converter. The end effector motion of the cutting tool holder and the expansion of PZT are measured simultaneously.

The frequency response is calculated from both the input and the response. These are Fourier transformed and calculated as the transfer function in the frequency domain.

The calculated result of input-output relation shows the good agreement with the simulated one. Mechanical resonant frequency can be observed around 120Hz. The peak at the resonant frequency is not serious for the non-circle cutting because it is enough high frequency compared with the spindle rotation during non-circle cutting. The effect of the oil fluid works as the fluid damper.

The steady state range of the frequency response shows from DC to 50Hz. This result is enough effective as the tool holder for non-circle cutting. Because the conventional non-circle cutting is executed less than 3000rpm equivalent to 50Hz, the developed cutting tool holder shows efficient performance for the practical use.

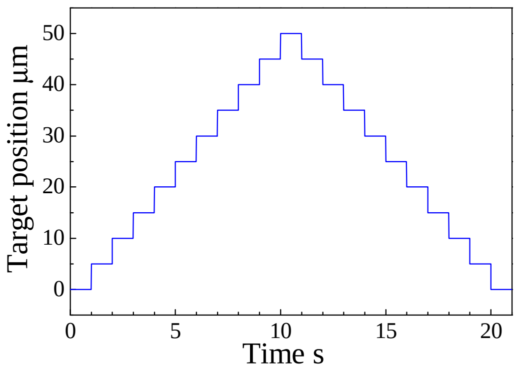

Fig.6. Target position of positioning control.

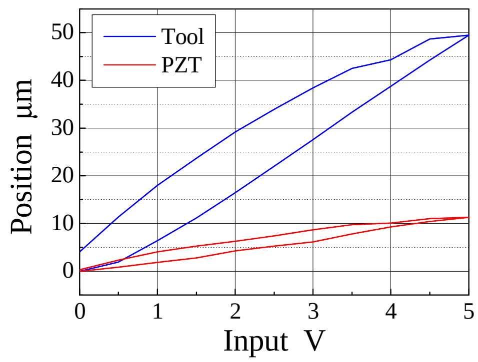

Fig.7. Positioning control result by open control open loop positioning.

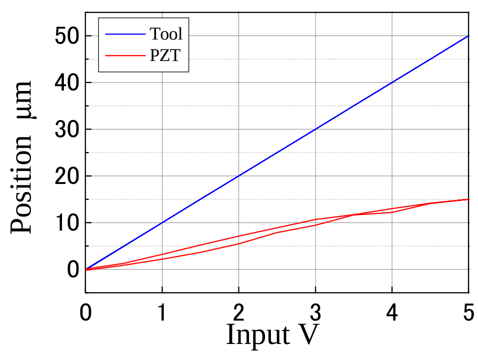

Fig.8. Positioning control result by PID control feedback loop positioning.

4. EVALUATION OF POSITIONING PERFORMANCE

4.1 Positioning performance of a cutting tool holder

The developed cutting tool holder shows the good result as the non-circle cutting tool holder. The positioning accuracy is evaluated in this section.

The position feedback is realized by the linear encoder (Mercury II 4000, 1.2nm resolution). The stepwise target position input is fed to the device as shown in Fig.6. The total stroke is set to 50µm. Each distance between stationary state positions is 5µm. Two positions of tool end point (Blue line; linear position encoder) and PZT end point (Red line; laser displacement sensor) are measured simultaneously and averaged as shown in Fig.7. This control result demonstrates that the elongation is realized by the proposed method. The hysteresis is observed because of the open loop positioning.

Then the feedback control is adapted to this positioning system. The results obtained are shown in Fig.8. The end of tool is controlled completely. The tool end position is controlled linear with the increase of input voltage. At the same time, the behaviour of PZT still remains the hysteresis as same as Fig.7. This result is sensible because the controlled point is the end of the cutting tool.

4.3 Positioning accuracy of a cutting tool holder

The positioning accuracy depends on the linear encoder strictly. The positioning accuracy is evaluated under the regulation of ISO230-2 as shown in Fig.9. In this test, a constant interval is commanded width bi-directional motions. The repeatability and the accuracy are calculated from the given equations.

Experimental procedure is executed by the output position from the linear encoder. The results obtained during motion are shown in Fig.10. The total stroke is set to 100nm. Each distance between stationary state positions is 10nm.Each position is controlled accurately.

Figure 11 shows the calculation results of the measurement. The average positioning error settles within 1.2nm from both directional positioning. The positioning accuracy of both directional motions shows 5.9nm. The repeatability of this device shows 4.5nm. These results demonstrates that this cutting tool holder is enough accurate for the precise non-circle cutting.

4.4 Rigidity of a cutting tool holder

The rigidity of the cutting tool holder depends on the linear guide set between the tool holder and tool base. This linear guide supports the cutting tool to endure the cutting force in spite of reducing the frequency response.

The thrust force is measured by the variation of positions of PZT as shown in Fig.12. The linear relation between PZT offset displacement and thrust force is obtained by this experiment. Therefore, the thrust force can be calculated by this coefficient during non-circle cutting.

Figure 13 shows the critical behaviour of the tool end under the condition of the thrust force loading. The maximum thrust force is 30N that is enough strong for the

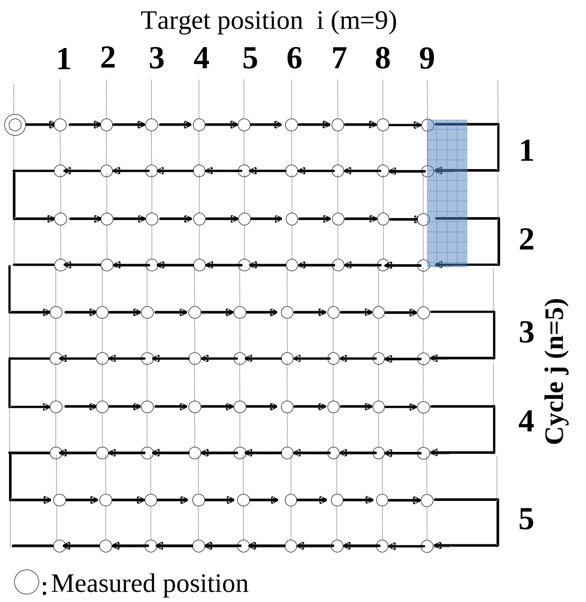

Fig.9. ISO 230-2 test pattern of positioning accuracy.

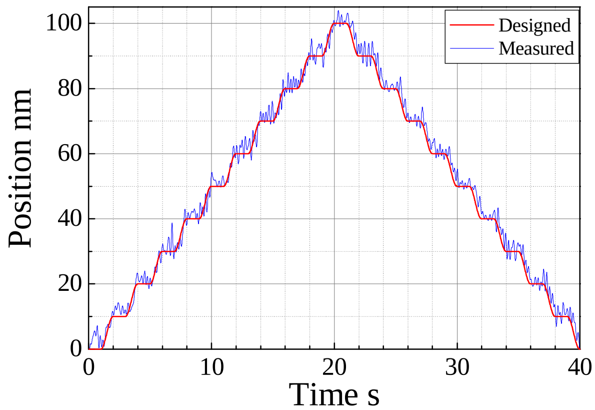

Fig.10. Positioning results of 100nm stroke.

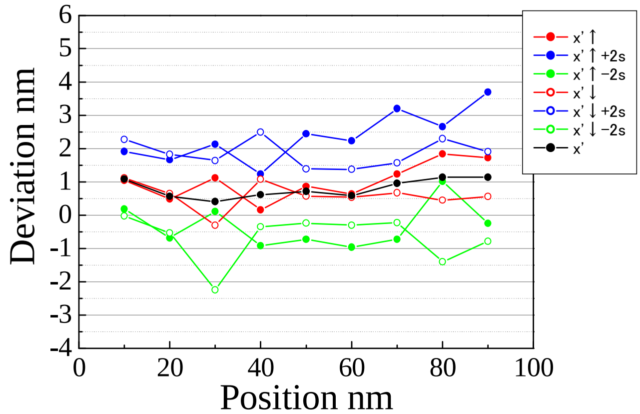

Fig.11. Measurement results of positioning accuracy.

non-circle cutting of aluminium alloy for the reciprocal piston.

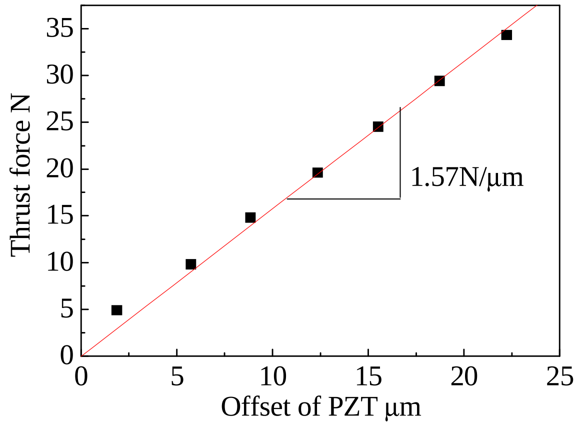

Fig.12. Measurement of tool rigidity.

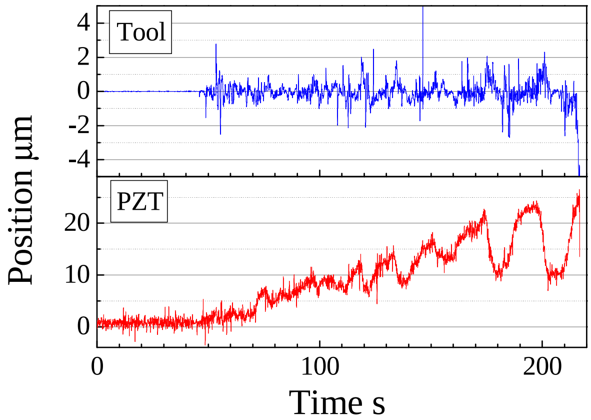

Fig.13. Tool and PZT behaviours loading thrust force.

5. MEASUREMENT OF THRUST FORCE

As the developed device has a function of measuring the thrust force during cutting, experimental procedure has been done to evaluate the cutting force. The calculating program is included in the control program.

Table 1 shows the cutting conditions of non-circle cutting. The spindle rotation is rather lower than the usual one. Both behaviours of tool end and PZT are observed simultaneously as shown in Fig.14. The elongation of stroke is realized even in cutting operation. The amplitude ratio of tool end to PZT is 4.

Figure 15 is the calculation result of the thrust cutting force. As same as Fig.14, the cutting force shows precisely in spite of small amount.

Figure16 shows the representative tool behaviour during one spindle rotation. As the sinusoidal input is fed to the amplifier of PZT, the tool is controlled precisely. The deviation between input and the tool motion settles in plus or minus 1.2μm. Further improvement is required to achieve the rigidity and long stroke.

Table 1. Cutting conditions

Spindle rev.	400 rpm
Depth of cut	50±25 μm
Feed rate	0.05 mm/rev.
Coolant	Dry
Cutting tool	DA150 Rake angle 6°
Workpiece	A2017 Diameter ϕ40 mm
Cutting data	360 data/rev

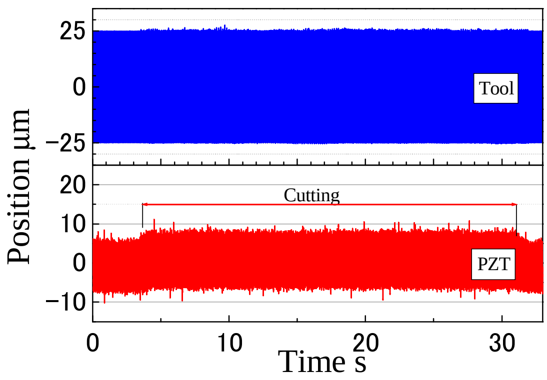

Fig.14. Tool and PZT behaviours during cutting.

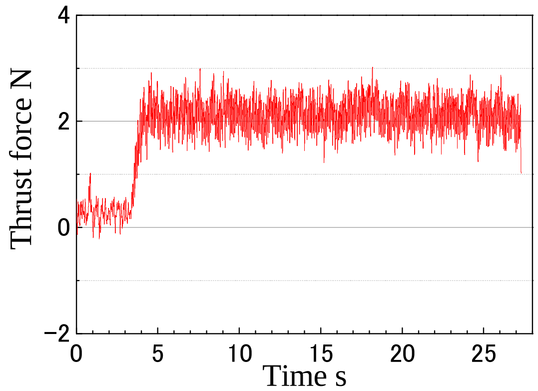

Fig.15. Thrust cutting force.

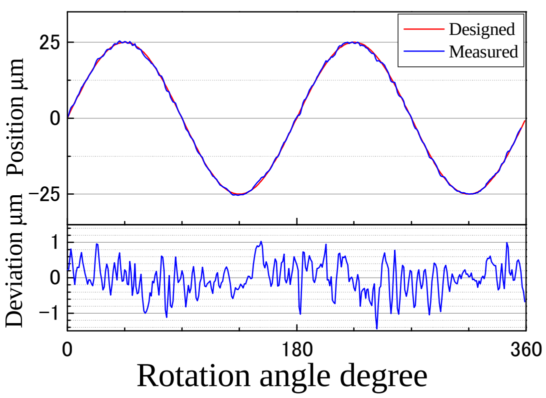

Fig.16. Tool behaviour during cutting and positioning deviation.

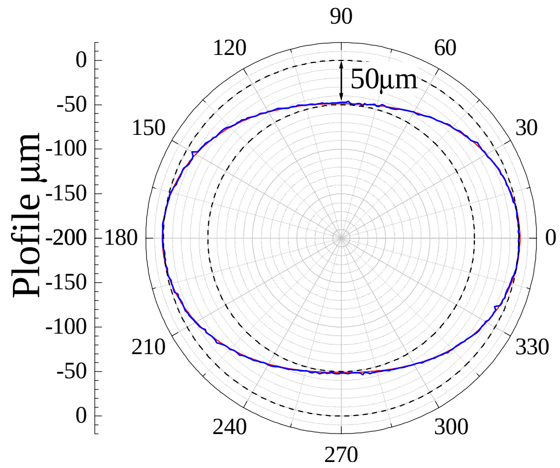

Fig.17. Machined profile of non-circle cutting.

The machined profile of aluminium alloy is measured by the circular tester as shown in Fig.17.

The total profile error settles in plus or minus 1.5μm. This result demonstrates the developed device is enough useful for the practical cutting.

6. CONCLUSIONS

A new cutting tool holder driven by the enlargement mechanism that consists of fluid chamber and a PZT drive has been developed. The fundamental performances of the developed device are evaluated. The following conclusions are obtained.

(1) The basic mechanism is modeled by one degree-of-freedom and the dynamic characteristics are obtained by simulation.

(2) The developed mechanism enlarges the displacement of PZT. The enlargement amplitude is 4 times of the original stroke of PZT.

(3) The PI control is adapted to positioning the developed device. The positioning results show the efficient performances for the non-circle cutting tool holder.

(4) The experimental frequency response of the developed device shows the stability up to 50Hz.

(5) Non-circle cutting to obtain the ellipsoidal profile is realized by the developed system. The amplitude of the ellipsoidal profile is 50μm as same as the desired value.

(6) The average positioning error settles within 1.2nm from both directional positioning.

(7) The positioning accuracy of both directional motions shows 5.9nm. The repeatability of this device shows 4.5nm.

(8) The maximum profile deviation settles within ±1.5μm that is enough useful for practical machining.

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