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Development of a fast tool servo in noncircular turning and its control

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ABSTRACT

To meet the main requirements of output displacement, bandwidth frequency and accuracy in noncircular turning, a fast tool servo (FTS) system based on piezoelectric (PZT) voltage feedback is developed. A flexure hinge structure is designed to amplify the output of PZT actuator and topology optimization is done to reduce the mass and compliance of the structure so that the output displacement and response frequency of FTS can be improved. A compound controller, into which repetitive techniques, PI and feed-forward control, are introduced, and the method that PZT voltage of the actuator is treated as feedback are put forward. The feasibility and reliability of this system are proved well by turning experiments.

1. Introduction

In industrial applications, many workpieces with an irregular surface are much better in improving the performance than traditionally flat or cylindrical ones. For instance, piston skirt and pinhole are noncircular surfaces in order to obtain more uniform pressure and improve the bearing capacity [1,2], and bearing rings also do not have a shape of a cylindrical surface in the machining process to diminish the effect of clamping forces [3].

Fast tool servo (FTS) plays a key role in free-form (non-axisymmetric) surface machining, noncircular turning, and can be used in conjunction with traditional machine tools, e.g. NC lathe, to accomplish machining the asymmetric geometric feature of these surfaces with respect to spindle rotation. For instance, the shape of the piston skirt is not a perfect cylinder, but middle convex in axial section and varying ellipse in cross section.

Fig. 1 is the profile of noncircular section of a piston at a certain height of the piston skirt, typically, an ellipse curve. The radial feeding of a cutting tool is $y(t)=(R-r)[1-\cos(2\theta)]$, R is the long axis of ellipse, r is the short axis of ellipse, θ is the rotational degree, and $\theta=2\pi\omega t/60$, where ω is the spindle speed in rpm.

In order to meet the requirements of noncircular turning or boring, FTS has to have large low frequency output displacement, high small signal bandwidth. In gasoline piston skirt turning, the output displacement of FTS is over 300 μm and the tool feeding frequency is $f=2\omega/60$. When the spindle speed is 3000 rpm, the response frequency of FTS, in which FTS will accurately respond to a control signal, is at least 100 Hz.

The methods of actuating FTS fall into the following categories: piezoelectric [4–6], magnetostrictive [7], Lorentz force which includes permanent magnet motors, voice coil and linear motor [8–11], and electromagnetic [12,13].

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Piezoelectric (PZT) actuators with their infinite resolution, high stiffness and high frequency are widely used in many areas. Otherwise, because the maximum output displacement of the stacked actuator, d_{33} type, is only 1/1000 of their length, and it has to be amplified to meet the long-travel requirement. A flexure-hinge structure is designed to magnify the output displacement of the PZT actuator.

Though the PZT actuator can be much increased in the output displacement, the whole FTS also in mass due to the amplifying structure is incorporated in it. The response frequency of FTS heavily depends upon the mass and the stiffness of tool holder and servo, in this paper, optimization is done to reduce the whole mass for bettering its frequency bandwidth. The controller, which employs the repetitive control techniques based on PZT voltage feedback and supplies high dynamic stiffness to the tool feeding mechanism, is put forward.

2. Design of FTS

The maximum stress of amplifying structure is on the free edge of a right circular flexure hinge [14], and is reversely dependent on its stiffness under the same deforming. The principles of design are to keep the maximum stress as low as possible and to obtain the maximum stiffness on the basis of having the output displacement satisfied in noncircular piston turning. These principles can also ensure the system to have higher natural frequency and better anti-vibration capability.

Fig. 2 is the schematic diagram of FTS. The structure based on the right circular flexure hinge is used to amplify the output of the PZT actuator. Because of the asymmetry of the amplifying structure, the tool feeding pathway is not only mainly in the *Y* direction but also very slightly in the *X* direction, and this effect is diminished by the round flexure hinge on the tool bar. Both the main cutting force F_z and the feed force F_x are carried by linear bearing. The thrust force F_y, which is transferred to the amplifying mechanism, is about 300 N when the maximum amount of feeding is 0.5 mm.

2.1. Right circular flexure hinge

The flexure hinge is an elastic joint, which connects rigid bodies or links, for small displacement. The flexure hinge is relatively slender, and often used to develop a compliant mechanism, when compared with other parts in the compliant mechanism. It functions as a rotational joint, however, without friction, wear and backlash.

The right circular flexure hinge [15–17] is precise in rotation, and its rotation center does not displace as other types of flexure hinge, and it is always treated as a torsional spring only around the *Z*-axis, see Fig. 3. In the right circular flexure

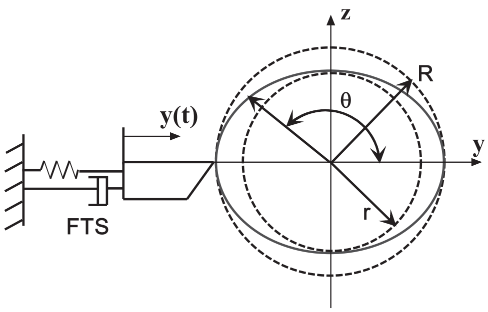

Fig. 1. Profile of noncircular section in piston machining.

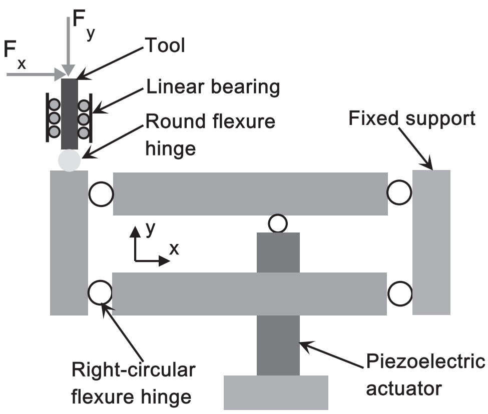

Fig. 2. Schematic diagram of FTS.