BALL SCREW AS THERMAL ERROR COMPENSATOR

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1. Introduction

Ball screws are predominantly used in machine tool feed mechanisms. When they are applied to high-speed machines[1], the performance is often limited by thermal problems due to their high DN value. The temperature change of ball screws has been studied in that sense[2]. This sort of thermal effects is particularly important in cases a machine runs in volume production lines, where frequent rapid traverses over a full stroke are not uncommon. In this work, however, thermal deformation of ball screws was used to compensate for thermal errors from other machine units showing considerable temperature changes, and this was based on purely mechanical means by considering axial symmetry principle. A conventional, slant-bed CNC lathe on production was the study object, and 5-fold enhancement in accuracy was the goal.

2. Structural reconfiguration

Before working on a compensation technique using a ball screw, we tried to modify structural configuration of a machine. A typical configuration of a slant-bed machine is shown in Fig. 1, comprised of a fixed headstock, a Z saddle traversing on Z slideways and an X cross-slide stacked on the Z saddle. The first step in designing precision machines is to apply the fundamental precision-engineering principles. Among many principles to choose from, the deployment of structural symmetry would be an easy first step.

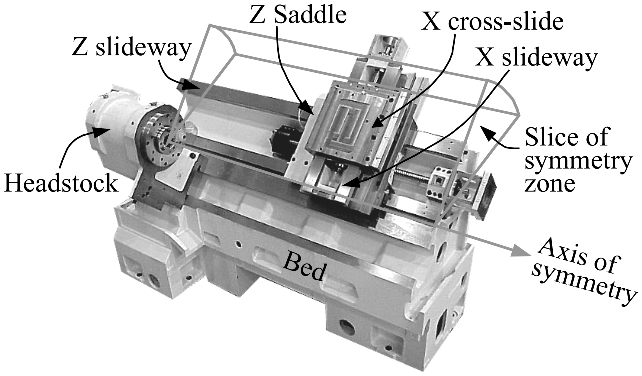
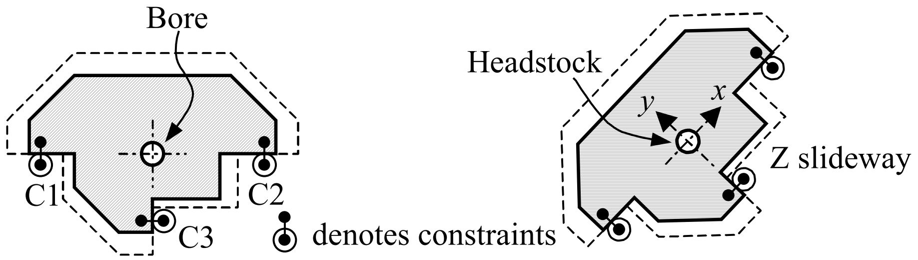


Figure 1 Typical construction of slant-bed CNC lathe

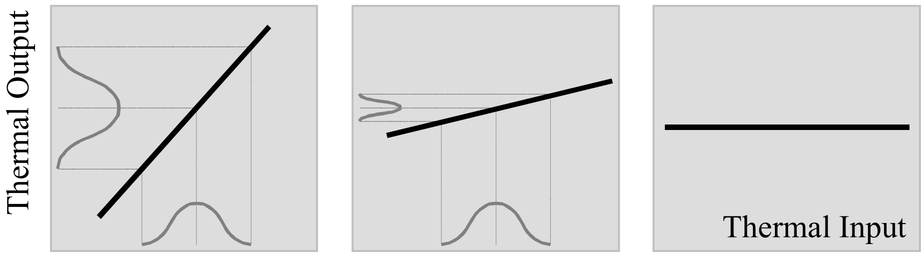
The first hurdle was how to apply the symmetry principle to 45-degree, slant-bed CNC lathes. Lastly, we found that symmetry about the spindle axis should exist to maintain the best possible mechanical accuracy irrespective of any thermal conditions. Fig. 2(a) shows a method of achieving thermal insensitivity of a bore centre by locating constraints in parallel with the radial direction from that centre[3]. In turn, the bore can be regarded as the headstock of a lathe and the constraints as the Z slideways such as shown in Fig. 2(b). The most important is the location and direction of a part of the Z slideways that constrains the Z saddle in the X direction, and the exact location should be just below the headstock centre line. As indicated in Fig. 1, application of the axial symmetry resulted in a slice of symmetry zone on the machine. This point of view lends itself to resulting in optimised constraints for each machine unit, and axial symmetry can be achieved on a 45-degree, slant-bed machine.



(a) Original figure from Blanding (b) Application to lathe

Figure 2 Constraints with axial symmetry

From the symmetry principle, a concept of thermal robustness can be considered as depicted in Fig. 3. In Fig. 3(a), a thermally sensitive machine shows a large degree of variation in thermal output, e.g. positional error, with the variation of thermal input, e.g. spindle speed. But, a thermally robust machine shows a relatively small variation as depicted in Fig. 3(b). When perfect thermal symmetry exists, the thermal output does not vary with the thermal input as shown in Fig. 3(c), that is, temperature increases do not generate any measurable thermal error. Because most of CNC machines do not run in precisely temperature-controlled environment, thermal robustness of a machine is important.



(a) Thermally sensitive (b) Thermally robust (c) Thermal symmetry

Figure 3 Concept of thermal robustness

3. Ball screw as compensation device

Under the axially symmetrical structure described above, the next problem was differences between workpiece dimension and sensitive dimension of the machine. In cases of turning, a machine can have 10 times larger sensitive dimension. For a steel part of diameter 10 millimeters, only 1.2 micrometers are changed with 10 degrees of temperature fluctuation. For a machine having a sensitive dimension of 100 millimeters, the same temperature fluctuation causes a change of 24 micrometers. The relative dimensional differences between a machine and a workpiece result in large errors. Because this problem could not be corrected by the symmetry configuration, other compensatory means were necessary. We found that ball screws could be used to minimise dimensional deviation under fluctuating temperature conditions from the following aspects:

- *Firstly, operating condition of a ball screw can be a representative indicator for overall thermal condition of a machine*.
- *Secondly, we can control the direction and magnitude of thermal growth of a ball screw once figuring out thermo-mechanical behaviour of a ball screw undergoing temperature changes*.

That is, the thermal deformation of a ball screw can be mechanically controlled to compensate for the dimensional gap between workpieces and a machine by introducing cancelling effects. The cancelling effects are devised in such a manner that thermal errors due to residual non-symmetry conditions, i.e. errors from structural components such as bed and saddle, become minimised by out-of-phase thermal deformation of a ball screw. Fig. 4 shows a structure of pre-tensioned feed mechanisms where two locknuts are used to generate internal tension force of a ball screw with the help from stiff support bearings.

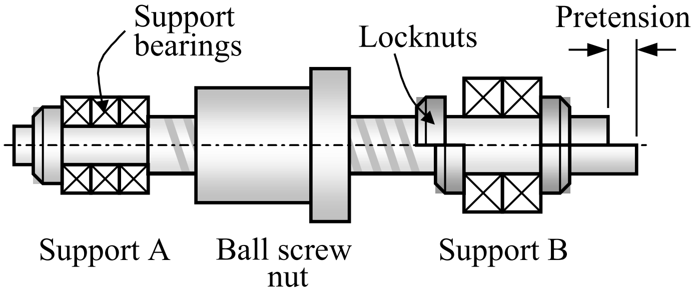
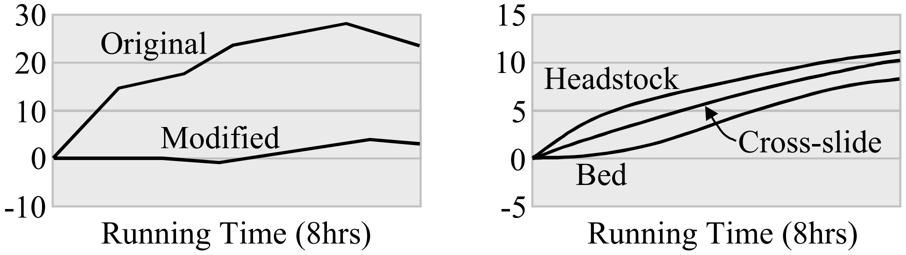


Figure 4 Feed axis mechanism with pretension

This sort of derivative means can be applied by manipulating tension force of a ball screw and stiffness of ball-screw end fixity, e.g. the axial stiffness of support A and B in Fig. 4. The elevation of a ball-screw temperature decreases internal tension force so as to produce thermal deformation of a ball screw in a predictable manner by end-fixity boundary stiffness conditions as described by the following governing equation:

$$\frac{d}{dz}(EA\frac{dw_0}{dz}) = -p(z) + p_{th}(z) \qquad \text{where} \qquad p_{th}(z) = \frac{d}{dz}\left(EA\alpha T'\right)$$

where E, A, w_0, p, p_{th}, α, T' are Young's modulus, cross-sectional area, longitudinal displacement, mechanical load per unit length, thermal load, thermal expansion coefficient, temperature change, respectively. Fig. 5(a) shows the final machining results in terms of diametral deviation. The modified machine achieved dramatic increase in long-term continuous machining accuracy under considerable temperature changes in the machine units as shown in Fig. 5(b).



(a) Machining accuracy [µm] (b) Temperature increases [ºC]

Figure 5 Continuous machining accuracy and typical temperature increases of machine

4. Conclusions

The current research shows 5-fold enhancement in accuracy to conventional CNC lathes on production. This implies that temperature change alone is not a significant error source, but important are how to apply fundamental precision engineering principles and how to deal with conditions where the principles cannot be satisfied. This work demonstrates that the direction and magnitude of thermal displacement of ball screws can be optimally manipulated by controlling end-fixity conditions.

References

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