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Measurement of Ball Screw Thermal Elongation with Torque Limit Skip

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Abstract
The thermal elongation of a ball screw is measured at the ball screw stop with the novel Torque Limit Skip (TLS) methodology for the measurement of thermal errors of precision machine tools. An excellent agreement is found between the TLS- and sensor-measured errors. Furthermore, a series of thermal test-pieces are manufactured on a Swiss-type lathe and it is shown that the thermal error of a machined diameter during warm-up is closely correlated to the ball screw elongation and can be compensated.

Thermal error, Ball screw, Torque Limit Skip, Thermal compensation, Swiss-type lathe

1. Introduction

Precision machine tools are susceptible to a variety of thermal influences, which cause a relative offset between the tool center point (TCP) and the workpiece. This offset is called the thermal error and accounts for up to 70% of the total geometric error on manufactured workpieces [1]. Influences contributing to the overall thermal error include internal influences such as the cutting process, mechanical friction, heat generated in electrical components, and external influences which are typically the environment and personal radiations [2]. Among these, a major cause of the thermal error is the linear ball screw, which directly influences the positioning error on the corresponding axis [3]. Ball screws are widely used in precision machine tools due to their high precision, efficiency and stiffness. During machining, the ball screw is subjected to temperature changes in the screw nut, bearings, motor etc., which leads to a deformation of the screw and a loss of position accuracy. Therefore, if the thermal deformation of a ball screw can be measured and/or predicted and subsequently reduced, a considerable reduction of the overall thermal error can be achieved.

Many different theoretical and simulation approaches exist in literature for the modelling of the thermal behaviour of ball screws. Accompanying validation experiments are usually performed via laser interferometry and measure the thermal error at the TCP. This work proposes a new measurement methodology to measure the elongation of the ball screw with the recently introduced Torque Limit Skip methodology for precision machine tools developed by Kaftan et al. [4].

2. Methodology

In CNC programming, the Torque Limit Skip (TLS) command skips over a specific sequence of code within a program when a user-specified torque limit (TL) override value is reached on an axis servo. If the TLS command is triggered during the motion of the ball screw nut, the movement is interrupted and the next block of code is executed. The axis position at the end of the skip can be extracted from the control and saved. In this work, the TLS function is triggered by a mechanical contact between the ball screw nut and the mechanical stop at the end of the ball screw to detect the elongation of the ball screw at that location. The movement sequence is described in Fig. 1. The nut moves towards the stop to a target coordinate C specified outside of the axis limit. The nut comes into contact with the stop at point A but continues moving to target coordinate C since the TL on the axis motor had not been reached at that point. The movement is subsequently terminated at point B where the TL value is reached and the skip signal is triggered. The axis position is recorded and the nut then moves back. Kaftan et al. [4] have shown that if the TL override value and axis feedrate are set to the lowest possible values, then the TLS command is executed almost immediately upon initial contact and the distance from point A to B is in the sub-micrometre range. Lowest possible TL override value here implies a value that is only marginally higher than that required for the motor to hold the axis. These values are machine and axis specific and must be determined experimentally. In this work, it is proposed that the repeated application of the movement sequence as described, i.e. the repeated triggering of the TLS over a time horizon of several hours, can be used to track the relative change in position of the axis at the end of the ball screw, which is due to the thermal elongation of the ball screw. This information can subsequently be used to assist the prediction of the thermal error at the TCP. To implement this methodology, the allowable axis limits must be extended and high caution must be taken that no collision in the working space takes place. The control type used is FANUC in which the TLS function is available as a G-code.

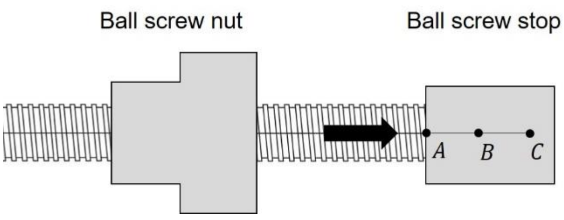

Figure 1. Ball screw nut movement during the TLS command. Black arrow indicates the direction of movement. A: first point of contact, B: position when torque limit is reached, C: target axis position.

3. Experimental Setup

The experiment is performed on a horizontal ball screw for the cross-slide motion of a counter-spindle on a Swiss-type lathe. The purpose of the experiment is to validate the proposed TLS method for ball screw thermal elongation measurement against a measurement with a linear displacement sensor. The sensor is mounted behind the ball screw stop as shown in Fig. 2. When the ball screw nut comes into contact with the stop, an artefact mounted on the machine tool table touches the displacement probe at the same time. In this way, both the TLS- and sensor-measured errors become available simultaneously and can be compared. In the experiment, the axis moves back and forth along the entire length of the screw for approx. 130 minutes and the error values are measured approx. every 1 minute. After this the motion stops, the ball screw cools down for approx. 40 min. and the axis moves only to make the error measurements.

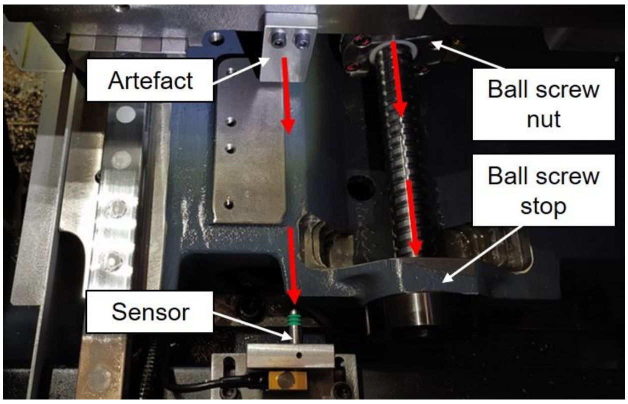

Figure 2. Setup of the validation experiment for the proposed method for the measurement of the ball screw thermal elongation with TLS. The ball screw nut touches the ball screw stop at the end of the ball screw stroke; at the same time, the artefact touches the sensor.

Additionally, tools are mounted in the working space of the lathe onto a stationary tool holder as shown in Fig. 3. A simple thermal test part is manufactured on the lathe, as shown in the bottom left corner of Fig. 3. The part is a round bar with several different diameters. The diameter indicated in Fig. 3 is machined with the indicated tool. The tool holder is stationary and the counter-spindle must move along the ball screw in Fig. 2 for the indicated diameter to be machined: a correlation between the thermal error and ball screw elongation is thus expected. Over the course of ca. 150 minutes, a total of 120 parts are machined (not every machined part is measured). After each part cycle, the ball screw moves to the stop to measure the elongation with the TLS.

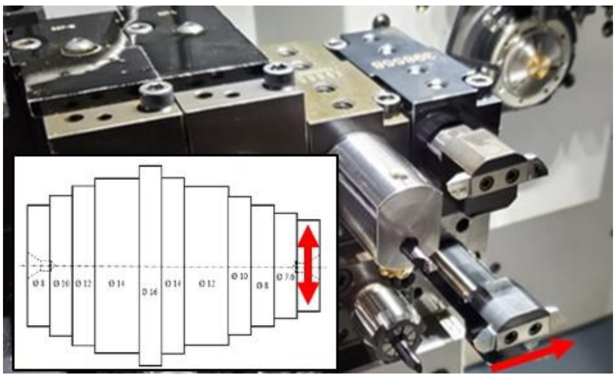

Figure 3. Tools are mounted onto a stationary tool holder in the working space of the Swiss-type lathe. The tool indicated with the red arrow machines the diameter indicated with the double red arrow.

4. Results

Figure 4 shows the result of the validation experiment, which is described in Fig. 2. The heat is induced into the ball screw by its servo motor, the temperature of which is also shown. The TLS measured values match almost exactly the values measured by the displacement sensor. The discrepancy in the final amplitude of 1 µm may be attributed to the fact that the errors are not measured at exactly the same location. Nevertheless, the results clearly demonstrate the suitability of the TLS for this application.

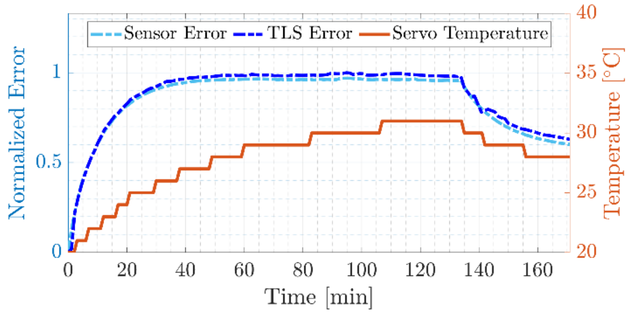

Figure 4. Ball screw thermal elongation measured with sensor and TLS

Figure 5 shows the relative error of the machined diameter *ΔD* of the part from Fig. 3. Each ▲ symbol represents one part. The thermal error of the part is clearly linked to the elongation of the ball screw and this can be used to compensate the thermal error. The major advantage of this compensation method is that no additional measurement equipment is required.

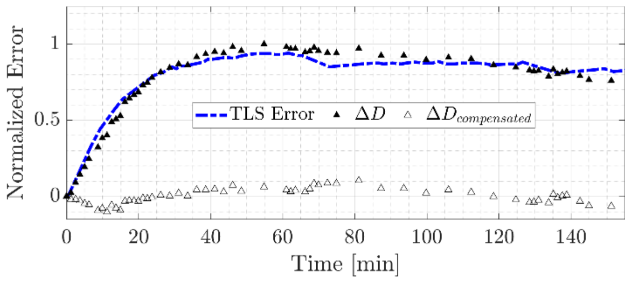

Figure 5. The relative thermal error *ΔD* of the machined diameter of the thermal test part is strongly correlated to the ball screw elongation.

5. Conclusion and Outlook

This work proposes a new methodology for the measurement of the thermal elongation of a ball screw with the Torque Limit Skip (TLS) function. The TLS method is successfully validated against a measurement with a linear displacement sensor and can be used to compensate a machined diameter.

References

[1] Mayr J, Jedrzejewski J, Uhlmann E, Donmez A, Knapp W, Härtig F, Wendt K, Moriwaki T, Shore P, Schmitt R, Brecher C, Würz T, and Wegener K (2012). Thermal issues in machine tools. *CIRP Annals*, 61:771–791.

[2] Wegener K, Weikert S and Mayr J (2016). Age of compensation – challenge and chance for machine tool industry. *Int. J. of Automation Technology*, 10:609–623.

[3] Shi H, Ma C, Yang J, Zha L, Mei X, Gong G (2015). Investigation into effect of thermal expansion on thermally induced error of ball screw feed drive system of precision machine tools. *Int. J. of Machine Tools and Manufacture,* 97: 60-71.

[4] *Under Final Review* Kaftan P, Porquez F, Mayr J, Pomodoro K, Trombert D and Wegener K (2024). Thermal Error Measurement with Torque Limit Skip in Swiss-type Lathe Manufacturing. *Precision Engineering.*