Ball-screw thermal errors – a finite element simulation for on-line estimation

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Abstract

Ball-screws are often used in machine tools with only a rotary encoder feedback on the end of the screw. Since this provides position feedback to the controller, any errors in the screw affect the accuracy of the machine. Also, these errors may change significantly when heating of the screw occurs during machining. This is often overcome by using a linear scale to provide the feedback. Unfortunately, fitting such scales to many machines may be mechanically difficult and costly.

This paper describes the development of a system that utilises a minimum of temperature measurements as inputs to a thermal simulation model of the ball-screw. Thus it is possible to estimate on-line the thermal errors of the ball-screw, assuming that position measurements of the nut are available from the rotary encoder. From these positions and the temperatures of the nut and bearings it is possible to estimate the speed of the screw and hence, assuming a knowledge of the frictional and heat transfer characteristics, the heat generated in the nut, bearings and screw. The thermal model constitutes a one-dimensional finite analysis of the whole length of the screw. The output of the model is a temperature distribution along the screw and an estimate of the thermal errors along the screw.

Also described is an experimental test rig, which provides facilities to test the model on-line. A laser position measurement is used to compare with the estimated position derived from the model. The results are graphically displayed and saved for future use in optimisation software to determine the parameters of the thermal model which best fit the experimental data. Improvements of better than 90% in the thermal error have been obtained.
The software is capable of making estimates of the thermal behaviour of a user-specified ball-screw in an off-line simulation mode. This can be used to aid design and help understand the effect of thermal errors on machine accuracy.

1 Introduction

Ball-screws are often used to drive the axes in machine tools, with only a rotary encoder feedback on the end of the screw. Since this is used to provide position feedback to the controller, any errors in the screw affect the accuracy of the machine. Also, these errors may change significantly when heating of the screw occurs during machining. This is often overcome by using a linear scale to provide the feedback. Unfortunately, fitting such scales to many machines may be mechanically difficult and costly. If the thermal error of the ball-screw could be estimated with a minimum of temperature measurements and an on-line mathematical model of the screw, then significant improvements in machining accuracy could be achieved without using costly instrumentation.

Machine tool designers and ball-screw manufacturers are interested in the thermal errors likely to be experienced under various duty cycles of a machine. An off-line simulation model capable of estimating such errors, even approximately, would be of great value. Also, users of machine tools could be trained in the likely effect of thermal errors on their machining capability by such a simulation.

Previous research reported a thermal error analysis of a CNC lathe feed drive system based on a modified lumped capacitance model of the ball-screw. [1,2] This involved a lumped parameter model of the screw with correction factors to compensate for the assumptions of the model. These were determined experimentally, which could lead to the requirement of re-calibrations at unpredictable time intervals due to wear changing the heating characteristics. Angular deformations caused by thermal deformations of the guide way were included by finite element analysis.

The aims of this work were:
1. To simulate off-line the thermal errors of a user-defined ball-screw under various conditions by one-dimensional finite element analysis. This should be easily calibrated and insensitive to the effects of wear.
2. To simulate on-line the thermal errors of the ball-screw.
3. To measure on-line the actual thermal errors of the ball-screw.
4. To optimise off-line the parameters of the thermal model of the ball-screw.

Eventually it is possible that real-time thermal compensation will be achieved by incorporating the thermal model into the geometric and thermal error compensation system produced by The Precision Engineering Centre at Huddersfield University.
2 The Thermal Simulation Model

The model is based on the schematic diagram shown in Figure 1. Heat is generated by friction in the shaft, nut and bearings and can pass down the shaft by conduction. Also, the nut, shaft and bearings can lose heat to the air, this depending on the relative temperatures and the coefficient of thermal contact resistance between steel and air. Figure 1 concentrates on the nut, but a similar model applies to each thrust bearing. The shaft is divided into N sections, usually 100, and each section is represented by a lumped parameter model. The heat can pass by conduction from one section of the shaft to the next. Also, heat can pass between the nut and bearings and the shaft wherever they are in contact. This depends on the position of the nut at any time and the thermal contact resistance between the nut or bearings and shaft.

Figure 1: Schematic diagram of the Thermal Model

The simulation program uses different thermal models for off-line and on-line application. This is because the on-line model assumes that the temperatures of the nut and bearings are known via thermocouple measurements, whereas the off-line model estimates these by simulation. This means that the off-line results are less reliable and are meant to provide a guide of the type of error to be expected, rather than to be highly accurate. However, the results will be of interest to users of ball-screws who want to appreciate thermal behaviour.

The difference between the two models are summarised by the thermal factors that they include as follows:
2.1 The thermal factors included in the on-line model:

1. Measurement of temperatures of nut, bearings, material and environment.
2. Estimation of the heat generated by friction in the screw and bearings, proportional to the speed of the screw.
3. Estimation of the heat passing from nut to screw through thermal contact.
4. Estimation of the heat passing from bearings to screw.
5. Calculation of the heat passing by conduction along the screw.
6. Estimation of the heat lost to the surrounding air by the screw.

2.2 The additional thermal factors included in the off-line simulation

Estimation of the temperature change of nut and bearings as lumped thermal models by:
1. Heat generated by friction in the nut and bearings - proportional to the speed of the screw.
2. Heat lost by the nut and bearings to the air.

2.3 The physical parameters in the model

There are eight physical constants associated with the thermal processes. These are the thermal contact steel to steel, the thermal conduction of steel, the thermal convection shaft to air, the thermal convection nut to air, the thermal convection bearing to air, the friction in the nut, the friction in thrust bearing 1 and the friction in thrust bearing 2.

The parameters defining the physical dimensions of the particular ball-screw include the length and radii of the screw, nut and thrust bearings.

3 Introduction to the real-time experimental set-up

To test the models an experimental ball-screw rig at the University of Huddersfield provided on-line measurement facilities. The rig, based on a production machine tool, consists of a cast iron bed on which is mounted a moving carriage using linear guide-ways. The ball-screw is pre-tensioned and has a travel of 440 mm from end to end. The total length of the screw is 1100 mm, the majority of the excess ball-screw length being at the motor end. A laser system and linear scale are available to enable comparison of the measured nut position with that estimated by the model.

The system shown in Figure 2 consists of the ball-screw test rig and a standard PC running DOS-based software written in a high level language. The interfacing consists of a Renishaw scalar card to read a Renishaw laser, an analogue scalar card to read either the rotary or the linear scale and a RS485 interface to incorporate a thermocouple amplifier and 16 bit A/D converter, the Talisman
Hence it is possible to measure various temperatures and positions at high speed.

The laser gives a reference measurement of the actual position of the nut at any time. This was fully compensated in software for ambient temperature changes and changes in material temperature, atmospheric pressure and humidity [3]. The linear scale gives a reading which is affected by any expansion of the glass scale, but this has been shown to be minimal since it is positioned away from the ball-screw. The rotary encoder gives the expected position of the screw assuming no errors in the screw.

The differences between the rotary scale and the laser at various positions along the screw give the errors in the screw. Before heating starts these are due to angular effects and screw inaccuracies, which are of little interest in thermal work and can therefore be used to compensate readings taken later by subtracting these initial errors.

4 The Real-Time System Software

The output for each time interval consists of:

1. Graph of temperature distribution along the screw.
2. Graph of nut, bearing and ambient temperatures vs. time.
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3. Graph of thermal error distribution along the screw.
4. Laser-measured error for comparison.
5. Graph of estimated errors at the furthest reference point
6. Average error of model as a function of time.
7. Results in a file the name of which can be specified at run-time.

A typical screen display is shown in Figure 3.

Each time a sample is recorded all the temperatures are measured, the laser recalibrated for the measured ambient temperature and the laser and rotary scale logged. The update time is several times per second, at which speed the system performs the finite element analysis of the screw for every time interval.
The bottom left window of the display shows an animated diagram of the screw, which follows the actual movement of the rig.

The error is estimated by subtracting the laser and rotary scale measurements, but these are not taken simultaneously. A test is performed on initialisation of the system to find the time delay between these measurements. The system uses this information and the estimated speed of the nut to estimate a correction to be applied to one of the positions to compensate for the effect of the delay. It is
possible to tune the value by running the ball-screw at high speed in both
directions and adjusting the delay to produce the least hysteresis in the plot.
A new graph is plotted on the simulated error (middle left) and simulated
temperature distribution (top left) versus position graphs every time a reading is
taken, but the graph of temperatures (top right) and errors (middle right) versus
time are only updated every time the screw stops for a measurable period. Thus a
duty cycle which stops the screw periodically will produce the most interesting
and useful results.

The data from the laser, if available, is plotted on the simulated error graph
every time a measurement is taken. However, the position of the point along the x
axis will be determined by the position of the screw. Thus if the duty cycle does
not cover the whole screw then only part of the x axis will have representative
points plotted. The plot is cumulative, so that any new points do not erase the old
points unless they are for the same 1/Nth part of the screw. Sometimes old data
that has not been refreshed in this way, because the duty cycle has changed, will
not accurately represent the true errors. The plot can be refreshed so that the old
points are erased. The plot is then cumulative once again.

The middle right graph of the display shows the thermal error predicted by the
model in microns at the end of the screw and if available the average absolute
error in the model when compared with the actual thermal error measured by the
laser. Thus a good model leads to values of error in the model near zero.
Typically, the error is <5 microns, but the plot may show considerable random
fluctuations. This is especially the case during periods of high screw speeds,
because of the uncertainty in the error due to the measurement delay.

5 The Off-Line Simulation Software

The off-line simulation software can be used for pure simulation. On running the
software there is a choice between an assumption of constant nut and bearing
temperatures or simulated nut and bearing temperatures. There is also a choice of
the type of duty cycle to be performed. These include customisable fixed,
trapezoidal, sinusoidal and random movement of the nut. The simulation is
performed faster than real-time and the results are displayed as described for the
on-line simulation. However, no actual errors are plotted since no measurements
are available. The results are to be taken as a rough guide to ball-screw behaviour
rather than as numerically accurate estimates.

A typical run might involve a simulation with simulated bearing temperatures
using a triangular wave input (representing constant speed) with a period of 10
seconds. The centre point might be 780mm and the magnitude of oscillation 220
mm.

The simulation now starts and takes 1-10 minutes approximately. Graphical
output is as follows:
1. Temperature along screw vs. position (temperature distribution)
2. Error in microns along screw vs. position (error distribution)
3. Picture of moving nut on screw.
4. Nut and bearing temperatures vs. time.
5. Error at end of screw in microns vs. time.

6 The Off-Line Optimisation of the thermal model

A general least squares optimisation based on the method of Levenberg-Marquardt was used [4]. The objective function was derived from the error at the end of the screw as a function of time. This was sampled each time the screw stopped at one end, so the measurements were therefore more reliable than those taken dynamically. Also, the results can be re-sampled to provide a manageable set for entry to the optimisation routine. Thirty to fifty points were found to be adequate for this purpose.

The program allows any subset of the parameters to be optimised, the rest remaining fixed. The thermal conduction of steel is known and was fixed. The parameters involving convection from the bearings and nut were not used in the on-line model and so were not optimised. They are used in the off-line simulation only.

6.1 Problem with sparse data

The data needs to be sparse for the optimisation routine to operate efficiently. However, the simulation, on which the optimisation is based, needs a much shorter sampling time to ensure reasonable simulation accuracy. Hence, the data needs interpolation between the known points when the nut was stationary to give positions and speed of the nut at intermediate points. These are based on an assumption of constant speed and are used in the simulation model and not directly in the optimisation. This assumption is valid for the trapezoidal duty cycle used in the tests performed to generate data for use in off-line optimisation. This complication leads to a different algorithm being required for the simulation model used on-line and off-line from that used in the off-line optimisation. Because of the approximations involved in the interpolation, difficulties were encountered reconciling the two algorithms to ensure consistency of predicted behaviour for the same physical conditions. However, these were overcome as a once off exercise by exhaustive testing and fine tuning of the algorithms.

7 Other Duty Cycles

Error prediction is normally +/- 5 microns when tested on other duty cycles using various parts of the screw. This represents approximately a 90% improvement in the thermal error, and is similar to the error to be expected from a linear scale with only a 1°C temperature rise. For a typical test involving various speeds and cooling periods the temperatures of the bearings and nut are shown in Figure 4. The predicted thermal errors and errors in the prediction are shown in Figure 5. The model error shows random fluctuations which originate from the dynamic error measurements, not the simulation.
Figure 4: Temperatures during duty cycle.

Figure 5: Typical thermal error (modelled) and model error during a duty cycle.
8 Conclusions

Optimisation based on an off-line analysis of a simple heating and cooling test should be adequate to identify the parameters in a ball-screw model. Real-time compensation has the potential to give better than 90\% thermal error reduction. Requiring only a temperature sensor on each thrust bearing, the nut and one for ambient temperature makes it a very cost effective error reduction strategy.

This study and the models developed have facilitated the understanding of ball-screw thermal behaviour and will be valuable for manufacturers and users of balls-screws.

References