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Improved machine tool linear axis calibration through continuous motion data capture

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ABSTRACT

Machine tool calibration is becoming recognised as an important part of the manufacturing process. The current international standards for machine tool linear axes calibration support the use of quasi-static calibration techniques. These techniques can be time consuming but more importantly a compromise in quality due to the practical restriction on the spatial resolution of target positions on the axis under test. Continuous motion calibration techniques have the potential to dramatically increase calibration quality. Through taking several measurement values per second while the axis under test is in motion, it is possible to measure in far greater detail. Furthermore, since machine tools normally operate in dynamic mode, the calibration data can be more representative if it is captured while the machine is in motion. The drawback to measuring the axis while in motion is the potential increase in measurement uncertainty. In the following paper, different methods of continuous motion calibration are discussed. A time-based continuous motion solution is proposed as well as a novel optimisation and correlation algorithm to accurately fuse the data taken from quasi-static and continuous motion measurements. The measurement method allows for minimal quasi-static measurements to be taken while using a continuous motion measurement to enhance the calibration process with virtually no additional time constraints. The proposed method does not require any additional machine interfacing, making it a more readily accessible solution for widespread machine tool use than other techniques which require hardware links to the CNC. The result of which means a shorter calibration routine and enhanced results. The quasi-static and continuous motion measurements showed correlation to within 1 μm at the quasi-static measurement targets. An error of 13 μm was detailed on the continuous motion, but was missed using the standard test. On a larger, less accurate machine, the quasi-static and continuous motion measurements were on average within 3 μm of each other however, showed a standard deviation of 4 μm which is less than 1% of the overall error. Finally, a high frequency cyclic error was detected in the continuous motion measurement but was missed in the quasi-static measurement.

1. Introduction

Measurement of the geometric errors of machine tools is becoming a more important part of maintaining the part accuracy of manufactured components. The measurement data can be used to evaluate capability when buying a machine and to monitor its performance during its operational lifetime. Furthermore, by measuring the errors it is possible to perform diagnostic tasks and remedial caution in the form of mechanical adjustment or numerical compensation. In order for machine tool owners to be able to manufacture with confidence, they must have assurance that their machines are working within a required tolerance. For high quantity, low value production, the tolerances are likely to be larger than that of low quantity, high value production such as aerospace where tolerances are at a micrometre level.

In order to ensure that parts manufactured are within tolerance (right first time production) a high quality calibration process must be in place to ensure that the production machine is capable. The calibration process will encompass a range of different techniques. For example, a laser interferometer measurement system can be used to measure many of the geometric errors shown in Fig. 1 [1], while linear displacement sensors and artefacts are used for others. The telescopic ball bar system [2] provides a popular way of assessing machine tool performance during contouring.

There are a total of 21 geometric errors (Fig. 1) for a three axis machine tool such as the c-frame machine which are found extensively in industry (Fig. 2). Machine tool owners will systematically calibrate their machines based on manufacturing requirements.

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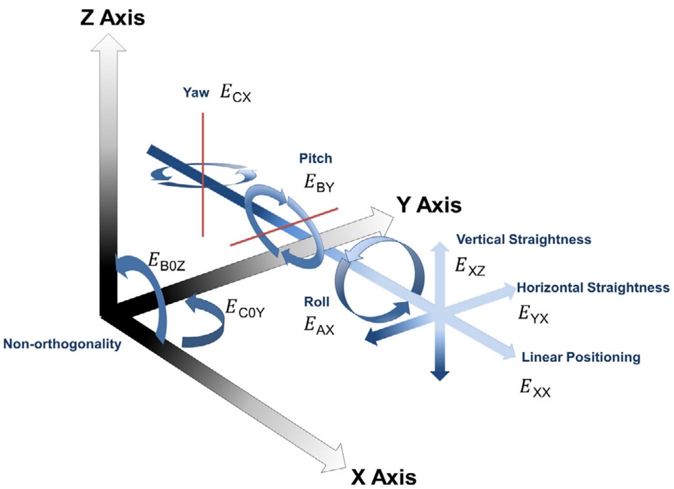

Fig. 1. Six-degrees-of-freedom and squareness error.

The current international standards for machine tool calibration of linear positioning deviations defined by ISO [3] supports the use of quasi-static calibration. Quasi-static measurement (QS-M) involves commanding the machine to move from point to point along the length of the axis under test. The machine is commanded to move to a target position, where it will remain stationary for a nominal time period while a measurement is taken.

Commanding the machine to move from point to point and dwelling until the machine has settled is time consuming, a problem that is exacerbated if a fine spatial target interval is selected, an example of which is provided in Section 3. Manufacturers want their machines to be in operation, minimising machine down-time for the measurement process. In order to achieve this, a coarse target interval might be selected. However, this could result in some errors of the axis remaining undetected due to the effects of signal aliasing; the true error form will not be sufficiently represented if there is insufficient spatial sample rate. Furthermore, when a machine tool is in operation, it is likely that the axis will not be stationary. Due to this, quasi-static calibration could be seen as an inadequate method for measuring the performance of machine tools during their intended operation; it is a reasonable compromise to indicate machine tool capability but will miss some potentially vital information.

Fig. 2. Three-axis machine tool.

Precision machining can be improved by applying numerical compensation, for which two requirements must be met: precise error prediction and accurate compensation (correction of error in the machine's controller) [4]. As QS-M techniques do not measure the machine tool in its usual mode of operation it is reasonable to argue that these techniques do not entirely meet the first requirement, making the second not possible.

By taking several readings per second on a time basis while the axis is in motion, continuous motion calibration has the potential to significantly reduce the overall calibration time while increasing calibration quality by removing the effects of signal aliasing.

During quasi-static calibration, the CNC part program provides the nominal positions for the measurement. The error is then simply calculated as the difference between the nominals from the part program and the actuals measured by the laser. The technical challenge for continuous motion measurements is in the ability to convert the measurement, which is typically in the form of a displacement measurement in the time domain (linear positioning measurement), to a geometric error in the position domain, since there is no explicit nominal position when using this method.

It is the aim of this paper to demonstrate the correlation between the quasi-static and continuous motion error of machine tools and how a continuous motion measurement can be used to enhance the calibration process while reducing the required number of targets for a quasi-static measurement. Different techniques for calculating the geometric error from a linear positioning measurement have been developed and will be discussed in the following section.

2. Background

CNC machine tools contain a range of different errors. These errors can be defined as: kinematic errors; thermo-mechanical errors; errors induced by loads on the machine; and continuous motion forces. All of these contribute to the overall geometric performance of the machine [5,6].

Kinematic errors are due to the machine's imperfect geometry such as axis misalignment and errors in the machine's measuring system [5]. Barakat [7] describes kinematic errors in relation to a coordinate measuring machine (CMM) as the error appearing in the ability of the CMM to reach the exact specified position by the controller. Due to the similarities in the kinematic chain and homogeneous coordinate system between machine tools and coordinate measuring machines the same definition can be applied to machine tools.

Thermo – mechanical errors are caused by internal and external heat sources resulting in thermo-elastic deformations of the machine tool causing geometrical inaccuracies [8]. Relative movement between the various elements of the machine causes heat to be generated at the contact zones and it is this heat that leads to the deformation of the machine elements [9]. Thermo-mechanical errors are said to be the cause of 70% of machine tool geometric inaccuracy [10]

Loads on the machine are caused by internal and external forces. For example, the location and weight of the workpiece could affect the machine's angular profile and so impair the overall accuracy [5,11].

The effect of the three error sources mentioned exist when the machine is stationary. *Dynamic errors* are the additional errors occurring when the machine is moving at a programmed feedrate. The dynamic errors result from varying alterations of the machine

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