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Measurement and analysis of machine tool errors under quasi-static and loaded conditions

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Highlights

- A novel methodology for the prediction of machine tool errors under quasi-static and loaded conditions
- Measurement and analysis of the combined effect of geometric errors and quasi-static load induced deviations on machine tools
- Estimation of deflections through the determination of the position- and direction-dependent static stiffness of machine tools
- Introduction how the static stiffness characteristic of machine tools is mapped on the part geometry

Abstract

Machine tool testing and accuracy analysis has become increasingly important over the years as it offers machine tool manufacturers and end-users updated information on a machine's capability. A machine tool´s capability may be determined by mapping the distribution of deformations and their variation range, in the machine tool workspace, under the cumulative effect of thermal and mechanical loads. This paper proposes a novel procedure for the prediction of machine tool errors under quasi-static and loaded conditions. Geometric errors and spatial variation of static stiffness in the work volume of machines are captured and described through the synthesis of bottom-up and top-down model building approaches. The bottom-up approach, determining individual axis errors using direct measurements, is applied to estimate the geometric errors in unloaded condition utilizing homogeneous transformation matrix theory. The top-down approach, capturing aggregated quasi-static deviations using indirect measurements, estimates through an analytical procedure the resultant deviations under loaded conditions. The study introduces a characterization of the position and direction dependent static stiffness and presents the identification how the quasi-static behavior of the machine tool affects the part accuracy. The methodology was implemented in a case study, identifying a variation of up to 27% in the stiffness response of the machine tool. The prediction results were experimentally validated through cutting tests and the uncertainty of the measurements and the applied methodology was investigated to determine the reliability of the predicted errors.

Keywords: Machine tool, accuracy, quasi-static stiffness, geometric error

1. Introduction

Thorough characterization of machine tools' accuracy requires quasi-static analysis under loaded and unloaded conditions. Machine tool accuracy analysis can be used to extract valuable information through identification of the separate effects of the various error sources, including kinematic, static, thermal, dynamic, and motion control [1].

For machine tool geometric error analysis, several different schemes have been proposed for 'direct' [2] and 'indirect' [3] measurements. Direct methods are implemented through error motion measurements of a single axis while indirect methods require simultaneous motion of two or more axis of the machine under test for estimating overall geometric errors. Analysis of superposed errors for a chain of axis uses a ''bottom-up'' approach, based on Hartenberg–Denavit transformation [4], where motion errors of individual components are added to the aggregated volumetric error [5]. The indirectly measured aggregated errors [6] can be analyzed through a "top-down" approach to derive the deviation matrix of the system.

ISO 230-1 [7] specifies methods and guidelines for testing the accuracy of machine tools under unloaded or quasi-static conditions accounting only for geometric errors and quasi-static load induced deviations. Under machining conditions, however,