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Accuracy evaluation of machine tools by modeling spherical deviation based on double ball-bar measurements ☆

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ABSTRACT

In this study, the accuracy of a machine tool was evaluated by modeling the spherical deviation based on double ball-bar measurements under unloaded conditions. Circular measurement paths on the *XY*-, *YZ*-, and *ZX*-planes were planned, and three linear axis drives were commanded to follow the paths describing a nominal sphere. The spherical deviation, defined as the maximum radial range of deviations around a least-squares sphere, is affected by the accuracies of the three linear axes together. Therefore, the spherical deviation represents the accuracy of machine tools by quantifying the effect of the accuracies of three linear axes, whereas the circular deviation only quantifies the accuracies of two linear axes among the three linear axes. In this experimental study, spherical deviations of vertical/horizontal machine tools were measured and analyzed under various nominal lengths of a double ball-bar for various feed rates. The measurement uncertainty of the measured spherical deviation was investigated to determine the confidence interval.

1. Introduction

Accuracy evaluation of machine tools to investigate the positioning accuracy between the tool and the workpiece is required as a criterion for acceptance testing and maintenance. In general, the accuracy is affected by various error sources, including kinematic errors, thermo-mechanical errors, loads, dynamic forces, motion control, and the control software [1]. Various measurement systems, including a dial gauge, straightedge, laser interferometer, and double ball-bar, have been developed with purpose of accuracy evaluation [2]. In particular, the double ball-bar is widely used to evaluate the accuracies of two linear axes using a simple circular test [3]. The double ball-bar consists of two precision balls, a sensor to measure the relative distance between the two balls, and fixtures to fix the two balls during the measurement. Using the double ball-bar measurement approach, specific errors such as backlash, servo-gain mismatch, and squareness error can be evaluated [4]. Fundamentally, the double ball-bar method measures circular deviation, i.e., the maximum radial range of deviations around a least-squares circle [5]. Circular deviation is used as one of the criteria for acceptance testing of built machine tools; it is caused by changes in the accuracy of the two linear axes drives controlled during the measurement. To calculate circular deviation, measured data from the double ball-bar must be transformed to the center of the least-squares circle to exclude the effect of set-up errors [6]. The center of the least-squares circle is referred to as the “eccentricity”, and the transformation is termed “centering” [7]. Commercial software is commonly used for the double ball-bar transformation. However, circular deviation only represents the effects of the accuracies of two linear axes. Thus, circular deviations for the *XY*-, *YZ*-, and *ZX*-planes are measured to evaluate the accuracy of machine tools. However, it is logically incorrect to consider the three circular deviations together, because each is derived using the center of a least-squares circle that is different from the others, resulting in “local optimization”. This means that the circular deviation at each plane results from only the effects of the accuracies of the controlled two linear axes, and not from the accuracies of three axes. This fundamental limitation is caused by the geometry of the circle that is defined on a plane representing two degrees-of-freedom (DOFs) for positioning.

In this study, spherical deviation is proposed as a criterion to evaluate the accuracy of a machine tool by overcoming the fundamental limitation of the aforementioned circular deviation. The geometry of a sphere defined in space represents three DOFs for positioning; therefore, spherical deviation provides a more accurate approximation of the accuracy of a machine tool with

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three linear axes. The circular paths of the double ball-bar in the *XY*-, *YZ*-, and *ZX*-planes were used in the measurement of spherical deviation. These paths are the same as those previously described for circular deviation measurements. However, the measured data on three planes was transformed to the center of a least-squares sphere, not to the center of the least-squares circles, thereby resulting in "global optimization".

The rest of the paper is organized as follows. Spherical deviation is defined and the measurement paths are described in Section 2. In Section 3, the proposed method is applied to vertical/horizontal machine tools with various nominal double ball-bar lengths at various feed rates to investigate the resulting spherical deviation. Additionally, the measurement uncertainty of the measured spherical deviation is derived. Finally, our conclusions are drawn in Section 4.

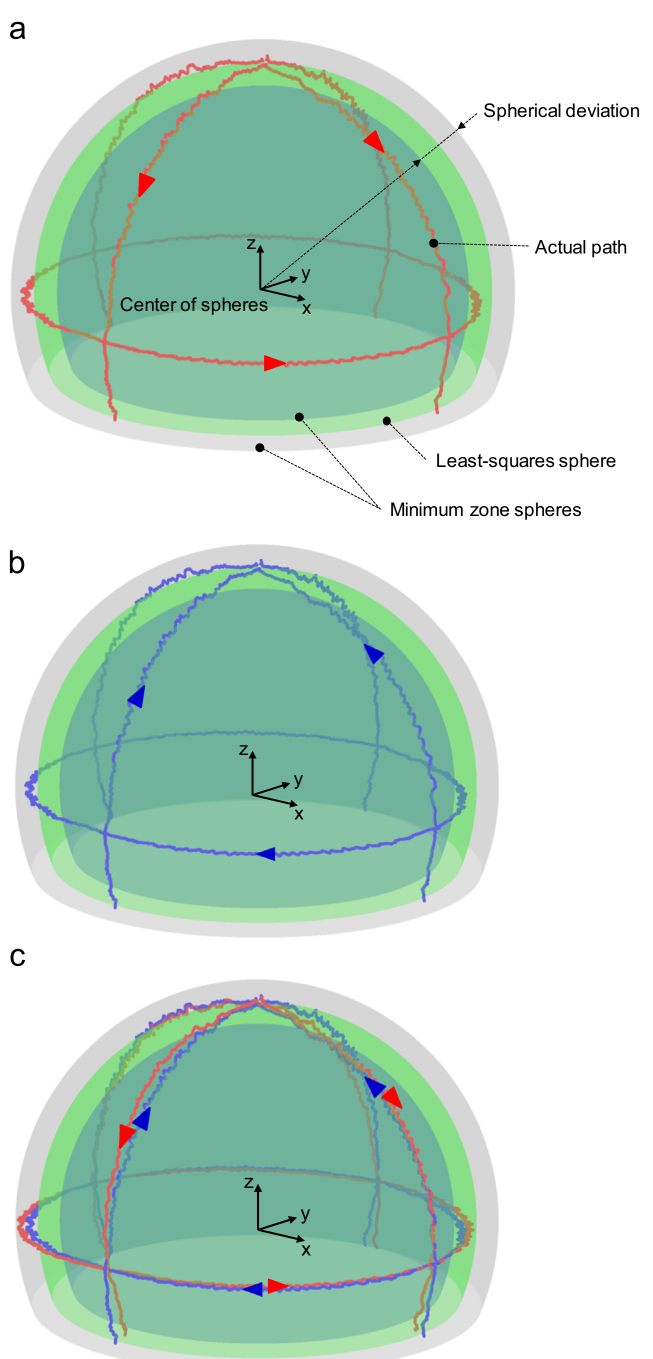

Fig. 1. Definition of spherical deviation. (a) Spherical deviation of a counter-clockwise (CCW) path. (b) Spherical deviation of a clockwise (CW) path. (c) Spherical deviation of a CCW path and a CW path.

2. Methodology for spherical deviation

Spherical deviation is defined as the maximum range of deviation around a least-squares sphere, as shown in Fig. 1. Here, spherical deviations S_{XYZ} and S_{ZYX} are the maximum range of deviation with respect to the nominal path for the counter-clockwise (CCW) and clockwise (CW) directions, respectively. Bi-directional spherical deviation $S(b)$ is the maximum range of deviation derived from the nominal paths of the CCW- and CW-components.

Any number of approaches can be used to plan measurement paths requiring simultaneous control over two or three linear axes on a nominal sphere for spherical deviation measurements. However, it is necessary to simplify the measurement paths to minimize the effort of the operator in field applications. Thus, the paths are chosen such that simultaneous control over two linear axes can be achieved; this is realized using circular interpolation. Circular interpolation, one of the fundamental functions of commercially available computer numerical control (CNC) devices, allows the operator to plan the paths for spherical deviation with no additional requirements. Circular paths in the *XY*-, *YZ*-, and *ZX*-planes were planned as shown in Fig. 2. The direction of the rotation angle θ with respect to each circular path was defined according to the right-hand rule, as in shown in Fig. 3. The planned paths only required a single set-up of the double ball-bar for a measurement to derive the least-squares sphere. For the circular path in the *XY*-plane, it was possible to fully trace the circle using the double ball-bar. However, the rotation range was limited for the paths in the *YZ*- and *ZX*-planes to minimize the likelihood of a collision between the controlled axis, the double ball-bar, and the fixtures that are used to fix the two balls. Therefore, it is recommended to plan circular paths with a maximum rotation range to minimize the chance for collision, maximize the measurement range, and improve the measurement uncertainty. This is discussed further in Section 3.

For the double ball-bar measurement, a ball is positioned on the workpiece table or origin of the workpiece coordinate system **{*w*}**; the second ball is located at the tool nose or origin of the tool coordinate system **{*t*}**, as shown in Fig. 4. The actual path is described as a projected path on the least-squares sphere. Using the appropriate command, the ball at the tool nose is directed to a nominal position (x, y, z) on a sphere of radius R. The relative

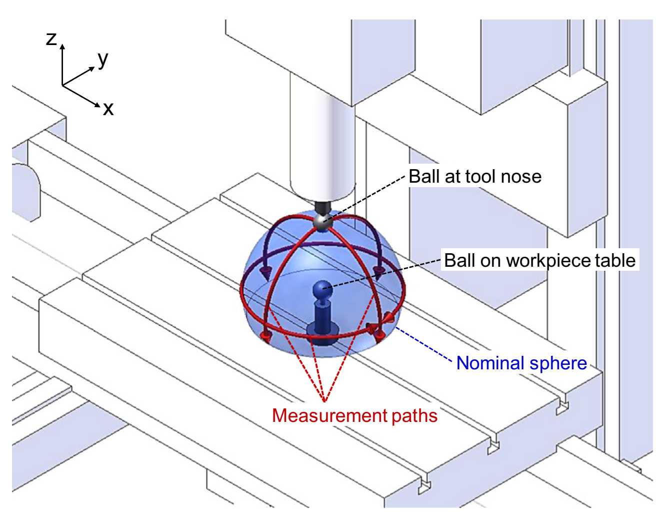

Fig. 2. Measurement paths for spherical deviation.