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Identification of position independent geometric errors of rotary axes for five-axis machine tools with structural restrictions

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ABSTRACT

Some of five-axis machine tools, which are widely used for micro-machining, have structural restrictions, such as the center line of tilting rotary axis being close to the surface of worktable or beneath the worktable. In this paper, simultaneous motions of both rotary and translational axes are combined with double ball bar to establish a measurement and one installation-based method for identifying the position independent geometric errors (PIGEs) of rotary axes for this kind of five-axis machine tools. Due to the existence of structural restrictions, the tool ball usually cannot be placed in the center line of the tilting rotary axis, and thus, actual spatial motion of ball bar is considered in the proposed identification procedure. For each rotary axis, two test configurations, i.e. the one along the radial direction of rotary axis and the other along the axial direction, are proposed to carry out the designed measurement and identification. Especially, to well avoid the potential negative problems induced by structural restrictions, rotary and translational axes are simultaneously controlled to carry out the measurement, and in the identification procedure, eccentricities together with angle shift and setup errors are comprehensively involved. Based on this basic consideration, spatial plane, on which the actual trajectory of table ball lies, is accurately constructed to integrate the actual movement of ball bar into the PIGEs identification procedure. Novel fitting strategies are developed to mathematically model both the actual trajectory and the spatial plane of table ball's motion, which are then adopted to formulate the expressions for identifying location and orientation errors. Both simulation and experimental verifications show that the proposed method is effective and helpful for checking and improving the status of five-axis machine tools.

1. Introduction

Five-axis machine tools have been widely used in manufacturing parts with sculptured surfaces such as blades, molds and dies with two more degrees of freedom introduced by the two rotary axes. The increasing demands for improving the precisions of these parts urgently require to improve the machine tools' machining accuracy. During machining processes, factors influencing machining accuracy include geometric errors [1,2], thermal errors [3,4], servo errors [5–7] and cutting force-induced errors [8–10]. Among them, geometric errors of machine tools are one of the biggest sources of inaccuracy. Compared to three-axis machine tools, five-axis machine tools increase the access of tool to the workpiece at different rotation angles, and this feature makes setup operation as minimal as possible. However, the two rotary axes also bring more error sources. There are overall 41 known geometric error items in five-axis machine tools, while there are only 21 known geometric error items in three-axis machine tools [2]. According to the conclusions reported in Ref. [11], geometric errors of rotary axes constitute the main contribution of machining errors. In order to improve the machining accuracy of five-axis machine tools, the geometric errors of rotary axes should be accurately identified and then be reasonably compensated. Especially, for the purpose of improving the identification accuracy of PIGEs, the identification method should correspond to the actual moving status of the machine as much as possible.

Geometric errors of machine tools can be classified into two groups, i.e. position dependent geometric errors (PDGEs) and position independent geometric errors (PIGEs) [12,13]. PIGEs are caused by the imperfect assembling of the machine components and are approximately treated as constants, while PDGEs are induced by the imperfection of machine components and vary from position to position in the workspace. In order to identify geometric errors, many instruments are developed, such as R-test device [14,15], touch-trigger probe [16,17], 3D probe-ball [11,18], Capball [19], Laser tracker [20] and Double ball bar [21,22]. Among these instruments, ball bar is widely used either in industry or in laboratory since it has been

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commercialized and adopted by ISO 230-1 [23] as the standard measurement instrument for circular tests.

Existing methods for identifying PIGEs can be classified into two kinds, i.e. model-based methods and pattern-based methods. Theories used for developing the model-based methods include homogeneous transformation matrix (HTM) [13,19], differential motion matrix (DMM) [24,25] and screw theory [22,26–28]. Abbaszadeh-Mir et al. [13] developed a model for identifying PIGEs based on HTM. The model was later adopted by Zargarbashi and Mayer [19] to identify PIGEs through fly measurement with Capball sensor. Fu et al. [24] used DMM to establish a geometric error model by considering the effects of both PIGEs and PDGEs of rotary axes, and then separated PIGEs from the measured results. Yang et al. [22] used screw theory to formulate a generalized PIGEs model, which can be applied to various configurations of five-axis machine tools. Using the reference coordinate system establishment method described in ISO 230-1, Yang and Ding [25] developed a DMM model in the reference coordinate system to ensure that the identified PIGEs are full but un-redundant. The G-codes of the measurement positions needed in the aforementioned methods were calculated by using inverse kinematic models [22,29,30]. The basic idea of these model-based methods is to establish the relationships between the tool tip deviations and the PIGEs. Subsequently, geometric errors are separated by least square algorithm or inverse of Jacobian matrix. It should be noticed that since these methods involve calculating the inverse of least square coefficient matrix or Jacobian matrix, special measurement locations [13,19,22,25] or setup positions [24] should be carefully chosen to avoid the singular problem. In order to solve the singular problem, special methods such as rank analysis method [13] and sensitive analysis method [31] were developed, and this in turn increased the complexity of the procedure for identifying PIGEs.

Ball bar is the most widely used instrument in pattern-based methods. The basic idea is to let the sensitive direction of ball bar be in the radial, axial or tangential direction of rotary axis during the measurement. Then, PIGEs are identified through establishing geometrical relationships between PIGEs and the measured ball bar trajectories. Most of the pattern-based methods need to locate the tool ball in the center lines of rotary axes. Lee and Yang [32,33] identified the PIGEs by conducting circular tests along the center line of rotary axis with two offset values. Xiang et al. [34] identified PIGEs for rotary axes under the condition that only rotary axes are simultaneously controlled. Jiang and Cripps [21] proposed a PIGEs testing method with the help of the extension bar provided by the standard ball bar toolbox. These methods are independent of translational axes, and thus, they are only suitable for part of machine configurations, in which only rotary axes are needed to be controlled. However, as shown in Fig. 1, for some machine configurations that have structural restrictions, the center line of tilting rotary axis is close to the surface of worktable or beneath the worktable. Under this situation, existing methods [21,32–34] are ineffective since the tool ball cannot be placed in the center line of the tilting rotary axis. Therefore, other methods involving simultaneous movements of rotary axes and translational axes have been invented [35–37]. Tsutsumi and Saito [35,36] indicated that PIGEs have close relationship with the eccentricities of ball bar trajectories in both axial and radial directions of rotary axes, and realized identifying PIGEs based on the relationships obtained from simulations. Tsutsumi et al. [37] compared the measurement method based on the Cartesian coordinate system with the method based on cylindrical coordinate system, and concluded that the method established in cylindrical coordinate system can reduce the influence of setup errors.

The aforementioned pattern-based methods, which involve the simultaneous motions of axes, only take the eccentricities of ball bar trajectories into consideration, while the influences of setup errors and angle shift are ignored. It should be noticed that the methods reported in Refs. [32–34] can also be developed to identify PIGEs with the simultaneous motions of rotary axes and translational axes. However, multiple installations of the ball bar are needed, and this will increase uncertainty due to setup errors. For machine tools with structural restrictions, this paper proposes a generalized method to identify PIGEs by comprehensively including eccentricities, angle shift and setup errors. Actual trajectories of ball bar are considered. Only one installation of the measurement setup is needed to establish the identification procedures for both rotary axes, and for each axis, two test configurations are proposed to facilitate measuring and identifying. Fittings are used to mathematically model the actual trajectories and spatial planes of table ball's motion, which are then adopted to formulate the expressions for identifying location and orientation errors. It is not necessary to develop any model for this method, and there is no need to specially select certain measurement positions for the sake of making Jacobian matrix invertible [13,19,22,24,25]. Especially, since the method is to use all geometric information of table ball's trajectories, it is consistent with the actual motion status of machine tools, and thus can be reliably used to identify PIGEs in practice.

This paper is organized as follows. Section 1 introduces the definition of PIGEs for rotary axes. The principles of the PIGEs identification method, including measurement means and analysis of test configurations are given in Section 2. Strategies for identifying PIGEs are detailed in Section 3 together with identification expressions. Verifications and experimental results are given in Section 4, followed by conclusions in Section 5.

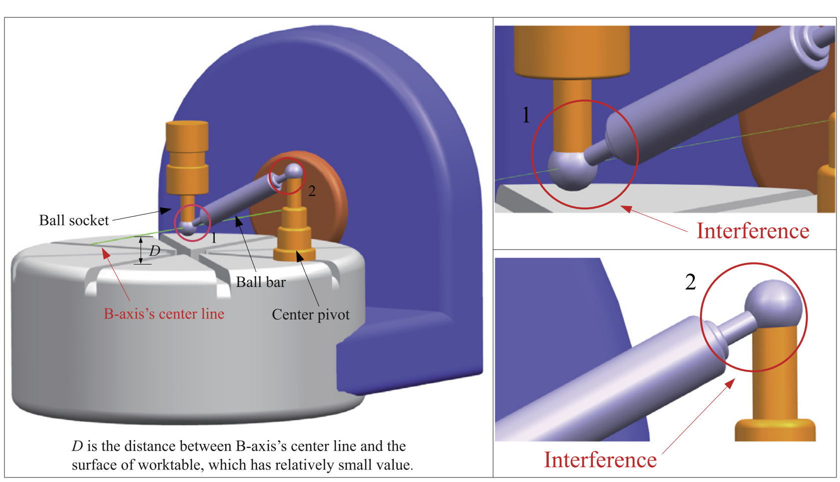

Fig. 1. Structural restrictions of tilting rotary axis of five-axis machine tools.