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Active Design Methodology of Positioning Precision of Machine Tools

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Abstract: Specification of machine precision is an important part of the design specifications and is essential to machine tools. Conventionally, the precision specification is generally conducted based on empirical experiences of machine tool manufactures. This may results in a failed design for insufficient precision specification, or a cost-ineffective design for over specification that will unnecessarily increase manufacturing cost and difficulty. To give a precise estimation of the cost-effective precision specification, an innovative machine tools positioning precision active design methodology is proposed to determine the cost-effective precision specification of machine tools derived from the machining precision requirements of the work-piece. The methodology consists of six steps: (1) characterization and selection of formation methods of workpiece features, (2) determination of motion axes and layout of machine tools, (3) modeling of workpiece surface formation in terms of the machining principle of the machine tool, (4) machining error modeling based on the machining model by considering geometric and axial positioning errors of the machine tool, (5) machining precision modeling based on the machining error model in terms of the geometric and axial positioning precision of the machine tool, and sensitivity analysis based on the machining precision model to determined the weights of the machine tool precision indices to machining precision, and finally (6) allocating the machining precision into machine tool geometric and axial positioning precision.

Introduction

Machine tool design starts from determination of design specifications. Among the design specifications precision is an important item and is essential to machine tools. Insufficient precision specification will cause design failure, while over sufficient precision specification will unnecessarily increase manufacturing cost and difficulty. Therefore cost-effective precision specification of machine tools should be critically determined based on specific requirements.

It has been well understood that precision of machine tools is the combined effect of the stiffness and thermal response of the structure, the precision of the main spindle, the slide ways and the servo drives, of machine tools [1]. In the last decades, many researches have been conducted on the precision of machine tools. Schellekens [2] summarized the rules and principles concerning dimensional metrology, kinematic design, thermal loop, structural loop, metrology frame, drive offset, force compensation, symmetry and repeatability in design for precision.

It is always necessary to enhance the precision of machine tools for manufacturing of precise mechanical components. Error compensation and error elimination are two basic methods for enhancing the precision of machine tools. Ramesh [3] and Ni [4] reviewed error compensation in machine tools, including source of error, methodology of error elimination, modeling, measurement and compensation of geometric or kinematic errors, cutting-force induced errors, and thermal errors. Chen [5] developed a computer-aided error compensation scheme to enhance the accuracy of multi-axis CNC machine tools by compensating the geometric errors and thermal errors. Wang [6] proposed an error prediction and compensation system composed of an interpolation algorithm based on shape functions and developed a practical error compensation system incorporated with an automatic NC code identifying system to increase the accuracy of multi-axis machines. Tsutsumi [7] presented an algorithm to identify and compensate the positional and angular deviations in 5-axis machining centers on the basis of the trajectories of simultaneous three-axis and four-axis control movements. Raksiri [8] proposed a method to compensate the geometric and force errors of a 3-axis CNC milling machine tool based on the nonlinear error compensation model taking into account geometric and cutting force induced errors. Yuan [9] presented a real-time error compensation technique for CNC machining systems, mainly including the general approach for developing real-time error compensation system, formulation of the error synthesis model, mapping of the machine errors, optimal modeling, thermal error mode analysis, optimization of the sensor locations, cutting force-induced error compensation, and compensation control implementation. Lei [10] also presented a real-time error compensation methods for five-axis CNC machine tool based on the error identification model by measuring and estimating the unknown link errors in the rotary block of five-axis CNC machine tools. Choi [11] presented an on-machine measurement and error compensation system to reduce machining errors of a three-axis machine tool using a touch probe. Fines [12] calculated error compensation values for axis positioning of a machine tool with artificial neural networks. Mou [13] presented a systematic approach to enhance machine tool accuracy for precision manufacturing, including modeling and rapid characterizing of the accuracy of multi-axis machines, applications of on-machine sensing and analysis, decoupling of process and machine related errors, and adaptive error correction for more accurate error modeling and compensation. Ouafi [14] presented an approach for improving the accuracy of multi-axis CNC machines by software compensation of geometric, thermal and dynamic errors based on a multi-sensor monitoring system. Zhu [15] presented a method for extraction of repeatable errors from random errors and compensation of the repeatable errors of machine tool component by incorporating statistical analysis of the measured data to improve machine tool accuracy. Fan [16] proposed an MBS based universal kinematics error modeling and analysis method.

Up-to-date literatures on precision issues mostly focused on precision enhancement of machine tools, no or less concerned the determination of the specification of machine precision. Precision specification is generally conducted by design experience. This may result in cost-ineffective or failed precision specification. To mend such a shortage of machine tool design and to give a precise estimation of the cost-effective precision specification, a methodology named 'active design' is proposed by the authors to determine the cost-effective precision specification of machine tools in terms of the machining precision requirements of work-piece. The term 'active design' means here to make the machine tools actively adapt to or satisfy the machining precision requirement of the work-piece in machine tool design. The methodology consists of six steps: (1) characterization and selection of formation methods of work-piece features, (2) determination of motion axes and layout of machine tools, (3) modeling of work-piece surface formation in terms of the machining principle of the machine tool, (4) machining error modeling based on the machining model by considering geometric and axial positioning errors of the machine tool, (5) machining precision modeling based on the machining error model in terms of the geometric and axial positioning precision of the machine tool, and sensitivity analysis based on the machining precision model to determine the weights of the machine tool precision indices to machining precision, and finally (6) allocating the machining precision into machine tool geometric and axial positioning precision.

Methodology

The idea of active design of positioning precision of machine tools is to determine the precision specification of machine tools in terms of the precision requirement of the work-piece to be machined based on the machining principle, especially for the case that the work-piece surface is formed with complex principle such as conjugative generation of gear surfaces.

As current work is focused on determination or design of the axial positioning precision specification of machine tools, following preliminary assumptions are made to simplify the problem definition: Omit elastic, thermal deformation and geometric errors of the machine tools, and the installation errors and geometric errors of the work-piece to be machined. This means the machine tool and the to be machined work-piece are ideal except that there exist axial positioning errors of the axes of the machine tool. A schematic illustration of the methodology is shown in Fig.1, which consists of following steps.

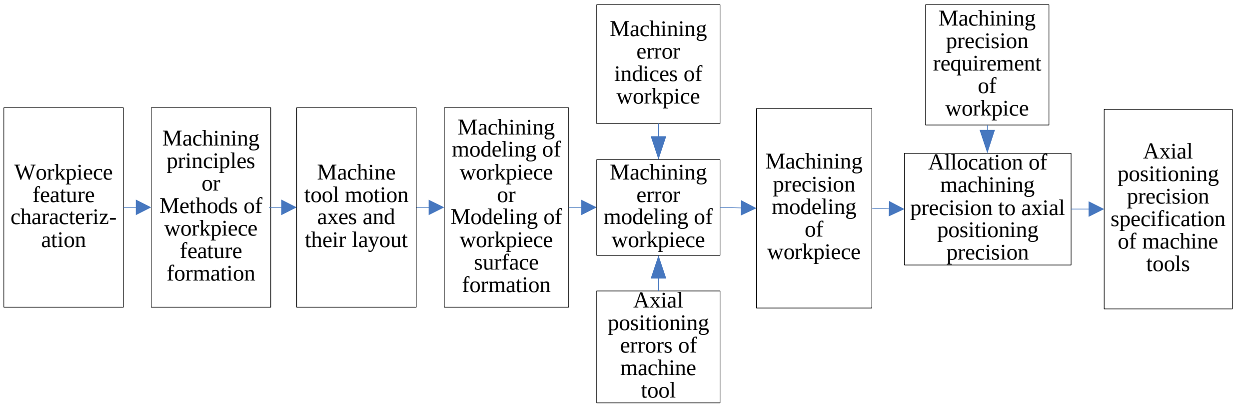

Fig.1. Schematic illustration of the methodology

Characterization Selection of Formation Methods of Work-piece Features

Machining is to generate new expected surfaces on the work-piece with desired precision by removal of material. According to geometry principles, a work-piece is composed of basic geometric features. The work-piece surface is a Boolean sum of surfaces of the features. Formation methods or machining principles can be selected by characterization of the features. For example, an involute gear tooth can be machined by shaping or generating method of machining.

Motion Axes and Layout Determination of Machine Tools

To form the work-piece features with the selected formation methods, there must be surface forming motion and feeding motion of the machine tool. The surface forming motion and the feeding motion can be realized by independent motions or compound motion of the axes of certain layout. By analyzing the surface forming motion and the feeding motion, the motion axes and layout of the machine tool can be determined. For example, in machining of spur gear by gear generating in a pinion-shaped gear cutter, a compound forming motion of rotation of the work-piece and the pinion-shaped gear cutter, an independent forming motion of axial stroke moving of the cutter, and a independent radial feeding motion of the cutter are needed.

When Steps 1 and 2 are finished, a conceptual design of the machine tool can be derived. More often, there already exist specific machine tools for machining features. In such cases, the active precision design can be started directly from Step 3.

Modeling of Work-piece Surface Formation

When the motion axes and layout of the machine tool are determined, coordinate frames can be set up, such as the machine coordinate frame $\sum_m$ and the work-piece coordinate frame $\sum_w$. By transformation of the coordinates of a point on the cutter from the machine coordinate frame to the work-piece coordinate frame in terms of the work-piece surface formation mechanism, a corresponding point on the work-piece is acquired. A set of all corresponding point constitute the surface of the work-piece feature. The surface of the work-piece feature, $\boldsymbol{r}_w$ can be modeled in the work-piece coordinate frame $\sum_w$ as a function of the machine motions $\boldsymbol{x}_m$.

$$\boldsymbol{r}_w = \boldsymbol{r}_w(\boldsymbol{x}_m) \tag{1}$$

Modeling of Work-piece Machining Error

By introducing positioning errors of the motion axes $\Delta\boldsymbol{x}_{\mathrm{m}}$ into Eqn. (1), a machined surface with error can be obtained. The machining error of the work-piece surface can be approximately expressed as

$$\Delta\boldsymbol{r}_{\mathrm{w}} = \Delta\boldsymbol{r}_{\mathrm{w}}(\boldsymbol{x}_{\mathrm{m}}, \Delta\boldsymbol{x}_{\mathrm{m}}) \approx \frac{\partial \boldsymbol{r}_{\mathrm{w}}}{\partial \boldsymbol{x}_{\mathrm{m}}}\Delta\boldsymbol{x}_{\mathrm{m}} = \boldsymbol{K}_{\mathrm{m}} \cdot \Delta\boldsymbol{x}_{\mathrm{m}} \tag{2}$$

Generally the components of $\Delta\boldsymbol{x}_{\mathrm{m}}$, $\Delta x_{\mathrm{m}i}$ (i = 1,2,…,n; n is the number of the axes of the machine tool.) are independent of each other and are normal distributed. In term of the principle of error synthesis, variance of the machining error, σ_{w} will be

$$\sigma_{\mathrm{w}}^2 = \sum_{i=1}^{n} K_{\mathrm{m}i}^2 \sigma_i^2 \tag{3}$$

where σ_i is the variance of positioning error of axis i, $\Delta x_{\mathrm{m}i}$.

Modeling of Work-piece Machining Precision

In terms of the six-sigma (6σ) principle, machine precision of work-piece, A_{w} (maximum of absolute value of error) can be defined as

$$A_{\mathrm{w}} = 6\sigma_{\mathrm{w}} \tag{4}$$

In terms of International Standard ISO 230-2:2006(E) of "Test code for machine tools —Part 2: Determination of accuracy and repeatability of positioning numerically controlled axes", the positioning precision of a motion axis when the system error is calibrated to zero, A_i can be defined as

$$A_i = 2 \times 2\sigma_i \tag{5}$$

Substitute Eqn. (4) into Eqn. (3), then relationship between the machining precision of the work-piece A_{w} and the positioning precision A_i of the axes is

$$A_{\mathrm{w}}^2 = \frac{9}{4}\sum_{i=1}^{n} K_{\mathrm{m}i}^2 A_i^2 \tag{6}$$

Allocating of Machining Precision to Axial Positioning Precision

By reference of the principle of equal effects [32-34] of tolerance allocation, assuming the positioning precisions of the motion axes follow such relationships as

$$K_{\mathrm{m}i}^2 A_i^2 = K_{\mathrm{m}j}^2 A_j^2 \quad (i \neq j) \tag{7}$$

Substitute Eqn. (7) into Eqn. (6), then the positioning precision A_i of motion axis i of the machine tool is

$$A_i = \frac{2A_{\mathrm{w}}}{3\sqrt{n}\left|K_{\mathrm{m}i}\right|} \tag{8}$$

When finishing this step, the positioning precision specification is acquired. As some other errors as geometric error, elastic and thermal deformation of the machine tool, are omitted in the modeling of work-piece machining error, the results of the current modeling only give a reference limits of positioning precisions of the motion axes. A safety discount should be taken on the acquired positioning precision specification when used to machine tool design.

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