Innovative accuracy design of in-site precise automatic inspecting machine of valve sleeve bore of aeronautical precision coupling

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Abstract. The diameter accuracy and geometric accuracy of the valve sleeve bore of aeronautical precision coupling are both high. It is necessary to inspect the bore diameter and cylindricity error frequently in machining, but there is a lack of in-site high accuracy and low cost automatic inspection methods currently. The scheme and accuracy design of a precise automatic inspecting machine (PAIM) of valve sleeve bore is carried out. Accuracy design of PAIM by traditional error distribution method fails to meet the requirement of measurement accuracy. Based on the idea of error avoidance and TRIZ technology system evolution theory, an innovative accuracy design method by using automatic dynamic disconnected measuring chain is proposed and realized. Accuracy analysis and experiment prove the correctness and validity of the proposed method.

1. Introduction

Valve sleeve is the component of Aeronautical precision coupling, whose bore consists of multiple sections of discontinuous internal cylindrical surface, and axial width of each section is less than 3mm. It’s narrow, small and deep. The tolerance grade of the valve sleeve bore diameter is higher than IT7, and its cylindricity tolerance is less than 1μm. Precision automatic measurement of valve sleeve bore is an important subject in bore machining and inspection. The measurement of small and micro internal scale is a new project in precision measurement field, which requires solving the problem of measuring accessibility and measurable depth in a certain level of measurement accuracy and range [1]. A tendency of precision machining is to develop in-site high accuracy and low cost inspecting device [2]. For the size and form error at any section of small bore in a certain depth, there is no effective measurement method presently. The goal of this paper is to explore a low cost solution of in-site precision automatic inspecting machine (PAIM) of valve sleeve bore.
Firstly scheme of PAIM based on pneumatic measurement is briefly introduced, and then accuracy design is intensively discussed. Accuracy design of PAIM by traditional error analysis and error distribution method fails to meet the requirement of measurement accuracy. Based on the idea of error avoidance and TRIZ technology system evolution theory, an innovative accuracy design by using automatic dynamic disconnected measuring chain of PAIM is proposed and realized.

2. Measurement method and scheme of PAIM

2.1. Measurement method

The measuring accuracy of on-line inspecting system mainly depends on the accuracy of the machine tool itself, but the accuracy of the grinder is difficult to meet the requirement of the measuring accuracy of valve sleeve bore. Because of the limit of geometric structure space of valve sleeve bore, it is difficult to implement on-line inspection in horning and grinding. Thus in-site inspection strategy is correct and reasonable choice. After the comparison with various methods from the aspects of aperture measuring range, accessibility, accuracy, and environmental suitability, it is found that pneumatic measurement is most suitable for in-site high precision automatic measurement of small bore [3, 4]. Pneumatic measurement can meet the requirement of measuring accessibility and accuracy of the valve sleeve bore. Thus pneumatic measurement is most adoptable for the measuring principle of PAIM. CAG2000 type electronic column gas-electric micrometer is used as the pneumatic instrument of PAIM, its measuring range is 0.05mm, resolution is 0.5μm, and measuring accuracy is 0.2μm.

Besides the pneumatic instrument body, pneumatic measuring probe is also a key part of pneumatic measurement system. It usually has a big length-diameter ratio for small diameter deep bore, and is also called pneumatic measuring rod. Cylindrical and rectangular are common shapes of measuring nozzle of pneumatic measuring rod. The measured surface of valve sleeve bore is too narrow to be measured by cylindrical nozzles, but only by rectangular nozzles. Since the pneumatic measuring probe with opposite nozzle structure is often used for bore diameter, pneumatic measuring rod with opposite rectangular nozzles with 0.4×1.5mm is adopted in PAIM design [4]. The opposite nozzle on the pneumatic measuring rod is used as both a probe and an aiming device in pneumatic measurement. Axial aiming is used to determine the axial positions of measured cross-sections of workpiece, and radial aiming is used to determine the positions of measuring points in circumferential direction of the measured bore in the same cross-section.

2.2. Mechanism scheme of PAIM

PAIM can be used to measure the diameters and cylindricity error of the valve sleeve bore. Bore diameters can be measured directly and the cylindricity error can be approximately replaced by measuring roundness and taper. According to the requirement of automatic measuring function and referring to the motion scheme of deep bore machining machine tool, the mechanical mechanism of PAIM is designed [4-6] and shown in figure 1.

Pneumatic measuring rod 5 is mounted on supporting bracket 6, and supporting bracket 6 is mounted on slider 7 of precision linear module used for straight motion of the pneumatic measuring rod along Z coordinate axis.
3. Error analysis and distribution of PAIM

3.1. Error analysis

Ideal position relation between the pneumatic measuring rod and the workpiece is shown in figure 2.

Because of the influence by machining error, installation error and adjustment error of the mechanical mechanism and the pneumatic measuring rod of PAIM, the position relation between the pneumatic measuring rod and the workpiece is not ideal practically, but rather the position error of the pneumatic measuring rod exists. The position error of pneumatic measuring rod is a main error in the measuring chain of PAIM [4]. Although PAIM has many error sources, such as pneumatic instrument body, pneumatic measuring rod, mechanical mechanism, measuring standard part and environment condition, only the position error of the pneumatic measuring rod and the geometric error of the mechanical mechanism are closely related to the function scheme of PAIM. A feature of pneumatic measurement is that, the geometric error of the mechanical mechanism leads to the position error of the pneumatic measuring rod, which will affect the gap between the workpiece and the pneumatic measuring rod and result in pneumatic measurement error.

It should be noted especially that, when the workpiece hangs on the pneumatic measuring rod by self-weight, pneumatic measurement error caused by the position error of the pneumatic measuring rod can be ignored [7-9]. It provides a new idea and basis for innovative accuracy design of PAIM.

3.2. Error distribution

In accuracy design of PAIM, traditional measurement error distribution method is used firstly. It’s assumed that only the pneumatic instrument, error the straightness error of guide-slider pair, the radial
run-out component of spindle rotation error and the centering error of the clamp are considered. The combined error after error distribution should satisfy
\[
\delta_0 + \delta_1 + \delta_2 + \delta_3 \leq \delta_{\Sigma}
\]  
(1)

Where \(\delta_0\) is the pneumatic instrument error, \(\delta_1\) the straightness error of guide-slider pair, \(\delta_2\) the radial run-out component of spindle rotation error, and \(\delta_3\) the centering error of the clamp. \(\delta_{\Sigma}\) is the total measuring error of PAIM.

As noted before, the diameter tolerance of a certain type of valve sleeve bore is 0.015mm, and the cylindricity tolerance 1μm. Since PAIM will be used to measure the diameter and the cylindricity error, the instrument measurement accuracy must be determined by the cylindricity tolerance. The Total measuring error of PAIM should not exceed 1/3 of the tolerance of the measured parameter, and is 0.3μm, i.e. \(\delta_{\Sigma}=0.3\mu m\). The measuring accuracy of CAG2000 type pneumatic instrument is 0.2μm, i.e. \(\delta_0=0.2\mu m\), then the sum of the other three errors is only 0.1μm. Following the equal action principle, the error distributed to each item is only about 0.033μm. Even if the spindle rotation accuracy, guide accuracy and clamp centering accuracy are raised to present top technical level, it is difficult to reach the total measurement accuracy of PAIM. Obviously accuracy design of PAIM cannot perform by traditional error distribution method. Based on TRIZ theory, a serious technical conflict exists in accuracy design of PAIM. The shackles of traditional accuracy design method must be taken off, and innovative accuracy design method must be explored.

4. Innovative accuracy design of PAIM

4.1. Composition of automatic dynamic disconnected measuring chain

The principle of error avoidance employs certain technical ways to reduce, eliminate and avoid the influence of error sources on measurement system, and to make error sources ineffective under certain conditions [10]. Different from traditional accuracy design, it emphasizes active design, manipulation and avoidance of errors. To solve the technical conflict in accuracy design of PAIM, an innovative accuracy design method based on the idea of error avoidance is proposed. Its basic idea is to avoid the influence of error of PAIM on the measurement by using automatic dynamic disconnected measuring chain. The mechanical mechanism transmission chain i.e. measuring chain corresponding to the scheme of PAIM is shown in figure 3(a).

As seen from figure 3(a), the measuring chain of PAIM corresponding to the function scheme only has seven composition rings, which includes pneumatic measuring rod, supporting bracket, slider-guide, bed, column, spindle and clamp/workpiece, which conforms to the principle of the shortest measuring chain and has Minimum number of error sources.

After the mechanism and function scheme of PAIM is determined, the measuring chain and its composition rings are usually all fixed, and they will not change even in working process. Based on...
the idea of error avoidance, an automatic dynamic disconnected measuring chain is proposed and established, which means that, partial composition rings of measuring chain of PAIM can be disconnected under certain conditions by automatic control in measuring process to avoid the errors of these composition rings. The number of composition rings of the measuring chain of PAIM will change dynamically with different working state and measuring action. The measuring chain in non-measuring state is shown in figure 3(a), and new measuring chain in automatic measuring state after partial composition rings are disconnected is shown in figure 3(b).

4.2. Realization of automatic dynamic disconnected measuring chain

The realization of automatic dynamic disconnected measuring chain is essentially to increase its dynamics and controllability. Based on one of the technology evolution patterns of TRIZ technology system evolution theory, by improving the flexibility, mobility, controllability and stability of the system structure, the system will evolve towards increasing dynamics and controllability [11, 12]. The evolution of the measuring chain of PAIM should be from fixed to flexible.

Composition rings of measuring chain of PAIM can be divided into static joint of mechanism and kinematic pair. Composition rings of static joint type include pneumatic measuring rod, supporting bracket, bed and column. To increase the dynamics and controllability of the measuring chain of PAIM, it is impossible to change the working state of the static joint of mechanism automatically. The breakthrough can only be found from the composition rings of kinematic pair type. Composition rings of kinematic pair type include spindle, guide-slider pair and clamp. Although the rotation motion of the spindle and the linear motion of the guide-slider pair are dynamic and controllable, they cannot make the measuring chain automatically disconnect. To realize automatic disconnection of the measuring chain and to increase the dynamics and controllability of the mechanism, the clamp can be only chose. Based on aforementioned TRIZ technology evolution pattern, the technology evolution route of the clamp is obtained as shown in figure 4.

![Figure 4. Technological evolution route of the clamp.](image)

The highest evolution state is field, but there is no some kind of field with advanced principle and mature technology to be used to design clamp currently. Thus a relatively advanced evolution state, that is, pneumatic form is adopted to realize the dynamics and controllability of the clamp. Since it’s
easy to realize automatic control of the working state, pneumatic mechanism is used to replace mechanical clamping mechanism. Because of its simple structure and high repeatability, pneumatic finger is adopted as the clamp to enable the measuring chain of PAIM to be disconnected automatically in measuring process. Thus fixed measuring chain can evolve into flexible automatic dynamic disconnected measuring chain. Only when the pneumatic finger is loosened and the measuring chain is disconnected, can PAIM be in automatic measuring state.

4.3. Accuracy analysis

When pneumatic measurement is taken after the measuring chain is disconnected, composition rings of the measuring chain of PAIM, such as the rotary spindle, the pneumatic finger, and the guide-slider pair do not affect the position relation between the pneumatic measuring rod and the workpiece, only the pneumatic measuring rod can influence the pneumatic measurement. As noted before, when the measuring chain is disconnected, the workpiece hangs on the pneumatic measuring rod by its self-weight and remains a relative static state, and then the pneumatic measurement error caused by the position error of the pneumatic measuring rod can be ignored [7-9]. Thus the influence of the position error of the pneumatic measuring rod and the errors of all other composition rings such as the spindle rotation, the guide-slider and the clamp on the pneumatic measurement can be both avoided completely. Thus the influence of all these error sources on pneumatic measurement accuracy is equal to zero except for pneumatic measuring rod and the pneumatic instrument body. The total measurement accuracy of PAIM basically depends on the pneumatic measurement. When high accuracy pneumatic instrument is selected and the pneumatic measuring rod is correctly designed and fabricated, the measurement accuracy of PAIM can be guaranteed. Besides, after the measuring chain is disconnected, the measured workpiece and the pneumatic measuring rod are always in an isoline contact, which can ensure the consistency and repeatability of their position relationship, and then the repeatability of PAIM can be guaranteed. In this way the dynamic automatic measurement by PAIM is essentially converted into a quasi-static pneumatic measurement. It can not only avoids the error caused by composition rings of measuring chain, but also reduce the dynamic measurement error of pneumatic measurement, thus the total measurement accuracy is ensured. The experimental results also show that proposed and designed PAIM can meet the requirement of high measurement accuracy of the valve sleeve bore.

5. Conclusions

(1) An innovative accuracy design method of PAIM of valve sleeve bore of aeronautical precision coupling based on the idea of error avoidance is proposed.

(2) Based on TRIZ technology system evolution theory, the automatic dynamic disconnected measuring chain is designed, and the pneumatic finger is used to realize automatic switching of the measuring chain. Accuracy analysis shows that, by this method the influence of the position error of the pneumatic measuring rod and the errors of all other composition rings to the pneumatic measurement accuracy can be completely avoided. The total measurement accuracy of PAIM only depends on the pneumatic measurement accuracy.

(3) The proposed and designed PAIM has been used in grinding production field. The experimental result shows that it can realize in-site precise automatic inspection of the valve sleeve bore of aeronautical precision coupling, and can reach high measurement accuracy.

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