Online detection method for holes co-axiality of aero-engine

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Abstract. In recent years, the requirement for the assembly performance of aero-engine is getting higher in the aviation field. As the key indicator which can affect engine performance, the demand of detection accuracy of rotor bearing holes’ coaxial error is increasing. In the engine’s assembly process, the traditional manual mechanical detection cannot measure the assembled holes’ coaxiality directly, and must be carried out by the fixed tools after the trial assembly. This results in the long assembly time, low productivity, and low detection accuracy. An online detection method which can better ensure the products’ assembly quality must be proposed. Based on the analysis of the related research status of coaxiality detection at home and abroad, combined with the laser alignment technology and the axle hole centering measurement technology, an online measurement method based on the laser alignment is proposed, and a coaxiality detection system of the turbofan engine for specific models is introduced, whose centering error is less than 4μm. Besides, a universal coaxiality detection method of the engine rotor shaft hole is obtained, which could optimize the assembly process and improve the assembly efficiency.

1. Introduction
The rub-impact of rotors and stators, the excessive unbalanced quantity of rotors, and the loose back-up bearings all belong to inducing factors of the engine vibration. Among them, due to the unqualified coaxiality of engines, the rub-impact of rotors and stators leads to the vibration fault, which accounts for a very high proportion of the total engine failures. [1, 2] Therefore, the coaxiality is an important indicator affecting the quality of engines, and reducing the coaxiality error can improve the running quality of engines.

In the overall assembly process of the engine, the efficiency and precision of the traditional manual mechanical inspection is quite low, which cannot meet the higher quality requirements. In contrast, the coaxiality test of the assembly could better ensure the assembly quality of the product. At present, the major assembly coaxiality measurement techniques include the CMM (Coordinate Measuring Machine) measuring technique, the laser displacement sensor measuring technique, and the image measuring technique [3]. Each of them has advantages and disadvantages, and can meet the assembly coaxiality measurement requirements of general hole-like parts basically. However, for the high-precision measurement of the assembly coaxiality of porous parts with the large span, the existing measurement method needs to change the measuring basis repeatedly, and it is difficult to achieve the accurate measurement under the condition of the same reference. Moreover, when the coaxial error of porous parts with the large span is measured by means of the traditional coaxiality measurement, there are practical difficulties such as the selection of the evaluation criteria, the manufacturing of...
measuring implements with the large distance, and the installation of test devices, which affect the measurement accuracy of the coaxial error of large-span parts. Therefore, it is of great practical significance to explore the high-precision measuring method of porous large-span parts’ co-axiality to ensure that the engine maintains good operating performance.

The construction of the datum axis is very important in the co-axiality measurement. The traditional co-axiality measurement can be roughly divided into the mechanical alignment method, the traditional optical alignment method and the laser alignment method [4]. The mechanical alignment method is shown in Figure 1. The steel wire or gauge is usually used as the reference. The steel wire itself will have a certain deflection deformation, and the gauge is susceptible to develop the abrasion under the long-term use, which cannot meet the high-precision measurement requirements.

![Figure 1. Mechanical alignment method for detecting co-axiality.](image1)

The traditional optical alignment method is shown in Figure 2. This method uses optical visual alignment, and the collimation reference is the instrument’s optical axis. The measurement of the deviation also uses the pure optical-mechanical method [5], which will increase the system measurement errors in different aspects.

![Figure 2. Conventional optical collimation method for measuring co-axiality.](image2)

The laser alignment method uses the laser with good coherence, high brightness and good directivity as the collimated light to hit the photoelectric receiving device, and analyzes the data collected by the photoelectric receiving device to obtain the coaxial error. The laser alignment method can avoid the limitations and errors caused by the visual aiming. The subjective error is small, and the measurement accuracy of the measuring system is high. When using the laser beam measurement, it can be flexibly adjusted in the case where it is necessary to measure while repairing, which won’t damage the reference axis. The system of measuring the co-axiality by the laser alignment method is mainly composed of four parts: the laser device, the photoelectric receiving device, the data acquisition and processing unit, and PC (Personal Computer) [6].

The co-axiality measurement of porous large-span parts has always been the research difficulty at home and abroad. Aiming at the coaxial error of large-scale parts, Guo Zhenying et al. rotate the measuring bar and penetrate it into the hole. Based on the variation of the rod, the change of the aperture works out to obtain the co-axiality [7]. Yuan Zhongwei uses the micro-alignment telescope to reflect the measuring baseline through the optical axis of the telescope, guide the hole machining of large-sized workpieces and measure the co-axiality through the cooperation of special checking tools [8]. With the continuous development of science and technology, some new photoelectric sensors have appeared, such as the PSD (Position Sensitive Detector), CCD (Charge Coupled Device) and COMS (Complementary Metal-Oxide Semiconductor) image sensor [9], which make the laser alignment technology can be used in high-precision coaxial measurement and get the rapid development. The
laser alignment measurement technology uses the laser as the measurement reference axis, and the CCD as the signal receiving sensor, to obtain the position variance of the axle hole’s center line and realize the co-axiality measurement of long length products [10, 11]. Aiming at the co-axiality measurement of deep holes, Wu Bin et al. proposed a kind of hole-hole co-axiality measuring instrument based on the PSD (Position Sensitive Device) and DSP (Digital Signal Processor) technology, and designed a kind of automatic centering mechanism with high practicability and measurement accuracy [12]. Yu Houyun [13] and Lian Qiangqiang [14] also proposed the co-axiality detection system based on the laser and PSD for the measurement requirements of large-span hole series’ co-axiality, and designed the corresponding self-centering multi-function measurement to meet the measurement requirements. The repeated accuracy and non-linear error of the measurement system can be eliminated to an extreme through experiments after determining the position sensor, auxiliary circuit and measurement environment [15]. The non-linear error can be optimally controlled based on the actual measurement requirements, with the accurate machine construction and lots of data processing algorithm [16].

The laser alignment measurement method is mostly based on the test condition of the ideal hole series. However, there are many parts and complicated technological processes in the final assembly process of the turbofan engine to be detected, and the on-line detection for the final assembly process cannot be realized on the basis of the general method. In order to solve the problems of existing measurement methods, improve the finished product ratio of assembly and raise the measurement efficiency, this paper proposes a kind of detection method based on the laser auto-collimation. This method converts the position information of the holes’ center line into the spatial coordinates, and then uses the least square fitting method to obtain the on-line measurement scheme of the co-axiality.

2. The design of detection system

In order to ensure the good working performance of the assembled engine, the co-axiality detection of the stator’s shaft hole is essential during the trial or final assembly of the turbofan engine. This co-axiality detection scheme is designed for the co-axiality measurement of the turbofan engine’s shaft hole. In the practical engineering application, the detection process mainly has problems such as the distribution distance of the holes to be tested is large and the detection process cannot cooperate with the assembly process. The co-axiality of the assembled shaft hole cannot be measured by the existing universal detecting instruments, but must be measured by the fixed tools after the trial assembly. This results in the long time consumption and low productivity.

Based on the modular design idea, it is necessary to meet the needs of the final assembly in the actual production while compacting the overall structure. When designing the overall scheme of the detection system, the various detection schemes designed should be analyzed, and the optimal structural form needs to be designed minutely and optimized finally.

2.1. Overall functional requirements of the detection system

The detection system is oriented to the final assembly process of the turbofan engine, it requires the function of stable clamping and reliable position control of the overall engine. Considering the pre-calibration of the positional relation between the auto-collimation laser beam, the corner cube prism and the engine in this system, it is necessary to give the auto-collimator the adjustable degree of freedom. The co-axiality detection process is combined with the final assembly process, and the detection system device does not interfere with the assembly system device.

The detection system device is oriented to the coaxial error detection of the stator’s shaft hole series with a span of 420 mm or 190 mm and a hole diameter of 79 mm, and its detection accuracy is better than 0.04 mm. Since the inspection process needs to be coordinated with the engine’s overall assembly process, the overall structure of the detection system is required to be compact and arranged reasonably to ensure overall rigidity. In order to ensure that the final co-axiality detection accuracy is better than 0.04mm, the manufacturing error of the centering mechanism is not more than 0.01°, and the ball screw’s positioning accuracy of each motion shaft is ±2μm/50mm.
2.2. Structural design of the detection system
The overall design of the detection system begins with a reliable basis for the moving parts and the mechanism arrangement. A granite platform with the homogeneous texture and good stability is selected as the whole device’s pedestal to ensure the overall stability of the system. The auto-collimation and the CCD rely on the stand column with the hollow cast structure, which has the large dynamic stiffness and damping and the stable and reliable structural machinability.

The detection system device is shown in Figure 3. It is mainly divided into the auxiliary unit (the stand column, sliding table and junction plate), measuring unit (the three-claw self-centering device, micro guide rail, CCD, corner cube prism, etc.) and engine clamping unit (the base, X displacement platform, rotary table, motor, tray, etc.)

![Figure 3. The structure schematic of the measurement system.](image)

A reliable clamping environment for the specified model of engine is required for the coaxial measurement. The clamping unit’s main function is to meet the requirements of the station and assembly during the engine’s assembly process. The guide rail and the lead screw need to be designed reasonably to meet the linear-displacement requirement in the assembly process, the rotary table is selected to meet the rotational degree-of-freedom requirement in the assembly process. The hollow rotary platform is used as the turntable, which needs to have the good loading capacity and high positioning accuracy. The bottom of the engine has a special structure, and a tray is designed to bear the weight of the assembled engine, which will perform different operations along with each station in the assembly process. The structure of the clamping unit is shown in Figure 4:

![Figure 4. Clamping unit.](image)

According to the system design requirements, the final detection accuracy should reach 0.04mm, and the selection of each moving component is based on the realization of the expected motion index.
The Yaskawa servo motor drives the X displacement platform, which connects and drives the precise ball screw by the coupling, in order to achieve the horizontal movement with the THK precise guide rail. The main components’ performance indexes are shown in Table 1.

| Parameter                        | Value          |
|----------------------------------|----------------|
| Motor                             |                |
| Rated torque (N·m)               | 5.39           |
| Moment of inertia (kg·m²)         | 13.9×10⁻⁴      |
| Repeatability of the ball screws (mm) | ±0.01       |
| X moving stage                    |                |
| Parallelism of the guide rails (µm) | 3.5           |
| Turning torque (N·m)              | 21             |
| Repeatability (arc sec)           | ±15            |
| Conceticity (µm)                  | 15             |
| Rotary table                      |                |

The auxiliary unit’s function is to fix the auto-collimation and CCD of the measuring unit and provide Z-direction freedom of movement for the system calibration. In order to adapt to the height of the engine, the stand column with the structural stability is designed as the strutting piece, and the Z-direction movement is realized by the precise ball screw and the guide rail. The guide rail’s parallelism of the THK precision ball screw is 3µm, and the lead screw’s positioning accuracy is ±0.01mm. According to the functional design requirements and the positional relationship of each component, the auxiliary unit is shown in Figure 5.

![Figure 5. Schematic diagram of the auxiliary unit.](image)

The measuring unit is the main part of the system. In order to measure the co-axiality, this unit uses the auto-collimation’s laser beam as the measuring basis, determines the center of the hole to be tested by the self-centering device, and reflects the positional relationship between the hole’s center and the reference by the corner cube prism. It includes the auto-collimation, PSD, corner cube prism and self-centering device. The self-centering device is a key part of the measuring unit, it mainly consists of the main body cover, centering cone, centering cylinder, steel ball, sleeve, forward and reverse lead screw, torque motor, corrugated pipe coupler and limit screw. The self-centering device structure is shown in Figure 6. During the measurement, the self-centering device is inserted into the hole, the torque motor drives the lead screw to rotate, and the lead screw dislodges the cone, which will push the centering cylinder to extend. When all the steel balls touch the hole wall and have a certain force, each claw of mechanism gets in contact with the hole wall to achieve the self-centering effect. After the self-centering device gets inserted into the hole, remains stationary and achieves the self-centering, it can be considered that the measured aperture’s center is the center determined by the device. Through the
calibration before measurement, the position relationship between the corner cube prism’s center and the center determined by the device is obtained, so that the coordinate value of the hole’s center is obtained indirectly using the laser signal coordinate value of the PSD.

![Corner cube prism diagram](image1)

**Figure 6.** The self-centering device in the detection unit.  
(a) Outline; (b) Internal structure

When measuring the co-axiality, the laser is projected onto the corner cube prism. Then, the laser beam returned by the corner cube prism is received by the PSD, which experts the coordinate value of the laser. The transformation of coordinates is used to obtain the coordinate value of the corner cube prism’s center in the absolute coordinate system built with the laser. By calibrating the known center determined by the self-centering device and analysing the relationship between the hole’s center and the corner cube prism’s center, the coordinate value of the hole’s center can be indirectly obtained in the absolute coordinate system. After all the holes have been measured, the co-axiality of all the holes is obtained by unifying the coordinate values of all the holes to be tested in the same absolute coordinate system and fitting out the least squares line.

2.3. The working principle of the measuring device

Before the measurement, the relative position posture of the self-centering device and the autocollimation needs to be calibrated to obtain the positional relationship between the PSD center and the center determined by the device. During the measurement, the engine components are placed on the tray in order of the final assembly. After clamping each shaft hole, adjust the Z-direction height of the PSD holding device to make the centering device protrude into the hole, and control the torque motor to drive the self-centering device to achieve the self-centering and fixation. After the centering device and the shaft hole are fixed, the PSD outputs the laser signal’s position coordinates, and the laser signal coordinates of the three shaft holes are measured. The height coordinates are obtained through the linear scale. The PSD center, the device center, the laser signal coordinate and the height coordinate which are calibrated before the measurement are input into the absolute coordinate system, and the co-axiality is fitted out by means of the coordinate transformation and the least square method. The working principle of the measuring device is shown in Figure 7.

After the transformation of coordinates, a series of hole cores’ coordinate values measured by the system are represented as \( O_t(x_i, y_i, z_i), i = 1, 2, \ldots n \) in the absolute space coordinate system, and \( n \) is the number of measured shaft holes.
Figure 7. The working principle of the measuring device.

Select the vertical measurement method, set the intersection of the least square line $L$ and the coordinate plane $XOY$ to $O_0(x_0, y_0, 0)$, and the direction vector is $(m, q, 1)$, then the equation of the space line can be simplified into

$$\frac{x-x_0}{m} = \frac{y-y_0}{q} = \frac{z}{1}$$

(1)

The required parameters are $x_0, y_0, m, q$.

The equation of a straight line can be simplified to:

$$\begin{cases} x = x_0 + mz \\ y = y_0 + qz \end{cases}$$

(2)

Written in matrix form:

$$\begin{bmatrix} m \\ q \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} \begin{bmatrix} z \end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix}$$

(3)

The equation for the $n$th point when there are $n$ points is:

$$\begin{bmatrix} m \\ q \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} \begin{bmatrix} z_i \end{bmatrix} = \begin{bmatrix} x_i \\ y_i \end{bmatrix}$$

(4)

Contact these $n$ equations to get:

$$\begin{bmatrix} m \\ q \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} \begin{bmatrix} z_1 \ldots z_n \end{bmatrix} = \begin{bmatrix} x_1 \ldots x_n \\ y_1 \ldots y_n \end{bmatrix}$$

(5)

Least squares fitting:

$$\begin{bmatrix} m \\ q \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} \begin{bmatrix} z_1 \ldots z_n \end{bmatrix} = \begin{bmatrix} x_1 \ldots x_n \\ y_1 \ldots y_n \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_n \end{bmatrix}$$

(6)

Simplified into:

$$\begin{bmatrix} m \\ q \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} = \left[ \sum x_i z_i \sum x_i \sum y_i \sum z_i \frac{z_i}{n} \right]^{-1}$$

(7)

Solving the matrix yields $m$, $n$, $x_0$, $y_0$, which are the parameters of the linear equation.

The distance from each measured point to the straight line $L$ is

$$L_i = \frac{|(O_i - O_0) \times S|}{|S|}$$

(8)

$O_i = \{x_0, y_0, z_0\}$, $O_0 = \{x_0, y_0, 0\}$, $S = \{m, q, 1\}$, $i = 1, 2, \ldots, n$

The co-axiality error sought by the system is
3. Analysis of the testing equipment’s stiffness and accuracy

3.1. Analysis of the system stiffness
The designed co-axiality measuring system requires the high measurement accuracy. Considering that the measuring unit is connected to the stand column in the form of a cantilever, the deformation caused by its own weight during the actual measurement has an influence on the measurement accuracy. Therefore, this section analyzes the stiffness of the designed device. Through the structural static simulation of the measuring device, the deformation and stress distribution state of each part in the device are analyzed, and the structural strength and stiffness state of the device are obtained. Then the model is modified in accordance with the engineering practice to meet the strength requirements. In the finite element analysis, it is assumed that all materials of the device are set as isotropic homogeneous elastic materials, and in order to improve the accuracy and speed of the finite element analysis, the model is simplified. The analysis neglects chamfers, rounded corners, threaded holes, unnecessary small parts and other negligible features. The simplified model is shown in Figure 8.

![Figure 8. Simple structural model of the measurement system.](image)

The simplified model is meshed, and the uniform gravity load is applied to the system after adding constraints to the system boundary. The finite element analysis shows the stress map as shown in Figure 9(a), and the strain diagram is shown in Figure 9(b). The finite element analysis results show that the maximum deformation of the structure is less than 4.15μm, where is located at the forefront of the connecting plate cantilever. The maximum stress value is about 0.22kPa, where is located at the root of the connecting plate cantilever. The maximum deformation of the structure is small enough. The auto-collimator and the self-centering device are calibrated during the actual measurement process, and the feedback compensation is adopted in the device. Therefore, the device deformation quantity meets the design requirements.

![Figure 9. Simulation results of the measurement system.](image)

(a) The contours of stress distribution; (b) The contours of strain distribution
3.2. Analysis of the system accuracy

Factors affecting the measurement accuracy in the system include: the self-centering device’s error, PSD setting error, and laser performance error. The measurement results are mainly affected by the self-centering device’s error. The self-centering device is manufactured in accordance with the design requirements of GB/T-6314. The manufacturing precision is \( \delta = 0.01^\circ \), the cone apex angle is \( 2\alpha = 20^\circ \), and the cone horizontal length is \( L = 1.8 \times 10^6 \mu m \), the radial error caused by the manufacturing error of the cone taper \( \Delta_1 \):

\[
\Delta_1 = L \times [\tan(\alpha + \delta) - \tan\alpha] = 18 \times [\tan(20^\circ + 0.01^\circ) - \tan20^\circ] = 3.558\mu m \quad (10)
\]

The apex angle of the cone is \( 2\alpha \), and the error caused by the cumulative error of the screw pitch is:

\[
\Delta_2 = \Delta_1 \tan20^\circ = 3.558 \times \tan20^\circ = 1.295\mu m \quad (11)
\]

The cumulative manufacturing error of the self-centering device is:

\[
\Delta = \sqrt{\Delta_1^2 + \Delta_2^2} = \sqrt{3.558^2 + 1.295^2} = 3.786\mu m \quad (12)
\]

According to the analysis results, the error of the self-centering device in the measurement system satisfies the required centering accuracy.

4. Conclusions

The measurement scheme which could meet the online inspection requirements of the turbofan engine’s final assembly process is designed using the laser auto-collimation technology. A laser with good collimation is used as the ideal axis in this system to ensure the datum features’ stability. The absolute coordinate system is established by the collimated laser and the PSD coordinate system in the measurement, and the coaxial error is further obtained by unifying the metrical data in the absolute coordinate system.

Based on the coordinate transformation method, the initial data in the measurement process is processed preliminarily. In order to feed back the coordinate information of the holes to be tested, the self-centering device cooperates with the corner cube prism to reflect the collimated laser beam signal in the designed detection system. Under the premise of calibrating the positional relationship between the self-centering device and the PSD, based on the coordinate transformation method, the collected coordinate information of the hole to be measured is unified into the absolute coordinate system to obtain the required coordinate data before the co-axiality fitting.

The detection method and detection system can realize the online co-axiality detection for the final assembly process, reduce the random error caused by the manual operation, and effectively improve the engine’s assembly efficiency and quality based on the existing assembly process.

Acknowledgments

The research is supported by the National Natural Science Foundation Joint Fund Key Project (Fund No. U153720042, U173720054).

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