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# Quantitatively evaluate the cylindricity of Large size pipe fitting via laser displacement sensor and Digital twin technology

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**Abstract:** The rapid development of intelligent detection technology guarantees accuracy in the assembly process. Aiming to solve the quantitative inspection of the cylindricity of Large size pipe fitting, this paper presents an online method technology using a laser sensor and Digital twin technology. The detection system comprises visual positioning, servo drive, and laser displacement sensor information acquisition systems. After positioning by the machine vision camera system, the servo system and laser displacement sensor scan the large-size pipe fitting layer by layer and establish the information interaction between physical space and virtual space through digital twinning technology. The digital twin scatters information model was found to calculate the maximum tangent circle and minimum peripheral circle, fitting the curve area of the closed point cloud layer by layer. And the least square method was used to calculate the center of the layered circle. The radial deviation of pipe fitting was evaluated comprehensively. The system makes a linear fitting of the center of the most miniature square circle of each layer, compares its deflection Angle with the solid center line, and calculates the center line deviation of the hole. Finally, the precision of the proposed method was validated by varying experiments. The cylindricity measurement of pipe fittings with an inner diameter of 300mm and height of 270mm was carried out by a pair of C-shaped semicircles fixed by the radial assembly. The cylindricity of the pipe fitting is 0.2372mm.

**Keywords:** Cylindricity; Laser displacement sensor; Digital twin technology; Large size pipe fitting; Machine vision system.

## 1. Introduction

With the high-speed development of sensor technology and digital twin technology, high-precision real-time detection in the online assembly process becomes possible. In this paper, the quantitative evaluation of the cylindricity error in processing large objects is carried out. Cylindricity can be considered as the superposition of three kinds of deviations: radial deviation, centerline deviation, and cross-section deviation. The existing traditional cylindricity error measurement is mainly based on the contact method, which includes a primarily two-point or Three-point method, a cylindricity meter, and a three-coordinate measuring instrument. The measurement accuracy of the two-point and three-point methods is greatly affected by manual operation; when the cylindricity instrument detects the roundness and cylindricity errors, a precision rotary table is required to drive the workpiece to rotate and detect, the three-coordinate measuring instrument is expensive. Moreover, the detection steps are complicated, and the measurement time is long, which is only suitable for measuring a small number of precision parts. The cylindricity of part elements, large or small dimensions, and complex shapes is even more challenging to achieve through traditional tactile measurement methods. Compared with the conventional contact measurement method, the sensor-based non-contact measurement method has the advantages of high measurement accuracy and high measurement efficiency. Typical non-contact measurement methods include laser triangulation, ultrasonic measurement, and machine vision measurement, widely used in the surface measurement of complex parts, shape tolerance measurement, and dimensional measurement of mechanical parts. Gangfeng Xiao proposed an online dimensional accuracy measurement method based on machine vision technology, which realized real-time measurement of straightness and roundness. The real-time image of the conical spinning workpiece is obtained through the image acquisition system, the camera is calibrated, and then a series of image processing techniques such as region of interest (ROI) extraction, image deblurring, denoising, and edge detection are used to extract the conical rotating workpiece the edge of. Finally, the straightness and roundness of the rotating workpiece are automatically calculated by a calculation program. Another device that uses a CCD camera to detect the inner wall of the pipeline was proposed by Moraleda and further developed by Choi. This system can use a pipeline robot crawling along a curved channel to carry a CCD camera and related lighting equipment. The CCD camera captures images of the inner wall in real time and uses manual or computer algorithms to process the captured images to identify defects on the inner wall. Its main technical difficulty and innovation lie in the design of the crawling robot rather than the inner wall detection part. Its disadvantage is that it can only identify and detect surface defects but cannot measure geometric quantities. Japan's TOKUJI OKADA and others use a pipeline robot carrying a closed-circuit television for pipeline inspection. Through experimental tests, we know that the analysis of images in this solution is more detailed, and the judgment is flexible and convenient. Still, there are problems, such as difficulty in automatic pipeline detection and high detection error values. Zhang Maowei et al. established a more comprehensive measurement model based on the two-dimensional linear laser sensor measurement technology, including component eccentricity error e, sensor lateral offset error d, sensor forward tilts error θ(x), and lateral sensor tilts. The error θ(y), and the tilt error of the turntable are modeled and separated step by step. The particle swarm optimization algorithm is used to solve the model error parameters. And through the residual simulation, observe the influence of different levels of offset errors on the measurement results. Kühnel et al. introduced an automated device for non-tactile high-precision measurement of roundness and cylindricity of ring gauges. The measurement system with dual interferometers and workpiece alignment combined with a high-precision turntable and automatic four-axis adjustment unit reduces classic problems in tactile and radial roundness measurements, such as errors in the alignment of the used turntable and workpiece influence, thereby improving accuracy and reducing measurement time.

The concept of the digital twin is widely accepted as a new generation of digital manufacturing research concepts and plays a vital role in the era of Industry 4.0. As the premise of deep application of digital assembly manufacturing, it is essential to collect, model, and utilize historical data of the machining process and detection of parts to provide data support for the whole manufacturing scene. Qiangwei Bao proposed an assembly-oriented digital twin modeling method for details. The design information of the part is obtained from the three-dimensional model through the model-based definition method. But the processing characteristics are defined and identified in advance. Then, the assembly constraint relationship in the assembly units in which the parts participate can be obtained, based on which the deviation transfer analysis can be completed, and the critical assembly features can be screened as the carrier of processing and detection data. JiekangHaw proposed a digital twin-based additive manufacturing virtual part inspection concept. Minghui HU proposed the gas turbine digital twin model and its application in performance fault warning. It combined the machine model and the measured data to build a high-precision performance model. The specific method is to adapt the initial point of the model to make the simulation performance match the actual performance. Then, the relative precision control strategy is proposed to improve the modeling efficiency. And the calculation amount of the model is appropriately reduced to avoid overstimulation and non-convergence. Therefore, the digital twin model obtained will meet the need for higher accuracy and lower cost. Finally, according to the model results, the deviation degree is defined as the warning feature of the gas turbine performance fault. Jinfeng Liu proposed a multi-dimensional modeling method (DT) technique for machining processes. The design and execution stages of the machining process are used to support intelligent machining based on interpreting the modeling and application methods of machining process design, the inspection process, fault diagnosis, and quality prediction based on digital twin technology. The working mechanism of machining process modeling, simulation, prognosis, and control was expounded.

In this paper, the laser displacement sensor is used to scan the inner wall of the pipeline layer by layer, establish the three-dimensional point cloud data, calculate the maximum tangent circle and minimum peripheral circle, fit the curve area of the closed point cloud layer by layer, and calculate the center of the layered process by using the least square method, and establish the digital model layer by layer. The information interaction between physical space and virtual space was established by digital twinning technology. The diameters of the maximum tangent circle and minimum peripheral circle were calculated, and the distribution of diameters was calculated. The radial deviation of holes was evaluated comprehensively. The center of the smallest square circle of each layer is fitted with a straight line, and the deflection Angle between the bar and the actual center line is calculated to calculate the deviation of the middle line of the pipeline. In this paper, the laser displacement sensor is used to scan the inner wall of the pipeline layer by layer, establish the three-dimensional point cloud data, calculate the maximum tangent circle and minimum peripheral circle, fit the curve area of the closed point cloud layer by layer and calculate the center of the layered circle by using the least square method, and establish the digital model layer by layer. The information interaction between physical space and virtual space was established by digital twinning technology. The diameters of the maximum tangent circle and minimum peripheral circle were calculated, and the distribution of diameters was calculated. The radial deviation of holes was evaluated comprehensively. The center of the smallest square circle of each layer is fitted with a straight line, and the deflection Angle between the bar and the actual center line is calculated to calculate the deviation of the middle line of the pipeline.

# 2. Real-time evaluation method of cylindricity error

## 2.1. Evaluation of midline error

The roundness and cylindricity error evaluation methods include the least region method, the least square method, the least external cylindrical method, and the maximum internal-circle column method. In the measuring system, because the least square method is a local optimization algorithm, the calculation is convenient, the program is simple, and the calculation result is accurate. Hence, the author uses the least square method to calculate the scent of the oss-section. Suppose a total of N sections are measured, and M points are uniformly measured for each team. The cartesian coordinates of each end of the actual contour $(x_i, y_i)$, poar coordinates are $(r_i, \theta_i)$ , i=1,2... M, the lmostdiminutivesquare circle center coordinate is $O(a, b)$, then:

$$\begin{cases} a = \dfrac{2}{M}\sum_{i=1}^{M} x_i = \dfrac{2}{M}\sum_{i=1}^{M} r_i \cos\theta_i \\ b = \dfrac{2}{M}\sum_{i=1}^{M} y_i = \dfrac{2}{M}\sum_{i=1}^{M} r_i \sin\theta_i \end{cases}$$

Find the least squares center O of each section in turn, then the center O of space $O(a_l, b_l, z_l)$, $l$ =1,2... N, carry out the least square space linear fitting for the center of the space $O(a_l, b_l, z_l)$.

$$\frac{x - x_0}{m} = \frac{y - y_0}{n} = \frac{z - z_0}{p}$$

By equivalent transformation of this equation, we can obtain:

$$x = \frac{m}{p}(z - z_0) + x_0 = k_1 z + b_1$$

$$y = \frac{n}{p}(z - z_0) + y_0 = k_2 z + b_2$$

Among them, the $k_1 = \frac{m}{p}, b_1 = x_0 - \frac{m}{p} z_0, k_2 = \frac{n}{p}, b_2 = y_0 - \frac{n}{p} z_0$, $(m, n, p)$for the linear equations in the direction of the vector;$(x_0, y_0, z_0)$ is a point on the line?

According to the space line fitted by the least square method, the center line error of the workpiece is calculated.

## 2.2. Minimum region circle fitting

The distance between each point and the center of the circle is calculated according to the section least squares center of the process. The small circle radius $R_{min}$ of the cylindrical surface in the minimum region is the closest distance from the center of all the measuring points, and the large circle radius $R_{min}$ of the cylindrical surface in the minimum region is the farthest distance from all the measuring points to the center of the circle. So, the cylindricity error $\emptyset = R_{max} - R_{min}$.

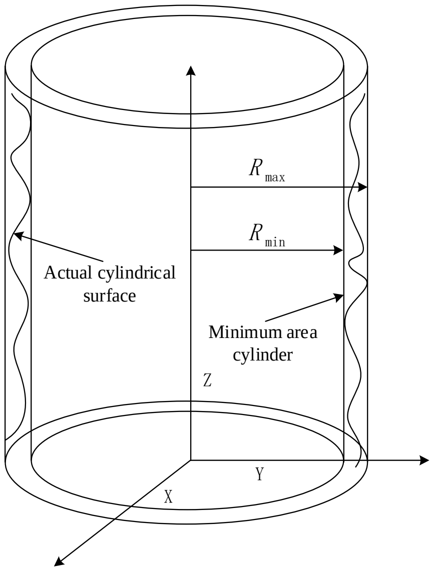


**Fig.1** Diagram of Cylindricity Error

## 2.3. Simulation of cylindricity error

The digital twinning three-dimensional point cloud map was constructed by establishing simulation data points. The feasibility of using a laser displacement sensor and digital twinning technology in the cylindricity detection of large-size pipe fitting was simulated and analyzed. As shown in fig. 2, it can be seen that in three-dimensional space, the three-dimensional point cloud image can directly know the diameter distribution inside the pipe fitting and the center of the section fitted by calculation and observe the midline error of the pipe fitting. Using the three-dimensional point cloud data, the minimum regional circle formed by each pipe fitting team can be calculated, and the cylindricity error of the cylinder can be calculated by comparing the maximum tangent circle and the minimum peripheral circle of all the measured sections.

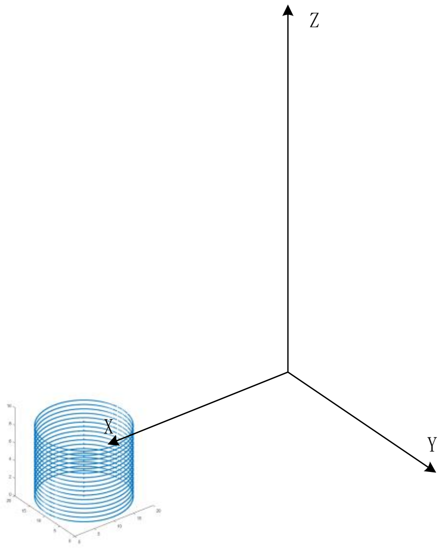


**Fig.2** Simulation Point Cloud Image

# 3. System development

## 3.1. Measurement system requirements

As shown in Figure 3, the tested object is composed of two C-type semi-circular parts connected by four pairs of bolts and nuts in the axial direction instead of the traditional radial fastening method. Due to this particular connection mode, extremely high assembly accuracy is required during assembly, and the bolts on both sides need to adjust the torque to achieve high-precision assembly. Moreover, the resolution of cylindricity detection should reach more than 0.05mm, and the high-precision real-time detection and error display of cylindricity cannot be realized using traditional detection methods. Because the unique structure of the test object cannot be stuck on the high-precision rotary shaft, cannot be aligned by clamping, and cannot rotate or move in a straight line, the detection mechanism must carry out active alignment and feed movement.

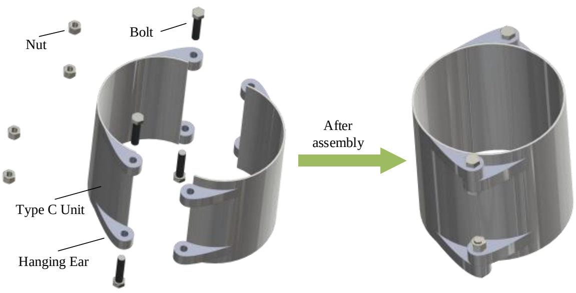


**Fig.3** Explosion Diagram of Large Size Pipe Fitting

## 3.2. Set up the system

As shown in Figure 4, the vision detection system comprises a three-axis motion system and a sensor scanning system. The motion system uses three servo motors to control the ball screw to drive the sensor scanning system to move in the direction of XYZ in space. At the same time, the servo system records feedback on the position of the scanning system and constructs the digital twin space coordinate system through the motion system. The scanning system includes a CCD camera, servo motor, and laser displacement sensor. First of all, the CCD camera takes the vertical photos of the workpiece, combines the image processing technology, locates the center of the workpiece, realizes the active alignment, determines the diameter of the workpiece, assists the laser displacement sensor in adjusting the rotation radius, and recognizes the optimal range of data acquisition. After judging the center of the workpiece through the image information collected by the vision system, the motion system controls the sensor scanning system to move to the designated position and sets the scanning layer distance according to the measurement accuracy. The miniature servo motor drives the laser displacement sensor to scan the workpiece layer by layer. The detection system establishes the connection between the spatial coordinate information, the rotation Angle information of the servo motor, and the information of the laser displacement sensor. The digital twin virtual space of cylindricity detection was constructed, and the 3D model of the workpiece and the cylindricity detection results were displayed synchronically.

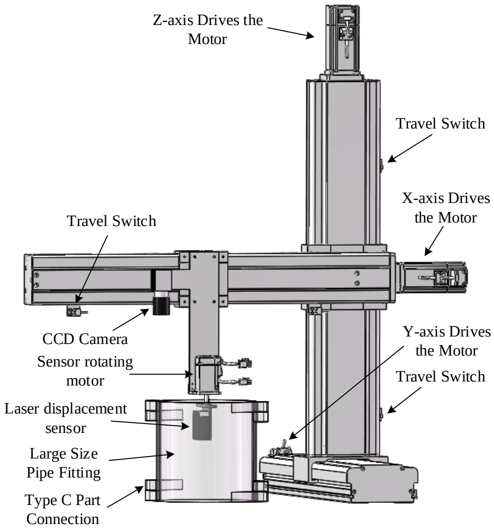


**Fig.4** Test Platform Diagram

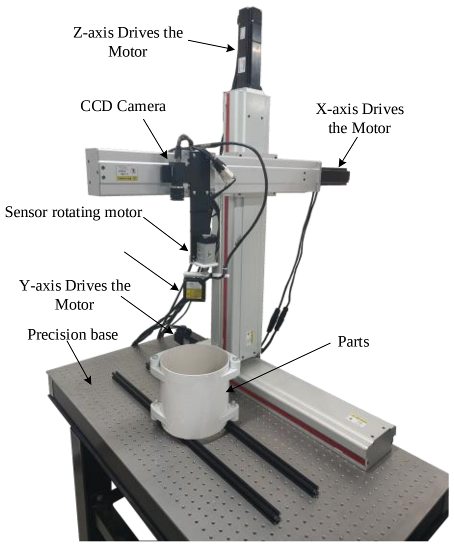


**Fig.5** Physical inspection system diagram

## 3.3. Build a digital twin model

To realize the online detection and sorting process of cylindricity of large-size pipe fittings based on digital twinning. It is necessary to establish the connection between virtual space and physical space. According to the five-dimensional model theory of the digital twin, the virtual entity of the digital twin needs to be described and portrayed from four aspects: geometry, physics, behavior, and rules. Therefore, based on the analysis of the detection elements, the digital twin model is established with a space motion module, camera, laser displacement sensor, and pipe fitting as the primary physical objects.

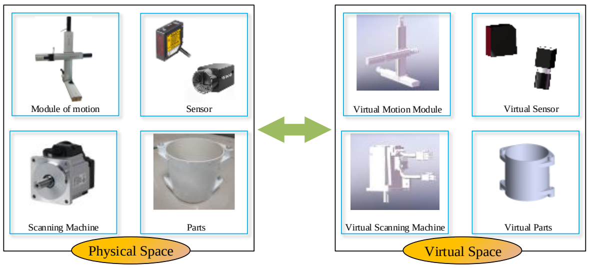


**Fig.6** Digital Twin System

# 4. Experimental analysis-

## 4.1. Principle of experiment

Select proper measuring equipment according to the principle of the detection scheme, and finally, build the detection platform as shown in Figure 4-2. Choose the Japanese Panasonic HL-G103-A-C5 diffusion-reflective laser displacement sensor. The sensor has a measuring accuracy of up to 0.5μm, a measuring range of 4mm (28mm to 32mm), and a sampling period of 200μs. The Z-axis servo motor drives the acquisition part to move up and down. The servo motor of the scanning system rotates and collects different sections of the cavity parts to obtain multiple measurement results, which are used for the last fitting of cylindricity. The effective stroke of the Z-axis feed is 300mm, the linearity is 0.01mm, and the accuracy is ±0.01mm. The servo motor of the scanning system rotates and drives the laser displacement sensor to turn 360° to measure a section inside the cavity. The sensor obtains multiple measuring points, and the rotation angles correspond to the measured data points one by one. According to the size of the sensor, the radius range of the measuring tube and shell of the measuring system is calculated to be 140 mm~260 mm. In the detection system, the motion of the sensor scanning system in XYZ space and the drive of the laser displacement sensor rotation is realized by the upper computer control PLC, and the measured distance value of the laser displacement sensor is received through the RS-422 interface.

### 4.1.1. Scanning system center correction

Firstly, the CCD camera is used for preliminary positioning of the workpiece, and then the scanning system is used for rotation center correction. The scanning system scans the inner wall of the workpiece once, calculates the maximum scanning distance value $l_{max}$ and the measurement value $l_1$ of the distance at the angle corresponding to the rotation of 180° . Set the radius of the workpiece to be detected as $R_0$, the rotation radius of the laser displacement sensor $r_0$, and the rotation angle at the maximum distance as $\theta_1$, the Angle of $l_1$ here is $\theta_1+\frac{\pi}{2}$ ,then:

$$2r_0+l_{max}+l_1=2R_0$$

The rotation center of the relative laser displacement sensor is the origin of the coordinates, and the coordinates of the above two measuring points can be calculated as follows:

$$A(x_{max},y_{max})\begin{cases}x_{max}=(r_0+l_{max})*\cos\theta_1\\y_{max}=(r_0+l_{max})*\sin\theta_1\end{cases}$$

$$B(x_1, y_1)\begin{cases} x_1 = (r_0 + l_1) * \cos\left(\theta_1 + \dfrac{\pi}{2}\right) \\ y_1 = (r_0 + l_1) * \sin\left(\theta_1 + \dfrac{\pi}{2}\right) \end{cases}$$

The rotation center of the laser displacement sensor moves $\left|\frac{l_{max}-l_1}{2}\right|$ along the direction of $\overrightarrow{BA}$, and this point is the rotation center of the scanning system after correction.

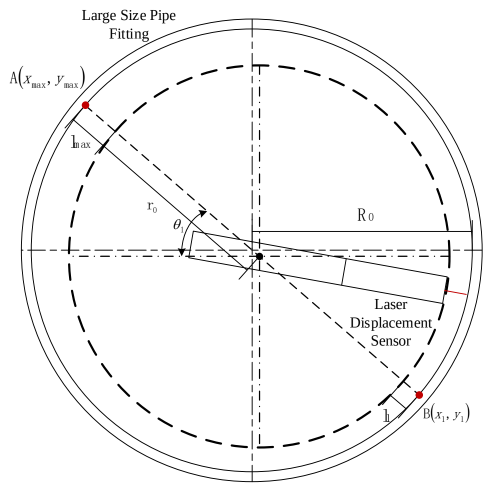


**Fig.7** Scan Center Deviation

### 4.1.2. Data Collection

After camera positioning and center calibration, the Z-axis servo motor, scanning system rotation servo motor, and laser displacement sensor move together through the upper computer. The cavity height is 240mm, the cross-section spacing is 10mm, and 20 cross-sections are scanned. The rotating servo motor speed of the scanning system is set to 3r/min, and the sampling frequency of the laser displacement sensor is set to 5kHz.The scanning system rotates around to obtain 100,000 measurement points for each section. Record the Angle of each moment from the starting measurement position.

$$\theta_i = \frac{2\pi}{M} * i$$

Where: $\theta_i$ is the Angle of the first measuring point relative to the initial measuring point, and M is the number of points obtained by the section.

### 4.1.3. Data processing

The upper computer collects the scanning information of the laser displacement sensor and associates the length information with the Angle information to calculate the coordinates of each point.

The coordinate of the NTH measurement point $i$ in the NTH row $(x_{Ni}, y_{Ni}, z_N)$ is

$$\begin{cases} x_{Ni} = (r_0 + l_i) * \cos\theta_i \\ y_{Ni} = (r_0 + l_i) * \sin\theta_i \\ z_N = 240 - 10N \end{cases}$$

Where, $l_i$ is the distance between the sensor and the measuring point $i$, and $\theta_i$ is the angle value of each measuring point relative to the initial measuring point; $x_{Ni}$ is the horizontal coordinate of the measuring point $i$ on the NTH layer, $y_{Ni}$ is the ordinate of the measuring point on the NTH layer; $i = 1, 2, 3, \cdots, n$; $N = 1, 2, 3, \cdots, n$;

## 4.2. Analysis- Real-time evaluation curve of cylindricity

The interior of the pipe fitting was scanned layer by layer to establish the data model. A total of 20 sections were observed in this experimental model. The scanned data were processed, and the results are shown in Figure 8. The coordinates in the X and Y directions of the center of the smallest square circle of each section were different, and the roundness error of the team fluctuated all the time. After the scanning of all areas is completed, the tangent circle's maximum radius and the outer circle's minimum radius in all sections are selected to construct the curve of the tangent circle's maximum radius and the outer circle's minimum radius, as shown in FIG. 9. The minimum cylindrical surface was constructed by calculating the maximum radius curve of the minimum outer circle and the minimum radius curve of the maximum tangent circle. The cylindricity error was calculated as =149.9129-149.6757=0.2372.

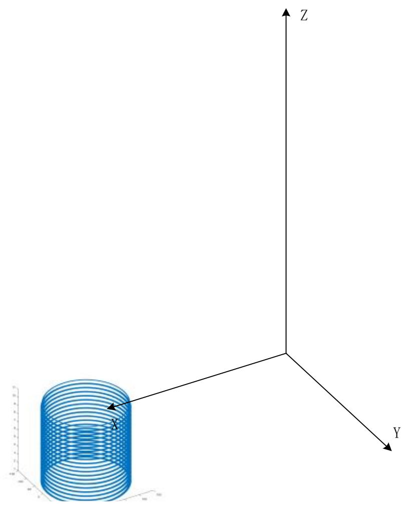


**Fig. 8** Digital twin scatter plot

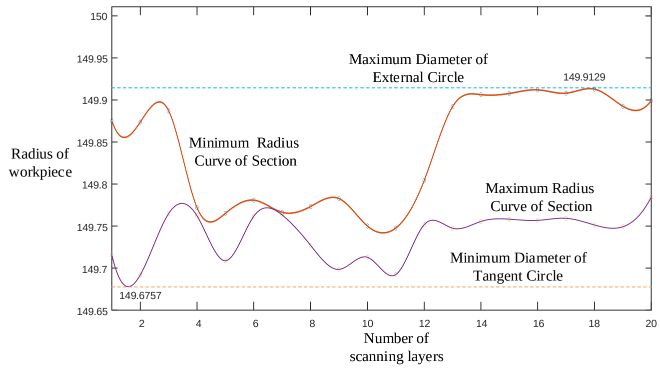


**Fig. 9** Cylindricity evaluation curve

# 5. Conclusion

This paper introduces a technology that quantitatively uses a laser sensor and digital twin technology to detect the cylindricity of large-sized pipe fittings online. By building a virtual and real interaction system, building a detection platform to carry out online real-time detection of pipe fittings, and using digital twin virtual models to intuitively reflect the significant cylindrical error of the object, as well as adjust the direction, improve the assembly efficiency and accuracy of axial fixed large-size pipe fittings, and increase the product qualification rate. And according to the size and range of the laser displacement sensor, the system can measure large pipe fittings with an inner diameter of 70-800mm and a depth of 30-350mm; of course, the system can replace different laser displacement sensors according to actual needs.

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