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Research on Curvature Adaptive Control Method for ABB Robot Blade Polishing Residuals

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Abstract

To address challenges in traditional blade polishing such as low error control precision, irrational path planning, and poor parameter matching of belt pulleys, error control methods were investigated using ABB industrial robots as execution platforms and belt pulleys as polishing tools, combined with curvature adaptive algorithms. By analyzing blade surface curvature characteristics, a correlation model linking polishing errors to parameters and surface curvature was established. A curvature-adaptive error control algorithm was designed to dynamically adjust polishing parameters across different curvature zones. Simulation environments were built using Robot Studio platform to validate error control through both simulation and experimental testing. Results demonstrate that: In high-curvature zones, polishing errors reach 0.012mm at 1500r/min belt speed and 80N polishing force; In medium-curvature zones, errors minimize to 0.009mm at 1700r/min belt speed and 70N force; In low-curvature zones, errors decrease to 0.007mm at 2000r/min belt speed and 60N force. The curvature-adaptive control strategy achieves an average error of 0.011mm and a maximum error of 0.021mm, both remaining within the target error range of 0.1mm. Compared to traditional fixed-parameter methods, this approach improves allowance control precision by 61.1%. These findings provide theoretical support and technical references for automated high-precision blade polishing.

Keywords

ABB robot; Blade polishing; Curvature adaptive; Allowance control; Path planning; Belt pulley; Robot Studio simulation.

1. INTRODUCTION

In high-end manufacturing sectors such as aerospace and energy power systems, blades serve as critical load-bearing components with complex profiles, significant curvature variations, and stringent requirements for surface quality and dimensional accuracy [1]. Polishing, as the final critical process in blade manufacturing, primarily removes surface machining marks, reduces surface roughness, and corrects profile errors to ensure compliance with design specifications. However, due to uneven curvature distribution across blade surfaces, traditional polishing methods predominantly employ fixed parameters and uniform paths, which struggle to adapt to varying curvature zones. This often leads to over-polishing (resulting in insufficient blade thickness and reduced strength) or under-polishing (failure to meet surface quality standards), significantly compromising blade performance and service life.

Foreign countries pioneered robot blade polishing technology with relatively mature techniques. ABB Group's automated path planning technology [2] enables collision-free path generation for robots, optimizes motion trajectories, reduces cycle times, and enhances polishing efficiency. This technology can be implemented offline in Robot Studio or adjusted online in real-time via RobotWare, providing robust technical support for robotic polishing path

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planning. Research institutions in the United States, Japan, and other countries have integrated robotics technology with adaptive control systems. For complex blade surfaces, they developed surface feature-based polishing parameter adjustment methods that dynamically regulate polishing speed and pressure through curvature detection, significantly improving error control accuracy. For instance, a research team utilized laser measurement technology to obtain blade surface data [3], combined with abrasive belt polishing principles, established correlation models between polishing errors and parameters, achieving preliminary error control. However, the study did not fully account for the impact of abrasive belt wear on error control.

In recent years, China has increasingly prioritized research on robotic blade polishing technology, achieving notable progress. Research institutions such as Northwestern Polytechnical University have conducted extensive studies on aeroengine blade polishing and grinding techniques, proposing multiple flexible polishing methods. By optimizing polishing tools and controlling polishing axis vectors, they achieved effective alignment between abrasive belts and blade profiles, significantly improving polishing accuracy [5]. Some scholars have developed path planning methods like equidistant trajectories and spiral paths for blade polishing [4], but these approaches fail to adequately account for blade curvature variations, resulting in uneven path coverage. Additionally, domestic research predominantly focuses on single-parameter adjustments, lacking integrated error control methods that combine curvature adaptation, path planning, and abrasive belt wheel polishing characteristics. Insufficient simulation validation also creates gaps between theoretical models and practical engineering applications, making it challenging to meet high-precision polishing demands for advanced blades [6]. Therefore, developing curvature-adaptive error control methods for ABB robotic blade polishing-integrating path optimization with abrasive belt wheel characteristics and designing adaptive error control algorithms to dynamically match polishing parameters across curvature zones-holds significant theoretical and practical value for enhancing polishing accuracy, efficiency, and consistency, reducing production costs, and advancing high-end blade manufacturing technologies.

This paper focuses on the error control of ABB robot blade belt pulley polishing, the core is to solve the problem of different curvature area error control is not uniform, the path planning is not reasonable. A kind of error control method combining blade curvature adaptive is proposed, the surface curvature as the core basis of polishing parameter adjustment, to achieve the precise control of different curvature area error.

2. ESTABLISHMENT OF THE SURFACE MODEL OF THE BLADE

2.1. Mathematical Model of Blade Surface and Curvature Calculation

Blade surfaces are complex free-form surfaces typically defined by discrete point coordinates. Establishing a mathematical model is essential for accurate curvature calculation. This study employs the Non-Uniform Rational B-Spline (NURBS) method to construct blade surface models. NURBS surfaces demonstrate high flexibility, superior fitting accuracy, and ease of modification, enabling precise representation of complex blade geometries.

The parametric equation of the NURBS surface for the blade is:

$$S(u,v)=\frac{\sum_{i=0}^{m}\cdot\sum_{j=0}^{n}\cdot N_{i,k}(u)N_{j,l}(v)w_{i,j}P_{i,j}}{\sum_{i=0}^{m}\cdot\sum_{j=0}^{n}\cdot N_{i,k}(u)N_{j,l}(v)w_{i,j}}$$

Here, and $(N_{i,k}(u))$ $(N_{j,l}(v))$ $(w_{i,j})$ $(P_{i,j})$ represent B-spline basis functions with k-th order in the u-direction and 1-th order in the v-direction, respectively; is the weight factor; is the control vertex; and u and v are parameter variables with values ranging from [0, 1].

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Surface curvature is a key parameter that characterizes the degree of surface bending, including principal curvature, Gaussian curvature, and mean curvature. For a NURBS surface S(u, v), its first fundamental form and second fundamental form are respectively:

$$I=Edu^2+2Fdudv+Gdv^2$$

$$II=Ldu^2+2Mdudv+Ndv^2$$

Here, E, F, and G represent the first fundamental quantities, while L, M, and N denote the second fundamental quantities. The calculation method is as follows:

$$E=S_u \cdot S_u,\ F=S_u \cdot S_v,\ G=S_v \cdot S_v$$
$$L=\frac{S_u \times S_v \cdot S_{uu}}{|S_u \times S_v|},\ M=\frac{S_u \times S_v \cdot S_{uv}}{|S_u \times S_v|},\ N=\frac{S_u \times S_v \cdot S_{vv}}{|S_u \times S_v|}$$

The principal curvatures κ_1 and κ_2 represent the maximum and minimum curvatures of a surface in two orthogonal directions at a given point, which are determined by the following characteristic equation:

$$\begin{vmatrix} L-\kappa E & M-\kappa F \\ M-\kappa F & N-\kappa G \end{vmatrix}=0$$

When expanded, it shows:

$$\left(EG-F^2\right)\kappa^2-(EN+GL-2FM)\kappa+\left(LN-M^2\right)=0$$

According to the Weida theorem, the sum of principal curvatures (mean curvature H) and the product of principal curvatures (Gaussian curvature K) are respectively:

$$H=\frac{\kappa_1+\kappa_2}{2}=\frac{EN+GL-2FM}{2\left(EG-F^2\right)}$$

$$K=\kappa_1 \cdot \kappa_2=\frac{LN-M^2}{EG-F^2}$$

This study employs Gaussian curvature K as the evaluation metric for blade surface curvature. A higher absolute value of Gaussian curvature indicates greater surface curvature (e.g., leading and trailing edges of blades), while a lower absolute value suggests flatter surfaces (e.g., leaf bowls and mid-back areas). The aforementioned formula enables calculation of curvature at any point on the blade surface, providing essential data support for subsequent curvature adaptive control.

2.2. Determination of Blade Curvature Model

To achieve accurate curvature description and regional segmentation of blade surfaces, it is essential to develop a blade curvature model based on the NURBS surface model and curvature calculation. The process begins with surface meshing, where continuous NURBS surfaces are discretized into regular mesh elements. Specifically, equidistant sampling is performed along both u and v directions within the parameter domain (u, v), with sampling intervals determined by surface complexity and precision requirements (typically 0.01-0.05 parameter steps) to generate extensive surface sampling points. For each sampling point, Gaussian curvature K

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values are calculated using the method described in Section 1.1, resulting in one or multiple curvature values per mesh element that form the initial curvature data distribution.

The Gaussian curvature calculated is normalized to eliminate the influence of dimensionality. The normalization formula is:

$$K_{norm} = \frac{K - K_{min}}{K_{max} - K_{min}}$$

The minimum (K_{min}) (K_{max}) (K_{norm}) and maximum values of the Gaussian curvature of the blade surface are respectively, and the normalized curvature is in the range of [0, 1].

Based on normalized curvature values and blade polishing requirements, the blade is divided into three curvature zones according to Table 2. The high-curvature zone (front and rear edges) features pronounced surface curvature, requiring precise control to prevent over-polishing or under-polishing. The low-curvature zone (middle of the blade bowl and back) has a gentle surface, allowing for higher polishing efficiency. The intermediate-curvature zone serves as a transitional area, balancing precision and efficiency.

Table 1. Criteria for leaf curvature region classification

curvature region	normalized curvature (K_{norm})	Gaussian curvature $(\lvert K \rvert)$ $(1/mm^2)$	Regional characteristics
High curvature region	0.6~1.0	≥0.05	The leading and trailing edges of the blade exhibit significant curvature, posing challenges for error control.
Medium curvature region	0.3~0.6	0.02~0.05	Transitional zone, moderate degree of curvature
Low curvature region	0~0.3	<0.02	The mid-back of the leaf petiole and leaf surface exhibit a gentle curvature with high polishing efficiency.

The blade surface is segmented into regions based on curvature values to establish a curvature region model. According to blade polishing process requirements and the impact of curvature on polishing quality, the blade surface is divided into low-curvature zones, medium-curvature zones, and high-curvature zones. Specific segmentation thresholds should be determined based on actual blade types and polishing tool characteristics. The Gaussian curvature absolute value $\lvert K \rvert < 0.05\ mm^{-2}$ is defined as the low-curvature zone, $0.05\ mm^{-2} \le \lvert K \rvert < 0.2\ mm^{-2}$ as the medium-curvature zone, and $\lvert K \rvert \ge 0.2\ mm^{-2}$ as the high-curvature zone. Each region exhibits similar curvature variation patterns, providing clear segmentation criteria for subsequent adaptive polishing parameter adjustments and path planning. Additionally, to facilitate simulation and experimental validation, the segmented curvature region information is correlated with the blade NURBS model to generate a 3D model containing curvature region attributes. This enables rapid location-based queries of corresponding curvature regions and characteristic parameters at any position. The blade 3D model is illustrated in Figure 1.

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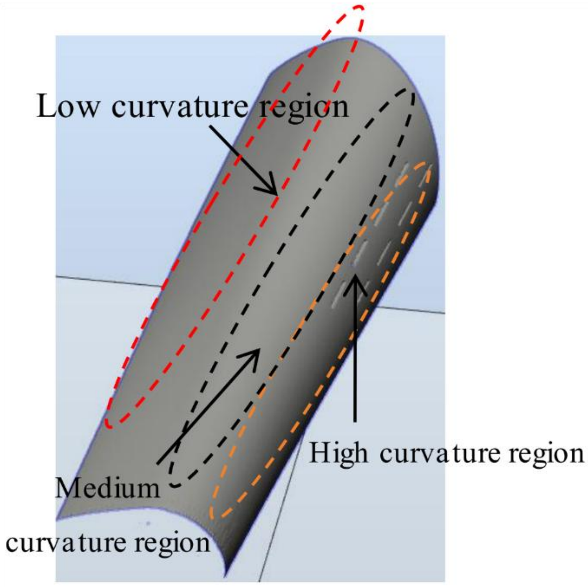

Figure 1. Three-dimensional model of the blade

3. SIMULATION RESULTS AND ANALYSIS OF ROBOT STUDIO

3.1. Simulation Environment Setup

This study utilizes ABB Robot Studio to develop a blade polishing simulation environment, which consists of: an ABB IRB 1200 robot model, a belt pulley polishing tool, a 3D blade model, virtual sensors (force and displacement), and a control system. The construction process is detailed below:

Importing the robot model: Launch Robot Studio, create a new workstation, import the ABB IRB 1200 robot model, configure the base coordinate system, set joint limits and motion parameters, and ensure the robot's movement range covers the blade polishing area.

Tool and work piece model import: Import the belt pulley tool model (diameter 80mm, abrasive belt grit size 240 mesh), and determine the center point (TCP) coordinates of the belt pulley through tool calibration. Import the three-dimensional blade model (STL format), fix it on the workbench, and adjust the blade orientation to optimize the polishing area for robotic operation.

Virtual sensor configuration: Add force sensors and displacement sensors. The force sensor is used to detect polishing pressure, while the displacement sensor monitors polishing error. Sensor data is fed back to the control system in real time to provide basis for error control. Additionally, a virtual abrasive belt wear model is configured to simulate wear conditions during the polishing process.

System Architecture Development: Write RAPID control programs in Robot Studio to integrate curvature recognition algorithms and path planning algorithms, enabling robot motion control, polishing parameter adjustment, and error feedback.

After completing the simulation environment setup, environmental debugging is conducted to ensure collision-free robot movement, accurate sensor data acquisition, and appropriate polishing parameter settings, thereby laying the foundation for subsequent simulation experiments.

3.2. Simulation Design

To validate the necessity of curvilinear region segmentation and differential parameter control in this study, and to investigate the variation patterns of polishing errors across different

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curvature regions with varying parameters, multiple comparative simulation experiments were designed. Based on the high, medium, and low curvature regions defined in Section 1.2, differentiated polishing parameters were configured. By comparing simulation results across different groups on identical blade models, the impact of curvature adaptive control strategies on polishing errors and efficiency was analyzed. Each experimental group was repeated three times, with the average value taken as the final result to minimize the influence of random errors on experimental conclusions.

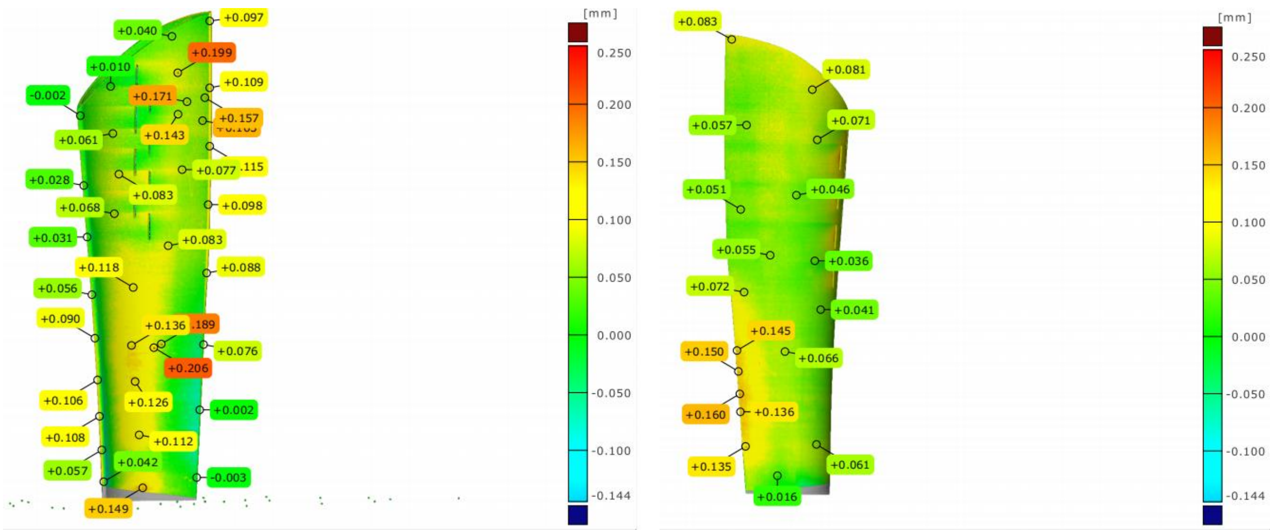
Parameter settings are as follows:

Blade specifications: The blade is made of 316L stainless steel, measuring 200mm in length and 50mm in width, with an initial surface roughness of Ra=3.2 μm and a target polishing error of 0.1mm.

Sand pulley parameters: diameter 80mm, sand belt particle size 240 mesh, initial thickness 2mm, wear rate 0.01mm/100s.

Robot parameters: repeatability positioning accuracy ±0.02mm, maximum movement speed 1000mm/s, polishing movement speed 500mm/s.

Test parameters: Polishing error: Polishing error in various curvature regions under different belt speeds and polishing forces. Additionally, the pre-polishing error analysis results are shown in Figure 2:



a) intrados b) convex surface

Figure 2. Blade margin analysis diagram (compared to the standard model)

3.3. Simulation Results and Analysis

After completing the simulation, displacement sensors were used to collect polishing error data across different curvature zones. The results are presented in Figure 3, which show the polishing errors for high, medium, and low curvature zones under varying belt speeds and polishing forces. Specifically, the high curvature zone operates at 1400-1600 r/min with forces of 70N, 75N, 80N, 85N, and 90N. The medium curvature zone runs at 1700-1900 r/min with forces of 60N, 65N, 70N, 75N, and 80N. The low curvature zone operates at 1400-1600 r/min with forces of 50N, 55N, 60N, 65N, and 70N.

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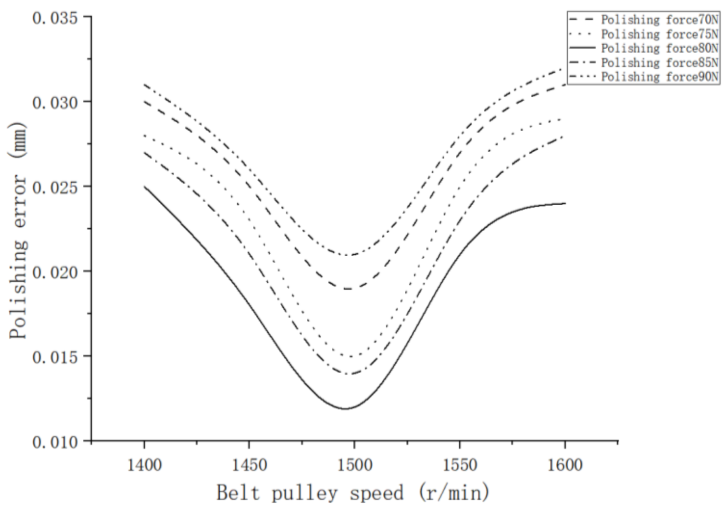
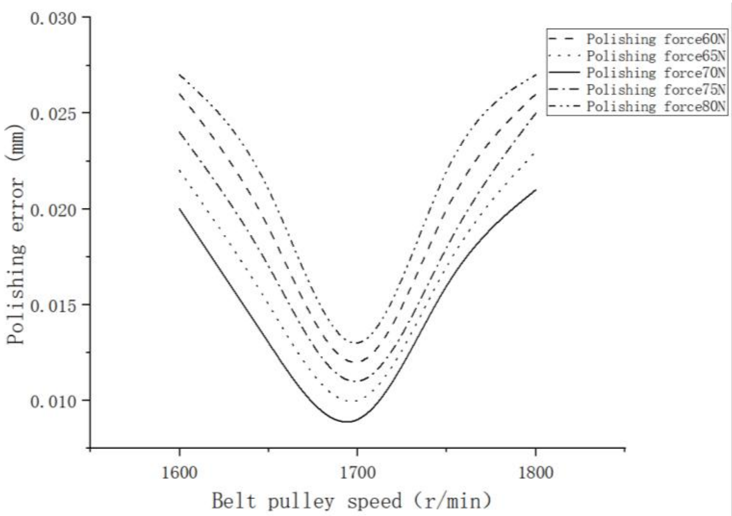
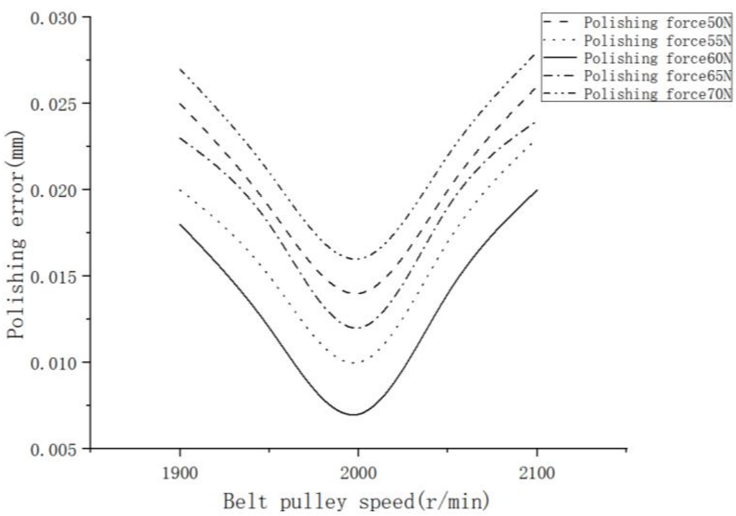


a) High curvature region



b) Medium curvature region



c) Low curvature region

Figure 3. Relationship between belt speed and polishing error under different polishing force in high, middle and low curvature areas

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Figure 3 demonstrates that in high-curvature regions, polishing errors initially decrease and then increase with increasing polishing force when the belt speed remains constant. For instance, at a belt speed of 1500 r/min, the polishing error gradually decreases as the force increases from 70N to 80N, reaching a minimum of approximately 0.012mm at 80N. However, further increasing the force to 90N causes the error to rise to 0.022mm. This occurs because moderate increases in polishing force enhance the belt's cutting action on the blade surface, reducing errors. Excessive force, however, creates excessive contact pressure between the belt and blade surface, leading to over-wear and localized overheating that compromises polishing precision. Under identical polishing conditions, the error decreases with increasing belt speed within the range of 1400-1500 r/min, but stabilizes after 1500 r/min. This indicates that moderate speed increases improve polishing efficiency and accuracy, though an optimal speed range exists. In medium-curvature regions, overall polishing errors are generally lower than in high-curvature areas. With a belt speed of 1700 r/min and a polishing force of 70N, the error reaches its minimum value of 0.009mm. Similar to high-curvature regions, polishing errors exhibit a pattern of initial decline followed by recovery as polishing force varies. However, the optimal polishing force range (65N-75N) remains relatively broad, with rotational speeds between 1600r/min and 1800r/min showing minimal impact on error levels. This characteristic aligns with moderate surface curvature in medium-curvature regions, which demonstrates lower sensitivity to parameter variations. Low-curvature regions achieve the smallest polishing errors, with measurements as low as 0.007mm recorded at 2000r/min belt speed and 60N polishing force. The gentle surface contours in low-curvature zones allow for larger polishing path step lengths, resulting in higher efficiency and stable belt-surface contact, thereby maintaining low errors across wide parameter ranges. Comparative analysis reveals maximum polishing errors in high-curvature regions, followed by medium-curvature zones, with low-curvature regions exhibiting the smallest deviations. These findings align with the regional characteristics described in Table 2, validating the necessity of curvature-based zone segmentation and differentiated parameter control strategies. Optimal polishing parameters and error values for each curvature region are detailed in Table 2.

Table 2. Optimal polishing parameters and minimum polishing error for each curvature region

curvature region	Sand belt speed (r/min)	Polishing force (N)	Polishing error (mm)
High curvature region	1500	80	0.012
Medium curvature region	1700	70	0.009
Low curvature region	2000	60	0.007

4. EXPERIMENTAL VALIDATION

4.1. Polishing Error Analysis

To validate the reliability of simulation results and the effectiveness of the curvature-adaptive control strategy in actual polishing processes, a blade polishing test platform based on the ABB IRB 1200 robot was established. The platform consists of an ABB robot body, a belt pulley polishing device, a force control system, a blade fixture, and a control system. The tested blades, identical to the simulation model, are made of 316L stainless steel with an initial surface roughness of Ra=3.2μm, and the target polishing error is controlled within 0.1mm. Comparative experiments were conducted using both a traditional fixed-parameter polishing method (control group) and the proposed curvature-adaptive method (curvature-adaptive group).

The control group employed fixed polishing parameters (sand belt speed: 1800 r/min, polishing pressure: 70N) without performing curvature adaptive adjustments. The curvature

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adaptive group strictly followed the optimized polishing parameters for each curvature zone derived from simulation (Table 2): high curvature zone using sand belt speed of 1500 r/min and polishing force of 80N; medium curvature zone using sand belt speed of 1700 r/min and polishing force of 70N; low curvature zone using sand belt speed of 2000 r/min and polishing force of 60N. To ensure experimental accuracy, each test was repeated three times, with the average value of three measurements used as final error data. After polishing completion, a 3D laser scanner was employed to scan the entire blade surface. Scanning data was compared with a standard blade model to calculate actual polishing errors at each sampling point, specifically the normal distance deviation between measurement points and corresponding points on the standard model, as shown in Figure 4.

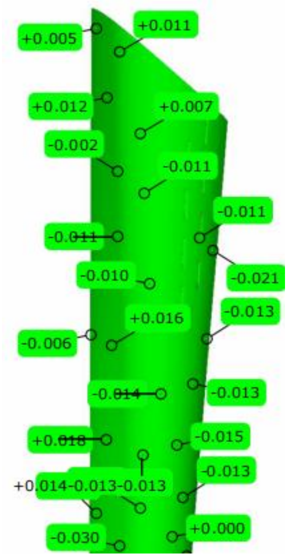

Figure 4. Three-dimensional scanning image of blade polishing error

Statistical analysis of polishing error data obtained from experiments was conducted by curvature region. The results indicate that: high-curvature regions (blade leading and trailing edges) exhibited an average polishing error of 0.015mm with a maximum error of approximately 0.021mm; medium-curvature regions showed an average error of 0.010mm and a maximum error of 0.014mm; low-curvature regions (blade basin and mid-backside) had an average error of 0.008mm with a maximum error of 0.011mm. Compared to simulation results, actual polishing errors in each region were slightly higher than predicted values, primarily due to factors including discrepancies between real sanding belt wear characteristics and virtual models, robotic joint clearance, and clamping errors during actual polishing processes. However, overall actual polishing errors remained within the target range of 0.1mm, with error magnitude relationships (high-curvature region> medium-curvature region> low-curvature region) consistent with simulation outcomes. This validates that curvature-adaptive polishing parameter control strategies effectively reduce errors across different curvature regions and enhance overall blade polishing precision. Statistical analysis of average and maximum polishing errors is presented in Table 3.

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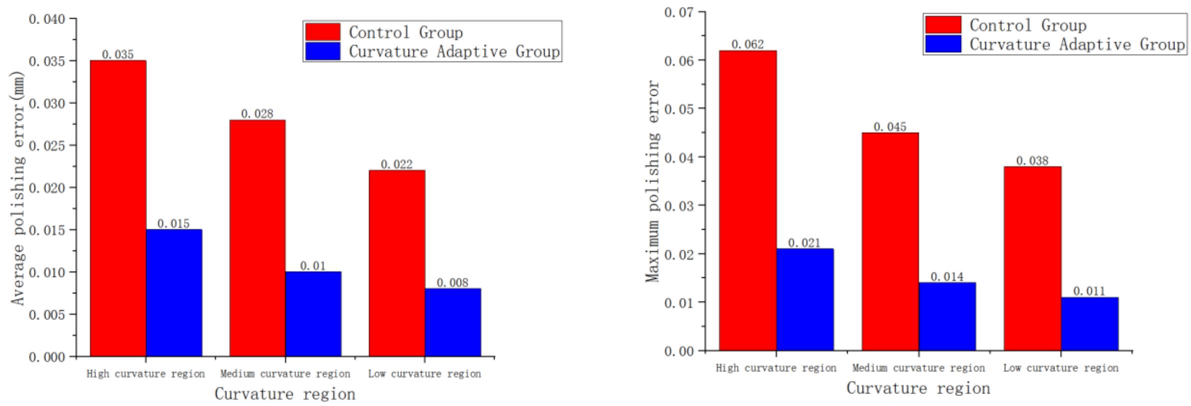
Table 3. Comparison of polishing errors between the two methods

test team	curvature region	Average polishing error (mm)	Maximum polishing error (mm)
Control group (traditional method)	High curvature region	0.035	0.062
	Medium curvature region	0.028	0.045
	Low curvature region	0.022	0.038
Curvature Adaptive Group (This Method)	High curvature region	0.015	0.021
	Medium curvature region	0.010	0.014
	Low curvature region	0.008	0.011

Table 3 data reveals that the control group (traditional fixed-parameter method) exhibited significant allowance errors across all curvature zones, with the maximum allowance error reaching 0.062mm in high-curvature areas-far exceeding target control precision. This primarily stems from the traditional method's failure to account for blade surface curvature variations while employing fixed polishing parameters and path step lengths. The pronounced surface curvature in high-curvature regions resulted in inadequate sanding belt wheel contact with blades, leading to uneven allowance removal and occurrences of over-polishing or under-polishing phenomena. Comparative polishing error diagrams between the two experimental groups are illustrated in Figure 5.



a) Average polishing error b) Maximum polishing error

Figure 5. Comparison of polishing errors between the two experimental groups

The curvature adaptive group (the proposed method) maintains allowance errors below 0.02mm across all curvature zones. In high-curvature areas, the average allowance error is 0.015mm with a maximum of 0.021mm, while mid-and low-curvature zones demonstrate even smaller tolerances, all meeting the blade polishing allowance requirements. This is achieved by segmenting zones through curvature recognition, which significantly enhances polishing error control precision.

To quantify the difference in margin control accuracy between the two (η)methods, the margin control accuracy improvement rate is defined as follows:

$$\eta=\frac{\Delta e_{con}-\Delta e_{pro}}{\Delta e_{con}}\times 100\%$$

Where, (Δe_{con}) (Δe_{pro}) represents the average residual error of the control group, and represents the average residual error of the experimental group.

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The calculations show that the average ($\frac{0.035+0.028+0.022}{3}$=0.0283mm) ($\frac{0.015+0.01+0.008}{3}$=0.011mm) residual error in the control group is, and the average residual error in the experimental group is. Substituting these values into Equation yields:

$$\eta=\frac{0.0283-0.011}{0.0283}\times 100\%\approx 61.1\%$$

The results demonstrate that the proposed method achieves a 61.1% improvement in margin control accuracy compared to conventional approaches, significantly outperforming traditional fixed-parameter methods.

5. CONCLUSION

Simulation results demonstrate that when the belt speed remains constant, polishing error initially decreases and then increases with increasing polishing force. Under identical polishing force conditions, the error also exhibits a similar trend of first decreasing and then increasing with belt speed. However, optimal control parameters vary across different curvature zones, requiring differentiated parameter adjustments. In high-curvature zones, polishing error reaches its minimum value of 0.012mm at a belt speed of 1500 r/min and polishing force of 80N. For medium-curvature zones, the minimum error is achieved at 0.009mm with a belt speed of 1700 r/min and polishing force of 70N. In low-curvature zones, the minimum error is 0.007mm achieved at a belt speed of 2000 r/min and polishing force of 60N.

Experimental results demonstrate that the curvature adaptive control strategy achieves a blade polishing average error of 0.011mm and a maximum error of 0.021mm, both remaining within the target error range of 0.1mm. Compared to traditional fixed-parameter polishing methods, this approach improves allowance control accuracy by 61.1%.

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