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Digital Simulation and Analysis of Assembly-Deviation Prediction Based on Measurement Data

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Abstract: For various power equipment items such as aircraft engines and gas turbines with numerous components demanding requirements on processing accuracy and high structural complexity, processing errors tend to cause such problems as assembly rework, forced assembly and prolonged research and development cycle. In this paper, the core machine of micro gas turbine is taken as the research object to construct a simulation model of assembly-deviation prediction based on the design tolerance and actual measurement data. Then, an analysis is conducted on the assemblability of the design model and the key factors causing the deviation of the assembly. After conducting deviation calculations and simulation analysis, it was determined that the current mounting position is deemed to be suboptimal. In light of this finding, an optimized solution is proposed, which involves advancing the mounting phase by 0.47 mm. This adjustment effectively resolves the interference issue resulting from the design error. Moreover, the geometry, shape and three-dimensional contour of the key components are measured with high accuracy and precision to identify the key characteristic parameters affecting the outcome of the assembly. With an assembly-deviation-prediction and -analysis model established on the basis of actual measurement data, the results of the assembly-deviation analysis are compared with the outcome of the assembly, showing high consistency. The assembly-deviation-prediction method proposed in this paper on the basis of design tolerance and actual measurement data is applicable to the manufacture of aviation and combustion engines.

Keywords: digital assembly; tolerance; deviation analysis

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1. Introduction

Aircraft engines, gas turbines and other power equipment components are characterized by a large number of components, complex shape and structure, demanding requirements on processing accuracy, a complex assembly process and so on, as commonly encountered in the manufacturing process. At the design stage, the lack of scientific evaluation system for component tolerance allocation or unreasonable tolerance allocation affects the accuracy of the assembly and the assemblability of the components. At the processing stage, the commonly used traditional one-dimensional and two-dimensional methods of measurement tend to ignore the impact of three-dimensional error. However, the assembly requires a perfect match between three-dimensional parts, which means that even the correct one-dimensional or two-dimensional size does not ensure that the parts can be successfully assembled. At the assembly stage, aircraft engines, gas turbines and other sophisticated equipment have demanding requirements on the accuracy of assembly for working in high-temperature and high-pressure environments [1]. When the processed component exceeds the allowable range of tolerance, it can result in rework that incurs unnecessary time and financial costs. Usually, assembly time accounts for about 20% to 50% of the total production time [2]. Forced assembly occurs even more frequently, which has a significant impact on the quality, performance and lifespan of gas turbines and other important equipment. In some cases, it even causes damage to all the equipment [3].

Assembly is realized in a three-dimensional space, where there are many 3D chains present in non-parallel planes, as well as the geometric deflation effects of angular tolerances and transfer coefficients. A 3D chain represents a kind of complex nonlinear dimensional chain. By establishing a mathematical model for the deviation of the 3D dimensional chain with space vectors, Zhang [4] analyzed the impact caused by the deviation of each constituent ring on the deviation of the closed ring according to the sensitivity matrix in it. Meng et al. [5] established the vector ring model of the 3D chain through the concept of vector and then applied it to build the "dichotomous" 3D model of deviation simulation.

Analytical verification of assemblability and simulation verification of assembly accuracy and performance are the two primary components of digital assembly. Developed countries place profound value on digital assembly. For instance, Boeing has employed model-based design (MBD) in the development of the 787 airliner to achieve rapid development under three-dimensional digital design and simulation technology, leading to a significant reduction in assembly process-planning time [6]. Companies such as GE, Pratt & Whitney and Rollo have optimized the original aero-engine rotor assembly simulation technology with augmented reality technology, resulting in a 50% reduction in the error rate of workers assembling the harness and a 25% reduction in completion time [7]. The digital assembly of aircraft engines and gas turbines has garnered immense attention from numerous scholars. Shi [8] has made strides in this area, by successfully establishing a diagnostic mathematical model of core machine performance, and subsequently analyzing the errors of significant measurement parameters associated with the core machine. Liu et al.'s [9] contributions to this field include the proposal of a dual-objective optimization principle, utilizing the Monte Carlo method to optimize rotor noncentricity and unevenness. Shan [10] has made remarkable headway by introducing the method of Pearson distribution family, which has been instrumental in the modeling and analysis of assembly deviation within typical rotor parts found in aero-engines. Similarly, Wang et al. [11] have made notable contributions, obtaining integrated runout results based on component-measurement outcomes, and determining optimal assembly angles via optimization calculations. Gao [12] proposed a core engine rotor assembly accuracy-prediction model utilizing the concept of elastic contact of the assembly surface. By adjusting and optimizing the installation phase of the rotor based on the model predictions, the assembly accuracy was significantly improved. Chen et al. [13] developed an assembly-prediction method by leveraging high-precision big data collection and "assembly deformation compensation and correction" technology. This method allowed for the prediction of the optimal assembly angle and position of each stage of the rotor disk, thereby improving assembly accuracy and reducing the potential for errors.

Hillyard [14] first proposed the use of computers to define the geometric shape, dimensions and tolerances of parts. With the progress in computer-aided tolerance analysis, there have been more and more studies conducted on digital assembly via 3D tolerance-analysis software. Zhang [15] conducted a study on dimensional deviations in engine compartments using 3DCS software and performed a root cause analysis of the resulting assembly deviations. Meng et al. [16] adopted the VSA software to investigate the cause of significant concentricity of pivot point for a type of core machine test part. Zheng et al. [17] used 3DCS software to analyze and optimize the tolerance of spacing in the landing gear intersection for the nacelle of the turboprop engine, which solved the problem with intersection spacing of the landing gear. The aforementioned studies present practical instances and methodologies for the analysis and optimization of assembly utilizing deviation-analysis software. However, these studies solely focus on the analysis and optimization of assembly deviations in design models, without further integrating real-world components with the design models. In addition, there is no guidance provided for actual assembly processes through the utilization of digitized assembly based on real-world components.

The assembly is realized in a 3D space, where a small amount of discrete 1D and 2D measurement data cannot reflect the 3D shape, the distribution of high and low points, and the exact location of the component. Therefore, for the assembly-deviation analysis of the machined parts, it is necessary to combine 1D, 2D and 3D measurement methods and to integrate the obtained data to better indicate the size, shape, deformation and contour error of the machined parts.

To perform 1D and 2D measurement of parts with high precision, various high-precision measurement equipment items such as coordinate-measuring machines, laser trackers and articulated arm coordinate-measuring machines can be used. Moreover, for the assembly of ultra-large equipment, high-precision digital photogrammetry can be used as well. In terms of 3D measurement, the high-precision 3D laser scanning equipment based on line laser, structured light and phase shift method is advantageous. Currently, many researchers are investigating and applying 3D measurement methods. For instance, Yu [18] employed binocular grating 3D measurement technology to measure an impeller, achieving a low-cost and high-accuracy 3D graphic visualization of the impeller. Tan et al. [19] utilized structural light to measure the surface differences of a body-in-white in 3D and addressed the issues of poor accuracy and low efficiency of manual measurement by fitting the reference line using the RANSAC algorithm. Lao et al. [20] utilized various 3D measurement instruments and proposed a 3D measurement process model-construction method for aircraft assembly.

In this paper, micro gas turbine is taken as the research object to establish a digital assembly-deviation-prediction and -analysis model based on design tolerance and actual measurement data. This not only improves the rationality of design and the reliability of assembly but also accelerates the process of equipment development and reduces production costs, which demonstrates its applicability in practice.

2. Digital Simulation Prediction and Analysis Method of Assembly Deviation

Figure 1 illustrates the digital prediction and analysis method developed in this paper for detecting the occurrence of assembly deviation, which involves the digital simulation of assembly deviation based on design tolerance, the in-machine 3D digital measurement of components and the digital simulation of assembly deviation based on actual measurement data.

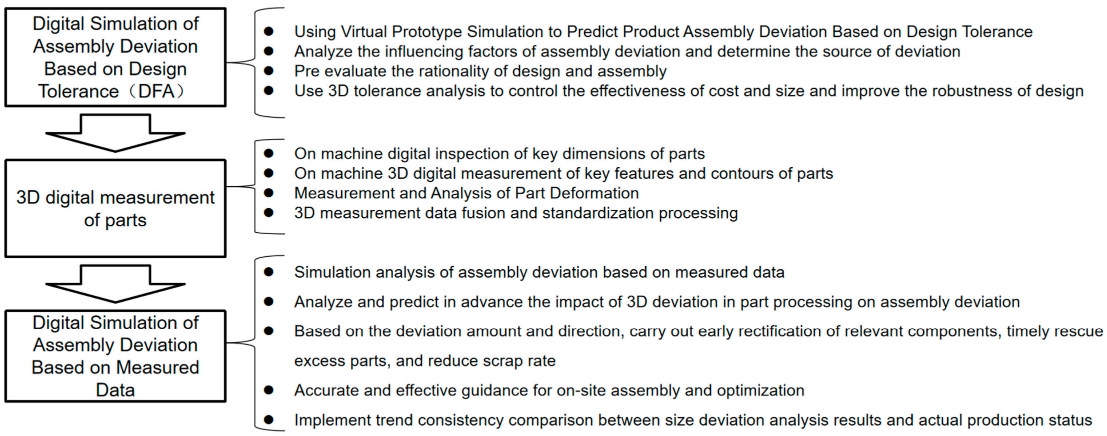


Figure 1. Digital assembly process.

Digital simulation of assembly deviation based on design tolerance.

Based on design tolerance, the digital simulation model of assembly deviation is established in 3DCS, and the Monte Carlo method is used to simulate the assembly at least 2000 times to obtain the prediction results of the assembly deviation. The simulation results are used to analyze the key influencing factors for assembly deviation, determine the cause of assembly deviation and evaluate the rationality of the design before actual production. If the design is reasonable, the parts of the machine can be produced, and if it is not reasonable, the design needs to be changed until the design meets the requirements.

By adopting advanced 3D tolerance analysis, cost and dimensional effectiveness can be controlled, improving design robustness.

Three-dimensional digital measurement of components.

By identifying the key influencing factors for assembly deviation and the causes of error through design tolerance analysis, the key dimensions, form errors and 3D contours of key features related to the assembly of the actual machined components are subjected to highly accurate measurement, 3D scanning. In this paper, the MetraSCAN 750TM | Elite handheld laser 3D scanning system is applied in combination with Hexagon's GLOBAL CMM for the measurement of key components of the core machine. High-precision dimensional measurement of parts is mainly carried out via CMM, and part contour scanning and part deformation measurement is carried out via a handheld scanner. The scanned data were processed in a standardized manner and extracted using Polyworks. Then, the part measurement data and the design model were fused in 3DCS to create a fusion model of the part.

The digital simulation of assembly deviation based on actual measurement data.

Based on the actual measurement data of the assembled parts, the assembly-deviation-simulation model was established in 3DCS to predict and analyze the impact of machining errors on assembly deviation. If the simulation results of assembly deviation meet the design requirements, the parts can be assembled into a machine, and if they do not meet the design requirements, the parts need to be repaired. By taking into account the extent and direction of assembly deviation as measured, the relevant parts with excessive deviation can be reworked in advance, which reduces the scrap rate and improves the efficiency of assembly. Moreover, the accuracy of on-site assembly can be ensured and the visual guidance and optimization of on-site assembly can be achieved.

3. Digital Simulation Prediction and Analysis Experiment of Assembly Deviation

3.1. Simulation Modeling and Analysis of Assembly Deviation Based on Design Tolerance

In the prediction and analysis model of assembly-deviation simulation based on design tolerance, the Monte Carlo method is used to carry out assembly simulation several times by transferring the changes of each element in the chain in the form of random numbers for the key characteristic tolerances of each component affecting the outcome of the assembly. At each time of simulation, the assembly-deviation data are collected for statistical calculation and analysis of the pattern and characteristics of distribution of assembly deviation, as required to evaluate the assembly qualification rate and to analyze tolerance allocation. Thus, the key factors affecting the accuracy of assembly and the main cause of error are determined.

In this paper, the assembly of the core engine used for micro gas turbine is studied through a verification experiment for the digital simulation and analysis of assembly deviation. The core engine consists of various key components such as compressor, combustion chamber and turbine, as shown in Figure 2. The turbine of the micro-combustion engine studied in this paper is a centripetal radial turbine, the assembly of which is required to ensure a sufficient clearance between the rotor blade tip and the guide of the core engine, so as to prevent the rotating parts from collision with the stationary parts during operation. All relevant dimensional features in the dimensional chain where the clearance is located are important. In this paper, the 3DCS tolerance simulation software is used to model and simulate the assembly deviation of the design model, with the simulation results referenced to assess the reliability and rationality of the design.

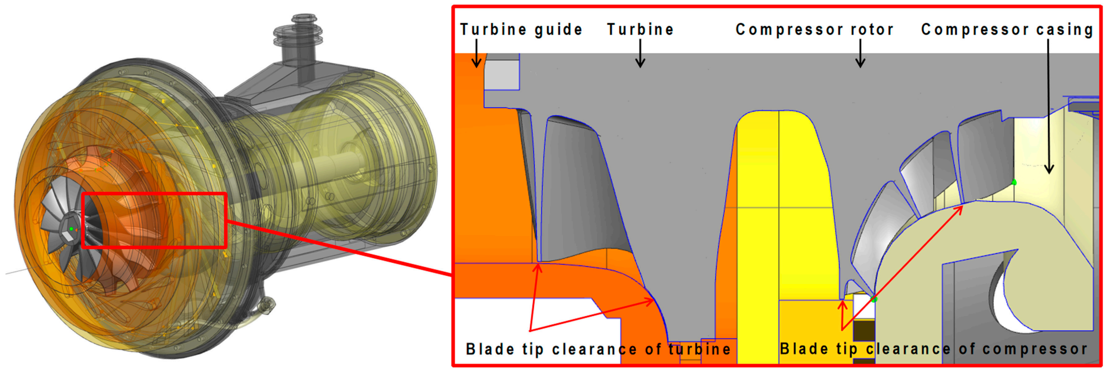


Figure 2. Schematic diagram of rotor assembly.

The process of modeling the simulation of assembly deviation based on design tolerance is as follows:

1. Import the assembly model of the part into 3DCS.
2. Establish part tolerances, construct feature meshes and select the appropriate feature tolerance scores according to the machining of the component, such as normal distribution, skewed distribution, Rayleigh distribution, etc.
3. Define the assembly scheme. The non-rotating parts of the motor and core machine are stacked assembly, and the rotor is a rotating part mounted on it by two bearings. The non-rotating parts are subjected mainly to stacked assembly, through flange connection, stop positioning, etc. The suitable assembly methods, such as feature assembly and two-point assembly, are adopted to construct a lightweight model for the assembly of the core machine.
4. Establish the measurement target according to the assembly requirements. As shown in Figure 3, it is difficult to perform mesh fitting for the complex curved parts such as the core machine rotor, and the measurement must be converted into the measurement of distance between discrete points. In this paper, the rotor blade tip surface is replaced by 16 blade tip key position points, and the cassette surface is changed into a mapping point for the blade tip point, with 16 measurement targets defined. In this way, the simulation error is significantly reduced.
5. Perform simulation and analysis optimization. Two thousand Monte Carlo assemblies are performed on the design model of the part to obtain its digital assembly results. Figure 4 shows the simulation results of an assembly gap-measurement target, with the probability of assembly interference reaching 28.75%. It is indicated that the reliability and rationality of the design are not satisfactory, which means the assembly must be optimized. Therefore, the assembly interference is solved in this paper by modifying and optimizing the position in which the rotor is mounted. The simulation reveals that the assembly no longer causes interference and the gap is uniform when the mounting position of the rotor is moved forward by 0.47 mm, as shown in Figure 4b.

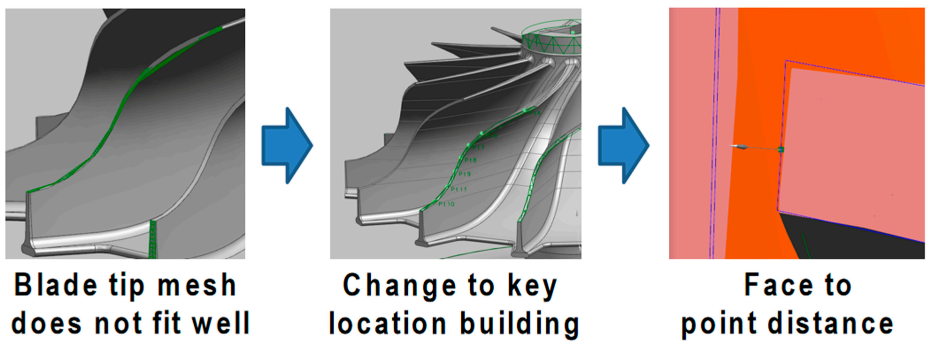
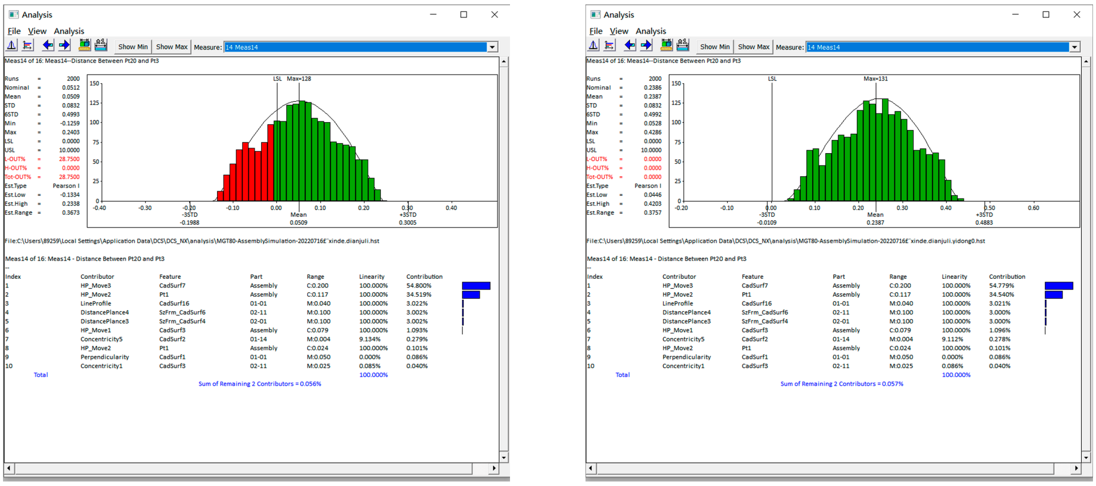


Figure 3. Discrete point distance-measurement model.



(**a**) (**b**)

Figure 4. Calculation results of measurement point 14 of the micro-turbin: (**a**) Before assembly optimization; (**b**) After assembly optimization.

3.2. Precision Measurement and Data Processing of Key Components

3.2.1. Three-Dimensional Precision Measurement of Key Components of the Core Machine

In this paper, the MetraSCAN 750TM | Elite handheld laser 3D scanning system is applied in combination with Hexagon's GLOBAL CMM for high-precision 1D, 2D and 3D measurement of key components of the core machine. Figure 5 shows how CMM and 3D scanning work.

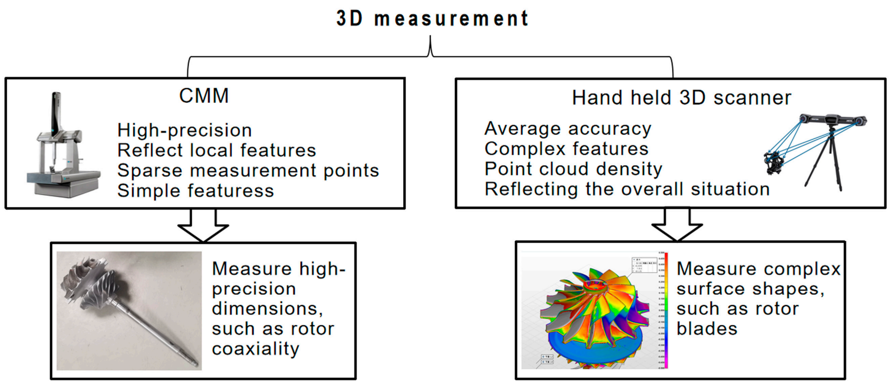


Figure 5. The division of labor and cooperation between CMM and 3D scanning.

The assembly of the micro-combustion engine is required to ensure a sufficient clearance between the rotor blade tip and the guide of the core engine, so all relevant feature dimensions along the dimensional chain where the clearance is located need to be measured.

The dense point cloud data obtained via laser 3D scanning reflect the 3D shape, the distribution of high and low points along with the exact location of the parts, etc., which makes it suitable for the scanning of complex and curved parts. There are many micro gas turbines with complex curved parts suitable for data extraction via 3D scanning, such as the compressor impeller and turbine impeller used in the combustion engine rotor. Herein, it is verified by repeated scanning of the standard ball with the handheld laser 3D scanning system that the instrument deviation is within 0.025 mm, which meets the need to measure the parts with a less demanding accuracy requirement than 0.05 mm. For the parts with smooth surfaces, the quality of the point cloud obtained via the laser scanner can be compromised. To solve this problem, such methods as powder coating of the part surface can be used to obtain high-quality point clouds [21]. To measure, the part is fixed to the fixture and then scanned with a 3D scanner to obtain all the point cloud data of the part. To avoid errors in the scanning results, each part needs to be scanned three times. For those large and complex parts, it is usually necessary to scan the part from multiple perspectives and then combine the point cloud data obtained from multiple angles to determine the complete 3D shape of the part.

CMM is characterized by sparse measurement points and high measurement accuracy, with the highest accuracy reaching up to 0.001 mm, which makes it suitable for the highly accurate measurement of dimensional and tolerances. There are many key components in the core machine requiring high processing accuracy; for example, the roundness, coaxiality and straightness of the combustion engine rotor must be within 0.004 mm. In this case, the measurement can be performed via the CMM with higher measurement accuracy. To measure, the workpiece is fixed on the CMM platform and then the probe is used to measure high-precision part assembly features with accuracy requirements within 0.04 mm.

3.2.2. 3D Scanning Point Cloud Data Processing

Figure 6 shows the process of 3D point cloud data processing for those key parts obtained via the 3D laser scanner, which mainly involves the collocation of multi-angle 3D scanned point cloud data, point cloud data denoising and the segmentation and feature extraction of point cloud data according to the needs for assembly features. In the processing of point cloud data, it is also a common practice to repair the holes of the point cloud. For the 3D point cloud needed to examine the actual processing quality of the parts, point cloud repair can lead to data distortion and affect the outcome of assembly simulation.

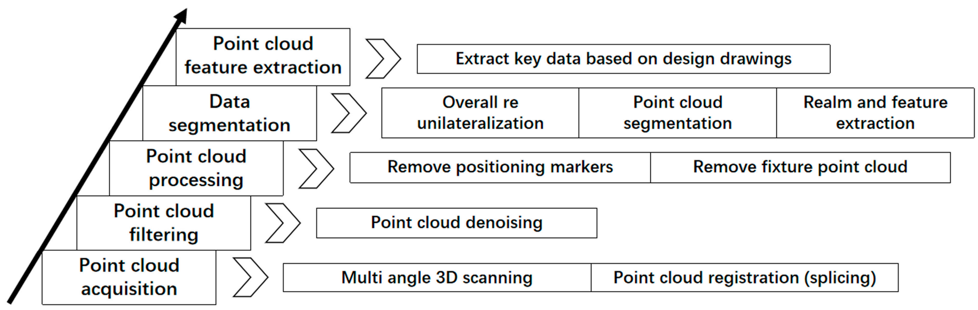


Figure 6. Point cloud data-processing flowchart.

To extract the key part feature parameters, conversion of the measured coordinate system into the design coordinate system of the part is usually required. For the parts produced with design models, the best fit can be aligned with the CAD model to create a complete picture of the error between the machined part and the CAD design model. The data of dimensions, form, deformation and contour of key features are collected by extracting the actual point cloud measurement data at the corresponding location of the CAD model, creating features based on the drawings of the part, extracting the key features.

To extract the parameters of key features from 3D scanned point cloud data, there are different methods available, such as probing, fitting, CAD model-based extraction, etc. The probing method employed in this study bears resemblance to a virtual CMM technique. Within the software, the scanned point cloud is treated as a physical entity, and a specific feature to be measured is selected. Subsequently, a virtual probe is employed to detect the point cloud, thereby determining the corresponding feature and its associated measurement value. On the other hand, the fitting method utilized in this research involves fitting the scanned data to standard features. To accomplish this, the point cloud is subjected to a least squares fitting approach using Polyworks software. Finally, the CAD model extraction method is an automated technique that leverages a designated region surrounding the corresponding feature in the CAD model as the actual measurement data area. This enables the direct extraction of the measurement data. The accuracy achieved with different methods varies. Take the mounting hole of the core machine studied in this paper as an example. In design, the diameter of the mounting hole is 170.43 mm, and the actual CMM value of the part is 170.593 mm. With the CMM data as the standard value, the data are extracted by using different methods. Then, the data obtained via different extraction methods are compared, the results of which are shown in Table 1.

Table 1. Measurement results of mounting hole (mm).

Serial Number	Probing Method	Fitting Method	CAD Method
1	170.584	170.602	170.637
2	170.586	170.595	170.637
3	170.568	170.603	170.637
4	170.590	170.610	170.637
5	170.538	170.583	170.637
Average value	170.573	170.599	170.637
Difference	−0.012	0.006	0.044

According to the findings presented in Table 1, the outcomes derived from the probing method exhibit the most minimal disparity when compared to the CMM values. This can be attributed to the enhanced capability of the probing method to comprehensively capture the intricate details of the features by utilizing a dense set of points. Thus, the presence of stray points is effectively eliminated during this process, thereby leading to an improved accuracy in the extraction of feature parameters. On the other hand, the probing method relies on sparsely distributed points, which fails to provide a holistic representation of the entire feature, resulting in substantial deviations in the measured values. Similarly, the CAD method, despite its automated extraction capability, is susceptible to erroneous selection of point clouds and extraction ranges, thereby leading to significant deviations in the measured values.

3.3. Modeling and Analysis of Assembly-Deviation Prediction Based on Actual Measurement Data

The assembly of the micro gas turbine core studied in this paper is representative of stacked assembly. Ideally, the axes of different parts are on the same reference axis after assembly, and the combined end face is a plane perpendicular to the cylindrical axis. However, the machined parts are flawed, and there may be various errors in form, thus resulting in a three-dimensional distortion caused to stacked assembly, as shown in Figure 7. To establish the assembly-deviation-prediction and -analysis model based on actual measurement data, it is necessary to extract the dimensional data, form tolerance, axis data and end face data of the machined parts. Then, these measurement data should be inputted into the assembly-deviation-prediction and -analysis model as established in Section 3.1 based on the design tolerance. Meanwhile, the replacement of the design value of the feature with the actual measured value is necessary. This is particularly crucial for the feature that extracts the actual data through point cloud scanning. In this case, the design tolerance must be substituted with the measurement uncertainty of the handheld scanning instrument, which amounts to 0.025 mm. In the validation experiments conducted in this paper, the axial data of the part are extracted through least squares fitting of the cylindrical surface point cloud data related to the assembly, while the three-dimensional point cloud data of the end face of the part are extracted through least squares fitting of the surface and three high points constituting the plane, respectively. Depending on the method of end face data extraction, two simulation models of assembly deviation are established on the basis of measurement data and then compared with the results of assembly to explore the extraction method that can produce the most comparable outcome to the actual results.

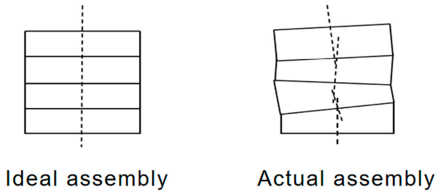


Figure 7. Ideal assembly and actual assembly.

3.3.1. Simulation Modeling of Assembly Deviation Based on Least Squares Fitting Surface

For the obtained 3D point cloud data, all the point clouds that form a certain plane in the scanned data are selected and a fitting plane is created via the least squares method. In Figure 8, Ls LCS indicates the least squares fitting plane. To obtain the assembly-deviation model based on the least squares fitting plane, the geometric center and normal vector data of the least squares fitting plane are introduced into the design model.

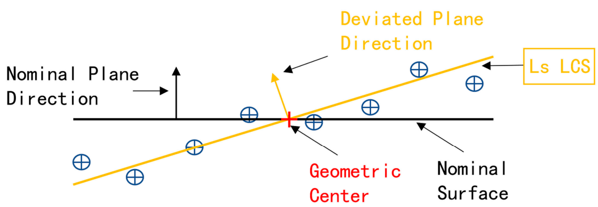


Figure 8. Least squares fitting surface of plane features.

3.3.2. Simulation Modeling of Assembly Deviation Based on Three High Point Composition Planes

Although the least squares fitted plane can reflect the characteristics of the bonding surface in general, the machined assembly plane is usually irregular in shape and characterized by "double high points" or "multiple high points". Apart from that, there are significant deviations arising between the least squares fitted plane and the actual plane shape, which affects the accuracy of predicting the tilt of the stacked assembly axis. Figure 9 shows the deviation color map of the processing plane point cloud data and the ideal plane. Compared with the ideal plane, point clouds with warmer colors are more prominent, while point clouds with colder colors are more concave. As shown in Figure 10, according to the deviation color map of the point cloud data, three representative high points that do not share the same line are searched for and a plane is established to reflect the tilt of the assembly. With the three high point fitting plane as the assembly plane, an assembly-deviation-simulation model is established on the basis of the plane formed by the three high points.

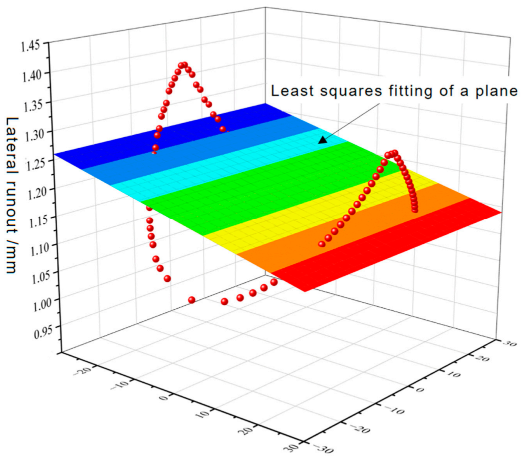


Figure 9. Least squares fitting plane of "double high point" plane.

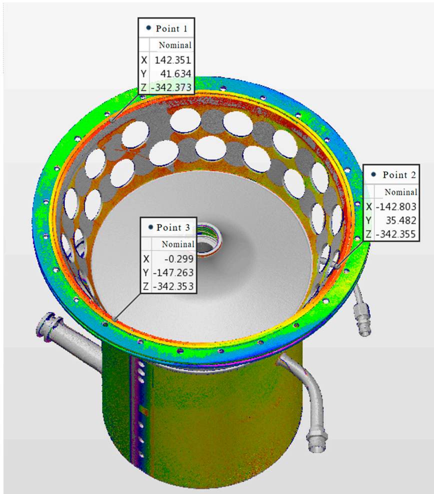


Figure 10. Extraction of representative three points on the mounting surface of motor housing.

3.3.3. Comparison of the Analysis Results of Two Assembly-Deviation-Simulation Models

For the assembly of the core part of the micro gas turbine, the total radial clearance of the outermost clearance of the rotor turbine tip and turbine guide is 1.2 mm, as determined by the measurement without interference and collision; the radial runout of the rotor blade tip is 0.183 mm. When the rotor is pushed backwards by 0.47 mm, the pressurizer rotor collides with the pressurizer magazine. Two-thousand Monte Carlo assemblies are carried out on the fusion model of part design and measurement to obtain the digital assembly results. The simulation results obtained through the two assembly-simulation models are compared with the measurement results, the results of which are shown in Table 2.

Table 2. Comparison of simulation results of different assembly methods.

	A	B	C
Actual assembly	1.2 mm	0.183 mm	100.0%
Assembly Based on Least Squares Fitting Surface	1.2 mm	0.194 mm	67.3%
Assembly Based on Three High Points Forming a Plane	1.2 mm	0.202 mm	99.5%

A—Radial total clearance between the turbine blade tip and the outermost clearance of the turbine guide. B—Radial runout of rotor blade tip. C—Collision probability of 0.47 mm pushed back.

As can be seen from Table 2, the simulation results of the assembly deviation based on the three high points of the composition plane are comparable to the measurement results of the assembly, which is conducive to the prediction of assembly deviation.

4. Discussion

The assembly-deviation-simulation model, based on three high points constituting a plane, considers the highest point of the point cloud constitution as the mounting surface, which is a closer approximation to the actual state of the axial length superposition than the least squares fitting model. As such, the prediction for the collision is more consistent with the actual state. However, this method employs fewer points, which results in a steeper slope of the fitted surface than that of the least squares fitted surface. Consequently, there may be a greater slope in the radial direction of the assembly model, leading to significant deviations in the predicted radial runout values.

When comparing the results with previous studies, it is important to note that the old studies provided practical examples and methods for analyzing and optimizing assembly utilizing deviation-analysis software [15–17]. Based on these examples and methods, a simulation model was successfully developed to predict assembly deviations using design tolerances and measured data, focusing on a micro gas turbine as the research object. However, the previous studies only focused on the analysis and optimization of assembly deviations in design models, without further integrating the measured data of the components with the design models. In this study, highly accurate measurements of the geometric shape, form and three-dimensional contour of key components were performed to determine the critical feature parameters that affect assembly results. An assembly-deviation-prediction and -analysis model was established based on the actual measurement data, and a comparison was made between the results of the assembly-deviation analysis and the assembly results to identify the best digital assembly-deviation-prediction model based on actual measurements. This research analyzes and predicts the assembly of actual components through a digital assembly based on measured data, providing a basis and guidance for the actual assembly process.

Although there are important discoveries revealed by these studies, there are also limitations. Further research can be conducted in the future on the following:

1. One avenue for further research involves exploring the digital assembly of thin-walled and easily deformable parts. While this study analyzed the micro gas turbine parts as rigid components, it is acknowledged that certain components within the turbine are thin-walled and deformable. As such, the established digital assembly model has inherent limitations. Expanding research efforts to encompass the assembly of these thin-walled and deformable parts could yield a more accurate simulation and analysis model of assembly deviation. Furthermore, such research has the potential to offer valuable insights for the assembly of advanced power plants, including aviation and combustion engines.
2. Additional investigation into the mathematical model of assembly is required. Several scholars have proposed novel mathematical models for digital assembly and deviation analysis. Further research on mathematical models can facilitate the integration of theory and practice, leading to the establishment of a digital assembly-deviation-analysis model that more accurately reflects the real-world scenario.
3. An in-depth simulation study is necessary to investigate the thermal deformation of core machine parts. As the core machine operates under high-temperature and high-pressure conditions, accurate predictions of its thermal assembly are crucial. To obtain the deformation of parts at high temperatures, factors such as thermal expansion coefficient, elastic modulus, density and deformation curve corresponding to the high-temperature deformation of the material can be assigned in CAE software based on the working temperature distribution of the core machine. This study can provide a better understanding of the thermal behavior of core machine parts and inform the development of more reliable and accurate thermal assembly models.

5. Conclusions

In this paper, the assembly of micro gas turbine core engines is taken as the research object to establish an assembly-deviation-analysis model based on design tolerance. Moreover, the key factors for the occurrence of assembly deviation and the causes of error are analyzed through Monte Carlo operations, which solves the assembly interference and collision caused by unreasonable design through optimization. This adjustment effectively resolves the interference issue resulting from the design error, indicating that digital simulation of assembly deviation based on design tolerances will help industry and researchers reduce design errors in practice. The assembly-deviation-analysis model is established on the basis of measurement data and different feature parameter-extraction methods. Then, the results of simulation analysis of assembly deviation based on the least squares fitting plane and the three high point fitting plane are compared with the actual results of assembly deviation. It is found that the simulation results of assembly deviation based on the three high point fitting plane are basically consistent with the actual outcome of the assembly, and the three high point fitting will help industry and researchers predict assembly deviations.

The method proposed in this paper to predict and analyze the assembly deviation based on the design tolerance and measurement data is applicable in practice.

Notwithstanding its contributions, this study is not without certain limitations, such as analyzing the micro gas turbine parts as rigid components, not further analyzing the deformation of thin-walled parts, not further investigating the mathematical model of assembly and not further analyzing the assembly deformation in the thermal state, which can be further investigated in the future.

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