A comprehensive study of three dimensional deviation analysis methods for aero-engine rotors assembly

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Abstract. Rotor assembly is a core task in the whole process of aero-engine manufacturing. The assembly deviation analysis is an effective tool to control deviation propagation. For aero-engine rotors assembly, the traditional deviation control methods focus on the modeling of plane dimension chain and extremum analysis, which is difficult to comprehensively consider the rich geometrical errors and their relationship to each other; meanwhile, the precision prediction is too conservative to reduce the parts’ rework frequency and adjusting difficulty; In addition, traditional methods overemphasize the promotion of parts’ machining precision, and ignore the means of overall stack optimization. In recent years, three dimensional deviation analysis and control methods have a lot of developments. These methods synthetically consider the matters of size deviation, form and location deviation, fixing structure and the positioning relationship. The poor concentricity problem of gyro black assembly can be exactly described, which is beneficial to control assembly deviation. This paper deals with aero-engine rotors assembly problem from two perspectives: deviation expression and deviation propagation, gives the difficulties of this topic, and provides a detailed review on the most recent approaches about partial deviation expression and three dimensional chain propagation. Finally, a perspective overview of the future research about aero-engine rotors assembly is presented, such as rotors deformation, surface morphology representation and matching, and the relationship between assembly precision geometry and performance physical quantity.

1. Introduction
With the world’s aviation industry development, China has accelerated the independent research process for new type of airplane, such as regional jet ARJ21 by self-designed and manufactured, twin-engine civil airplane C919 and long-range plane C929 which China developed with Russia [1]. However, the foundation of China's aviation industry is weak. The manufacturing technology of commercial aero-engine is still a blank space in domestic [2]. The engines used in ARJ21 and C919 respectively are CF34-10A developed by GE aviation and LEAP-1C developed by CFM, a franco-american joint venture. Chinese aircraft have a long history of “heart problems”. To avoid long-term foreign domination, China's State Council announced the "Made in China 2025" program of action, and developed a blueprint for the future grand transformation of China's manufacturing industry. Large aero-engine projects will be included in China's key manufacturing areas [3], to promote the development of the national economy and science & technology.

Rotor assembly is a core task in the whole process of aero-engine manufacturing [4]. If the centering scheme of rotors is not designed properly, or parts are assembled incorrectly, or dynamic balancing test is poor, rotors will vibrate acutely in the course of service due to the great inertia force,
aerodynamic force, torque and vibratory loading, which will directly affect the security and reliability of aero-engine. As shown in Figure 1, the rotor assembly consists of drum-disc type parts, which are characterized by large rigidity, multiple locating constraints of fixing structure, complicated bolt connection process, and complex hierarchical relations between stages [5]. Take GE90-115B aero-engine for example, its rotor system consists of up to ten-stage HPC rotors, two-stage HPT rotors and six-stage LPT rotors. Assembly sequence adopts bottom-up approach with multiple coordination procedure and low degree automation. Assembly work accounts for nearly 30% of the total production work.

For aero-engine rotors assembly, the traditional variation control methods focus on the modeling of plane dimension chain and extremum analysis, which is difficult to comprehensively consider the rich geometrical errors and their relationship to each other; meanwhile, the precision prediction is too conservative to reduce the parts’ rework frequency and adjusting difficulty; In addition, traditional methods overemphasize the promotion of parts’ machining precision, and ignore the means of overall stack optimization. There is still no effective theoretical method to control the aero-engine assembly precision and design the rotors assembly process systematically. Due to the dependence of foreign technology and experience, the rationality of assembly deviation analysis is insufficient, and the efficiency of multi-stage installation and control is low. Usually, a successful assembly needs four to five days, with four to five times disassembling and assembling. The parts repeatedly endure cold and hot processing, which greatly affects the rotor life. This assembly way can no longer meet the needs of modern aero-engine manufacturing.

The assembly variation analysis is an effective tool to control deviation propagation. It can quantitatively analyze and predict the assembly precision by establishing a mathematical model to describe the transitive relation of geometric deviations in the assembly process. At present, the three-dimensional deviation analysis model for aero-engine rotors assembly mainly includes two aspects: One is deviation expression, which solves the over-positioning problem of multiple pairs of datum feature from the perspective of partial deviation expression; the other is deviation propagation, which constructs the deviation propagation model by the dimension chain.

2. Deviation expression model of rotor’s partial feathers
In terms of the deviation expression of partial feathers, the fixing structure with the locating spigot round is often used in the rotor assembly of aero-engine, as shown in Figure 2. The fixing structure consists of a pair of plane pairs and a pair of cylinder pairs, which influence and restrict each other. The deviation is made to form a partial connection loop in the propagation path. In engineering, this type of assembly connection relation is called partial parallel dimension chain.
Figure 2. Connection type of the rotors.

Zeng et al. [6] distinguished and listed all types of partial connection pairs, and summarized five common partial over-positioning structures, using the object of spiral bevel gear transmission. Yang et al. [7] systematically discussed the deviation representation method of connection characteristics in the stacking process of rotating bodies. Ding et al. [8] proposed a geometric feature extracting and fitting technique based on REM-GA method. The feasibility of the method is demonstrated by experiments. But they oversimplified the construction and solution of the fixing structure. There is a big error between the predicted value and the measured value. To clarify and quantify the utility of partial parallel chains, Chen et al. [9] analyzed and verified the crank-link mechanism of the engine. The results show that the positioning structure of the locating spigot round greatly affects the solution accuracy, which cannot be easily ignored. For the expression of partial features of the rotors, the following four types can be mainly summarized:

1. **Boolean algebraic operations (BAO):** Chen et al. [9] from Shanghai Jiao Tong University improved the capability of Jacobian-Torsor model to deal with partial parallel chains by introducing Boolean operation rules into Jacobian-Torsor model. But the whole merging process is for feature sets, which is more suitable for statistical tolerance analysis. There are some limitations in the deterministic deviation analysis. Meanwhile, a large number of "intersection" and "union" operations make the calculation efficiency low and the process cumbersome.

2. **Localization tolerancing with contact influence (CLIC):** French scholars Chavanne and Anselmetti [10] proposed CLIC method to address the expression and reconstruction of tolerances in partial feature contacting. Partial feature interference was avoided by simulating a set of virtual boundary surfaces with extremely contact points, to calculate cumulative tolerances. Based on this method, Benichou and Anselmetti [11] considered the influence of thermal expansion effects on functional dimension, and compared the importance order of tolerance amount, thermal expansion amount and temperature uncertainty in dimensional chain. CLIC method emphasizes more on the leverage effects of geometric structure, and has certain limitations in solving the deterministic deviation problems of partial over-positioning structure.

3. **Contact points-based solution (CPS):** Jin et al. [12] from Shanghai Jiao Tong University established a three-dimensional deviation expression model that was suitable for the contact characteristics of aero-engine rotors. They introduced the small displacement torsor model with contact deviation points into the traditional torsor theory. This method is used to model macroscopically rigid parts, and all locating points are considered as an independent rigid-body system. The effect of mesoscopic scale deviations cannot be considered.

4. **Finite element method (FEM):** Professor Shi's team [13] from Shenyang Aerospace University designed flexible stacking tools for disk-type rotors, solved the tooling deformation under different loading conditions by using finite element method, discussed the main deviation sources that affect the positioning accuracy of tooling, and proposed a quantitative compensation method. Professor Hong's team [14, 15] from Beijing University of Aeronautics and Astronautics proposed wave finite element theory, studied the air band gap properties of reinforced shell parts and designed the vibration isolation. The optimal plane outer band gap and the overall structure quality were obtained. At the same time, the nonlinear contact analysis of finite element method was used to design the robust structure of high-speed detachable rotors, and the measures of increasing the local stiffness
and designing the fitting tightness were put forward. Andersson [16] of Volvo Aero Corporation established the finite element model of supersonic turbine blade, discussed the influence of manufacturing deviations on supersonic turbine efficiency, and determined the main sensitive parameters that affect turbine efficiency. Forslund et al. [17] from Chalmers University of Technology studied the functional robustness of TRFS relative to the assembly reference points, and pointed out that geometric deviations would bring negative effects of structural stress and thermal stress. The detailed simulation results can be obtained by using the finite element method from the whole to the local and from the static analysis to the complex working conditions. However, the overall modelling process is difficult and the solving efficiency is low. It is more suitable as an auxiliary validation method for other analytical models.

3. Deviation propagation model of multistage rotors stacking

In the aspect of deviation propagation, scholars generally establish the mapping relationship between characteristic’s deviations and functional requirements from the perspective of three-dimensional dimension chain. The modeling methods of rotor’s deviation propagation can be summarized as follows:

(1) **Direct linearization method (DLM)**: Wittwer et al. [18] from Brigham Young University linearized the nonlinear-size chain by using the first-order Taylor series expansion. Seven kinds of moving hinges are used to describe the relative assembly relation of parts. Only the influence of geometric deviation on assembly results was considered by DLM method, and the mesoscopic scale effect was ignored. It is more suitable to describe the deviation propagation process, and cannot achieve the unity of expression and transmission.

(2) **Connective assembly model (CAM)**: Hussain et al. [19] from University of Nottingham proposed two deviation control methods of direct assembly and parallel assembly using this model. The optimal concentric control and the optimal mounting angle of aero-engine rotors stacking were designed. The propagation of geometric deviation was considered well. Based on homogeneous coordinate matrix transformation theory, CAM optimized the optimal locations of the target points by using a set of constraint inequalities. Its solution efficiency and precision are limited by assembly complexity and optimization algorithm.

(3) **Deterministic locating model (DeLM)**: DeLM is a deviation propagation model based on discrete contact points. Cai [20] deduced the function expression of the deterministic positioning model by combining with the linear variational method. The relationship between positioning deviations and manufacturing deviations of fixed points was revealed. However, under the condition that six degrees of freedom of parts was completely restricted, how to select the unified specification of location points according to the limit function of specific features was an urgent problem to be solved at present.

(4) **Jacobian-Torsor model (J-T)**: The unified J-T model has the synthesized advantages with Jacobian matrix that is good at tolerance propagation and torsor model that is appropriate for tolerance representation. Cao et al. [21] combined torsor theory and state space method to predict the assembly accuracy of aero-engine rotors, and proposed an error compensation method. However, this method only aims at processing compensation, not assembly adjustment compensation during actual process, practicability of which is limited. Ding et al. [22] extended the Jacobian matrix and constructed the propagation path of deviations along feature’s height and angle. The multi-stage rotary characteristics and deviation’s linkage effects of rotors were revealed. But this model cannot express the deterministic partial geometric deviations and local deformation characteristics.

(5) **Design of Experiment (DOE)**: Chen et al. [23] used the improved Taguchi method and combined with Pearson theory to analyze the deviation’s abnormal distribution of turbine rotors. The computational efficiency was obviously improved relative to the Monte Carlo method. But the deviations sample was small and the probability distributions depended on human assumptions. The simulation experiment method is proposed by Pierce and Rosen [24]. B spline surface fitting was carried out for the measured point cloud data. By introducing machining mode variable and combining
penalty function method, the constrained optimization problem was transformed into an unconstrained problem. The "minimum distance in the best matching process" was calculated. But this method is based on the hypothesis of random deviation disturbance of adjacent mating surfaces, which is difficult to predict the contact effects between multistage rotors accurately.

Table 1. Deviation models comparison.

| Application object | Deviation expression | Deviation propagation |
|--------------------|----------------------|-----------------------|
| **Type**            | **BAO**              | **CLIC**              | **CPS** | **FEM** |
| Object type         | rigid                | rigid                 | rigid    | rigid, flexible |
| Geometric deviation | Face-based           | Point-Based           | Point-Based | Face-based |
| Morphology error    | ✓                    | ✓                     | ✓        | ✓        |
| Deformation error   | ✓                    | ✓                     | ✓        | ✓        |
| Deviation coupling  | ✓                    | ✓                     | ✓        | ✓        |

Characters and functions of these typical 3D models are listed in Table.1. The symbol “✓” means it can be achieved and “-” represents unknown or unable to calculate based on the published literature. Table 1 comprehensively compares the above typical deviation models from the aspects of application object, deviation type, solution method, efficiency, engineering application and algorithm difficulty. It can be seen that, on the one hand, many scholars have carried out a lot of in-depth and detailed work on the traditional rotors assembly process. A large number of theoretical and experimental researches have been carried out on deviation expression method, propagation mechanism and control strategy, having formed a more perfect theoretical system and research methods. On the other hand, the traditional deviation model cannot consider the important sources of assembly deviations such as morphology error, local contact, micro-convex deformation and assembly force. The assembly precision requirement of mesoscopic scale cannot be met. The study of deviations expression and propagation mechanism must be emphasized to provide guidance for rotor design and assembly process.

4. Conclusion

It can be seen from the research status of assembly deviation analysis for aero-engine rotors that, at present, there are still some problems to be solved in the deviation expression of rotor fitting structure, and the modelling method for the deviation propagation of multi-stage rotors assembly still needs to be further improved. Aero-engine rotors stacking has the characteristics of high continuity and long process. In the face of this extremely complicated and high accuracy demanding work, all types of deviation source and their constraint-coupling relations should be considered as comprehensively as possible. Meanwhile, the assembly characteristics of fixing structure and rotors rotation characteristics should be fully incorporated, to construct the deviation propagation model of multi-stage rotors, and determine effective deviation control ways. The research of this paper not only provides a new technical support for deviation control of aero-engine rotors stacking, but also lays a theoretical foundation for assembly precision analysis of other revolving symmetric components.

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