Research on Reliability Analysis of Axial-Symmetric Vectoring Exhaust Nozzle Based on Parametric Modeling

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Abstract—According to the motion characteristics of Axial-Symmetric Vectoring Exhaust Nozzle (AVEN), its motion process is divided into the convergence deflection of the adjusting piece of the A8 sub-mechanism and the expansion deflection of the adjusting piece of the A9 sub-mechanism. Taking the A9 sub-mechanism as an example, proposing a method based on Solidworks-Abaqus-Adams multi-software platform to establish a rigid-flexible coupled parametric model and run the motion simulation model to analyze the influence of different factors on the motion accuracy of the mechanism. Basing on the Monte Carlo sampling algorithm to design a program of automatic sampling solution that is separated from Adams platform. Under the condition of meeting certain accuracy requirements, the degree of automation in the sampling process is greatly improved. Finally, the probability distribution of the performance parameters of the A9 mechanism is obtained, and its reliability is calculated. The research results show that when considering various influencing factors, the motion accuracy of the mechanism will have corresponding deviations, which will have a certain impact on the reliability of the mechanism.

1. Introduction

The current mechanical system is constantly developing in the direction of lightness, large size, flexibility and complexity, which is a more severe challenge to ensure the high reliability of the mechanism [1]. AVEN is a key component in aero-engines to meet the control requirements of aircraft, many researchers have done a lot of research on AVEN about the dynamic model and the reliability analysis of motion functions. Shiqiang Liu established the motion model of a aero-engine tail nozzle by considering the influence of the random characteristics of the mechanism components and using the mechanism kinematics method, and then calculated the reliability index of the mechanism motion accuracy and the corresponding failure probability[2]. Yang Gao proposed a method to establish an AVEN mechanism model under multi-software platforms and perform motion simulation, using the method that combined the response surface method and the Monte Carlo method to obtain the probability distribution of the performance parameters of the vector nozzle and calculate its reliability[3]. The former has higher calculation efficiency, but the simulated working conditions are not real enough, and less influencing factors are considered. The working conditions simulated by the latter are consistent with the actual conditions, but the influencing factors considered are not comprehensive enough, and the simulation calculation efficiency is low, requiring manual operation to obtain a large amount of sample data.
In this paper, the parametric model of AVEN is established in the Adams software by combining parametric modeling method and virtual prototyping method and the problem of repeated modeling caused by size dispersion is solved by parametric modeling. Then, the simulation model was run to analyze the effect of the dispersion of the size on the motion accuracy of the mechanism. Flexibility is adopted for the easily deformable parts, and the rigid-flexible coupling dynamic simulation model of the mechanism is established. At the same time, the influencing factors of the kinematic pair clearance are considered. Finally, a related program is designed, which uses the Monte Carlo algorithm to automatically sample the mechanism to solve and calculate the mechanism reliability.

2. The structure and function of AVEN

2.1. Structural analysis of AVEN

The basic structure of AVEN device is composed of casing, A9 steering drive ring, convergence adjusting piece, expansion adjusting piece, converging section sealing piece, expansion section sealing piece, connecting rod, A8 adjusting ring, actuator, outer fairing and other components. The convergence angle of the convergence adjustment piece is determined by the A8 adjustment ring; the expansion angle of the expansion adjustment piece is jointly controlled by the A9 steering control ring and the A8 adjustment ring.

According to the mechanism composition and its connection relationship, AVEN can be decomposed into three parts: front part, middle part and rear part[4]. The front part is the part connected with the casing, the middle part is the driving mechanism of the expansion adjustment piece, and the rear part is the expansion adjustment piece. The basic structure of AVEN is shown in Fig.2.
The front part is mainly used to control the adjustment area of the A8 sub-mechanism, which is directly connected to the engine combustion chamber. The external casing is used as the base platform in the sub-mechanism, and the A8 adjusting ring is equivalent to the moving platform. They are connected by 6 retractable hydraulic actuators.

The middle part is the drive mechanism of the expansion adjustment piece formed by the A9 steering control ring and the casing. Similarly, the casing serves as the basic platform of the A9 sub-mechanism. The A9 steering control ring is equivalent to the moving platform. The basic platform and the moving platform are connected by three retractable hydraulic actuators.

The rear is the geometric part of the space movement. The spatial shape of the geometry will be changed with the pose of the A8/A9 ring.

2.2. Functional analysis of AVEN

The functional analysis of AVEN mainly includes system-level functional analysis and subsystem-level functional analysis. According to the composition analysis of AVEN and the characteristics of the mechanism, the main functions of the system level are defined as follows:

(1). The electro-hydraulic servo valve on the actuator adjusts and distributes high and low pressure command oil to the rod cavity and empty cavity of the actuator according to the control current from the VNC to form the driving displacement.

(2). The six actuators synchronously drive and control the A8 adjusting ring, and finally achieve the effect of adjusting the size of the nozzle.

(3). The three actuators asynchronously drive and control the A9 steering control ring, which in turn drives the deflection of the expansion section of the nozzle to realize the function of vector control.

The AVEN system mainly includes the A8 subsystem and the A9 subsystem. The A9 adjustment mechanism is mainly composed of a control system, a support system, a transmission system and an adjustment piece synchronization mechanism. Its function is mainly to complete the deflection of the expansion section of the nozzle and realize the function of vector control. The function level of the A8 adjustment mechanism is the same as that of the A9, and its function is mainly to achieve the effect of adjusting the size of the nozzle area[5].

3. The establishment of Adams parametric model

Through the above analysis of the composition and motion function of the AVEN mechanism, this paper mainly adopts the method of parametric design, and takes the A9 sub-mechanism of the AVEN mechanism as an example to establish its parametric model by Adams software.

3.1. Define design variables and point coordinates

When there are no other external factors, the rotation angle value of the expansion adjustment piece of the A9 sub-mechanism is determined by the length and installation position of each part. In order to analyze the influence of the part size error on the adjustment accuracy of the A9 mechanism, the size parameters of the key parts such as hydraulic actuating rod, fixed bracket, and triangular tie rod are defined as design variables. Then, according to the connection relationship of the A9 mechanism, the key points of each component are established to determine the spatial position.

3.2. Create the geometric model of the A9 mechanism and define component kinematic joints

First, the command flow is input to Adams/View and an empty part is created without any properties. Then the Marker is established through points and use design variables to complete the model creation in the empty part. The parameterized model of the A9 mechanism is shown in Fig.3.
According to the kinematic relationship between the various components of AVEN, the kinematic pair constraint is added to make the expansion adjustment piece achieve the purpose of deflection. Finally, the displacement drive is applied to the moving pair of the hydraulic actuator rod, the script is set, and the solution analysis is carried out to obtain the ideal deflection accuracy of the expansion adjustment piece of the A9 mechanism.

4. Simulation analysis of AVEN’s expansion motion

According to the motion function requirements of the mechanism, it is necessary to take into account various influencing factors in the analysis process and determine the influence of different factors on the motion accuracy of the mechanism.

4.1. Dimensional error simulation analysis

The machining and manufacturing of parts will produce certain dimensional errors and manufacturing errors. During simulation analysis, each component can be set as a design variable. Under the condition of considering the size error, the influence of the size error of each component on the deflection accuracy of the adjustment piece is analyzed. In the dimensional error analysis of the A9 mechanism, the main parts analyzed are the vector deflection ring, the hydraulic actuator, the triangle tie rod, the fixed bracket, the hydraulic actuating rod, the connecting hole between the fixed bracket and the triangle tie rod. As shown in Table 1, the numerical values of each dimensional tolerance.

| Part Name                     | Size Parameters     |
|-------------------------------|---------------------|
| The hydraulic actuating rod   | 240 ± 0.0435        |
| The hydraulic actuator        | 50 ± 0.031          |
| Vector deflection ring radius | 494 ± 0.1           |
| The fixed bracket             | 170 ± 0.037         |
| The triangle tie rod          | 242 ± 0.0435        |
| Connection hole radius        | 4 ± 0.026           |
The dimensional error of each component is brought into the simulation model for analysis, and it can be concluded that the dimensional error of the fixed bracket has the greatest influence on the deflection angle of the expansion adjustment piece. Fig.4 is a comparison of the normal simulation results and the simulation results considering errors.

![Fig.4 Deflection angle of the expansion adjustment piece under the influence of dimensional error](image1)

It can be seen from Figure 4 that the maximum value of the deflection angle error of the expansion adjustment piece is 0.002°. Therefore, it is necessary to focus on the influence of the size error of the fixed bracket in the reliability analysis.

4.2. Rigid-flexible coupling simulation analysis of A9 mechanism

According to the analysis of the structural characteristics of the A9 mechanism, it is found that from the perspective of motion constraints, the A9 vector deflection ring and the triangle rod cannot have large deformation during the movement of the mechanism[6]. Therefore they are considered as rigid bodies during simulation. However, due to its thin thickness, the expansion adjustment piece has a large deflection range, so it is considered as an elastic body in the simulation analysis. At the same time, the hydraulic actuating rod has great acceleration and impact load when it is started, so consider the hydraulic actuating rod as an elastic body for simulation analysis.

The solid models of the expansion adjustment piece and hydraulic actuating rod were established in Solidworks software, and then imported into Abaqus for flexibility processing. Finally, it is imported into Adams software for overall motion simulation of the mechanism. The deformation effect of the two elastic bodies is analyzed separately, and the deflection angle change curve of the expansion adjustment piece is obtained as shown in Fig.5.

![Fig.5 Deflection angle of the expansion adjustment piece considering the influence of flexibility](image2)
It can be seen from Figure 5 that the influence of the flexible hydraulic actuating rod on the deflection angle of the adjustment piece is smaller than that of the expansion adjustment piece, and the maximum influence angle is 0.0126°. When analyzing the reliability of the movement accuracy of the adjustment piece, the flexibility of the expansion adjustment piece should be seriously considered.

4.3. Analysis of the influence of the kinematic pair clearance

For the collision of gaps, the Hertz contact model is widely used[7], which is suitable for elastic conditions, but cannot explain the energy loss process. Lankarani and Nikravesh defined the contact force as the combined force of the normal elastic force and the tangential damping force to make up for the deficiency of the Hertz model.

\[ F_n = K\delta^n + D\delta \]  \hspace{1cm} (1)

In the formula (1), K is the stiffness coefficient, n is the force index, D is the viscous damping coefficient, \( \delta \) is the collision depth, and \( \dot{\delta} \) is the relative moving speed during collision. The force index \( n \) is 1.5 for the metal material, and the equivalent stiffness coefficient K is determined by the contact force between the spherical sphere and the concave sphere, and the expression is:

\[ K = \frac{4}{3} E^* \left[ \frac{R_1 R_2}{R_2 - R_1} \right]^{\frac{1}{2}} \]  \hspace{1cm} (2)

In the formula (2), \( R_2 \) is the radius of the concave sphere, \( R_1 \) is the radius of the sphere, and the material parameter \( E^* \) is defined as:

\[ \frac{1}{E^*} = \frac{1 - v_1^2}{E_1} + \frac{1 - v_2^2}{E_2} \]  \hspace{1cm} (3)

In the formula (3), \( v_1 \) is the Poisson's ratio and \( E_1 \) is the elastic modulus. The damping coefficient expression is:

\[ D = \frac{3K(1 - e^2)}{4\delta^n\delta} \]  \hspace{1cm} (4)

In the formula (4), \( e \) is the coefficient of restitution, which is taken as 0.84 in this study. The contact force is defined by the IMPACT function in Adams. The contact force is defined based on a nonlinear spring damping model, which is suitable for the collision depth \( \delta > 0 \). In the simulation, the Adams solver can give the velocity, acceleration, displacement and contact force of contact elements. The contact force of normal direction is divided into two parts: rigid force and viscous damping force. The contact force of normal direction is defined as the IMPACT function in Adams as the formula (5):

\[ \text{Impact} = \begin{cases} 0 & \delta \leq 0 \\ K\delta^n + \text{STEP}(\delta, 0, 0, \delta_{\text{max}}, C_{\text{max}})\delta & \delta > 0 \end{cases} \]  \hspace{1cm} (5)

When the collision depth \( \delta \) is less than 0, the damping coefficient \( C \) is 0; when the collision depth is greater than \( \delta_{\text{max}} \), the damping coefficient is \( C_{\text{max}} \); when the collision depth is between 0 and \( \delta_{\text{max}} \), the damping coefficient is automatically fitted by the STEP function. Considering the numerical convergence in Adams, \( \delta_{\text{max}} \) adopts the recommended value of 0.01mm in Adams.

5. Reliability evaluation of AVEN

The purpose of the mechanism motion simulation is to obtain the randomness law of the target variable through the randomness of the mechanism design variables, so as to obtain the reliability of the mechanism system according to the established reliability mathematical model. The theoretical core of the mechanism motion accuracy reliability simulation test is the Monte Carlo method based on random sampling and statistical test[8]. After obtaining a large number of sampling data, the distribution histogram of the target variable is obtained. However, the traditional Adams simulation analysis software is usually interrupted when it runs about 20 times due to the limitation of computing power in the process of multiple simulation solutions. For thousands of sample requirements, this operation is obviously not suitable. Therefore, this paper proposes an automatic sampling calculation program, which uses the Command Server module in Adams to communicate with external programs through TCP. In the client program, control commands are sent in the form of strings through TCP to realize
sampling analysis outside Adams. Taking the A9 mechanism as an example, its geometric size is regarded as a random variable, and Monte Carlo simulation calculation is carried out[9]. Set the number of simulations to 1000 and start the program. Finally, the distribution histogram of the deflection angle data of the expansion adjustment piece of the A9 mechanism is obtained as shown in Fig.6.

![Distribution histogram](image)

Fig.6 Distribution histogram of deflection angle of expansion adjustment piece of A9 mechanism

According to the distribution histogram shown in Figure 6, after the sub-parameter test, it can be considered that the corresponding population obeys the normal distribution. The mean and variance of the sample are used as estimates of the mean and variance of the population. When the absolute value of the angle error is greater than 0.0008°, it can be considered that the motion fails. According to the obtained simulation data, the reliability value of the motion accuracy of the A9 mechanism of AVEN can be calculated as the formula (6):

\[
R(\theta) = \frac{n}{N} = \frac{997}{1000} \times 100\% = 99.7\% \quad (6)
\]

n is the number of valid samples and N is the total number of samples.

6. Conclusion
Through the above analysis of the reliability of motion function of AVEN, the following conclusions can be drawn:

(1). The parametric model of the mechanism is established by using multiple software platforms, which simplifies the simulation process. It is not necessary to repeatedly establish the model, but only to change the design variables of the components. Then, simulation data of different samples can be compared to achieve the purpose of reliability evaluation.

(2). It is not difficult to find from the above analysis that the size error and elastic deformation of the components will have a certain influence on the reliability of the mechanism's movement function. For A9 mechanism of AVEN, it is found in the analysis process that the size error of the fixed bracket and the elastic deformation of the expansion adjustment sheet have a great influence on the motion accuracy of the mechanism, which should be considered in the reliability analysis.

(3). Sampling simulation analysis based on Monte Carlo method, using python language for program design, to realize sampling analysis outside of Admas, which greatly improves the automation degree of the sampling process. The reliability of the motion process of the mechanism is calculated from the viewpoint of the random process, and the maximum probability distribution of the process is considered, and the reliability of A9 mechanism is well dealt with.
Acknowledgments
This research is funded by National Science and Technology Major Project (J2019-IV-0002-0069). 
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