Research of Parametric Modeling and Simulation Analysis Methods of Aero-engine’s Rear Variable Area Bypass Injector of Mapping Dispersive Dimension Based on ADAMS

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Abstract—Aiming at the problem of motion accuracy caused by dispersive dispersion in the design of the aero-engine rear variable area bypass injector, a multi-body dynamics model mapping dimension tolerance, part flexibility, and collision contact is established based on multi-body dynamics theory and ADAMS. The simulation results are verified with the theoretical solution, which is calculated in MATLAB to ensure the correctness of the simulation’s results. The effect of key design variables on the motion accuracy of the mechanism is analyzed by the parametric module. The reliability calculation method is studied based on the improved Latin hypercube Monte Carlo method mapping the dimension dispersion. The method provides the relevant basis for the structural design of the RVABI.

1. Introduction

RVABI is one of the critical components of VCE to realize culvert ratio conversion. The MSV (Mode Selector Valve) determines the operating mode at the beginning of work, and then the common area in the bypasses is changed by the RVABI to change the engine’s bypass ratio. It can independently control the fan system of the core system to control the flight speed. Therefore, the position and attitude accuracy of the RVABI is an important kinematics criterion [1]. It is of great significance to ensure a stable flight and achieve the variable cycle function of the VCE.

The traditional analytical solution method of kinematics, which is calculated during a long period, needs to write many related formulas and programs. With the development of virtual prototypes, ADAMS provides a good platform for solving the modeling and simulation analysis of multi-DOF and complex structures [2-3]. When the user changes the relevant variables to realize the difference in the parameter values, the entire motion model can be automatically updated. And a series of simulation analyses can be performed to present the changes in the motion results during the rigid-flexible coupling simulation.

It is necessary to evaluate and analyze the motion reliability of the RVABI to ensure that the output of the RVABI provides the expected function reliably. The main reliability analysis methods are the Taylor series expansion method and the Monte Carlo method. The reliability of the Taylor series expansion method is calculated by the correlation expansion of the mean, the standard deviation, and the nonlinear function at the mean of the random variables, but the type of distribution of the random...
variable can’t be taken into account [4-5]. In this paper, the reliability is calculated based on the Monte Carlo method improved by Latin hypercube sampling. While circumventing the complexity of the probability density function, it ensures that all probability zones are covered by sampling points, reducing the number of necessary samples and improving the sample quality and simulation efficiency.

2. Structure and failure mode effect analysis of RVABI

2.1. The working principle and structural analysis
When the RVABI works as shown in Figure 1, the hydraulic drive device 1 drives the outer rocker arm 4 to rotate around the rotational shaft 5, and shaft 5 drives the internal rocker arm 6 to rotate simultaneously. Then, the flow control ring 2, which is connected by the moving link 3, moves along the axial direction to achieve the purpose of changing the area of window 7. It is divided into three systems by function: hydraulic drive mechanism, motion actuator, and support mechanism.

![Fig.1 The model of RVABI via Solidwork](image)

Part 1: The hydraulic drive device. Part 2: The flow control ring. Part 3: The internal link. Part 4: The outer rocker arm. Part 5: The rotational shaft. Part 6: The internal rocker arm. Part 7: The window. Part 8: The out-cartridge receiver.

The functions of each mechanical system are as follows: (1) Hydraulic drive mechanism: two hydraulic drive cylinders are used to drive the active arm to provide the driving force for the system as the power source of the mechanism; (2) Motion actuator: It achieves the axial direction of the flow control ring within a specified time; (3) Support mechanism: It plays the role of fixation and support to hold the VABI stably.

2.2. Failure mode effect analysis
FMEA (failure mode effect analysis) is an effective method to find the common failure modes and main failure causes of RVABI. The primary failure mode of RVABI is the deformation of the link. Generally, the change of the parts’ material properties affected by the temperature load leads to deformation, which causes errors during the movement. Therefore, it’s necessary to take the effects of the deformation of the parts on the motion accuracy into account during the modeling process.

3. Parametric modeling of RVABI

3.1. Design of parametric variables and determine assembly relationships
Designing variables aims to identify the structural parameters that can completely describe the entire model and establish the corresponding relationship from design variables to model objects. The design variables are used to define the required functional expressions and change the relevant part parameters and the coordinate points of the assembly position.

The displacement error of RVABI is not only caused by the manufacturing error of the parts but also may be caused by the error of the measuring tool, the error of the environment, and the error of the operation during the assembly and positioning process. Hence, defining a reasonable assembly process is the first step in parametric modeling.

It is necessary to determine the spatial coordinates of points and the model element space pose. The geometric and assembly relationships between each part are described by the parameterized definition of POINT and the constraint relationship to ensure the reasonable assembly relationship of the model in
ADAMS View. When confirming the assembly relationship, the first thing is to determine the relative coordinates of the rotational shaft with the origin of the global coordinate system. Secondly, the position of the shaft is used as the basis to establish an assembly connection point with the connected components through the mathematical relationship expression of the design variables with dimensions to complete the creation of assembly points among parts.

3.2. Create geometry and define kinematics pair

The links are mostly made of superalloy. In this paper, the material of the link is ZSGH alloy, which has excellent comprehensive properties, good process plasticity, and superplasticity. It has good anti-oxidation, anti-fatigue, and anti-radiation properties below 650 degrees Celsius. Components such as driveshafts, the main arm, hydraulic transmission system, driven arm, the link, the flow control ring, and the duct are established for creating the model with assembly relationship through the above-created assembly points as the reference point. It can be simplified for the actual motion relationship. The geometric shape, direction, centroid, and other positions of the parts can be adjusted through the Market point to create complex spatial components. The simple parametric model of the RVABI is shown in Figure 2.

![Fig.2 The parameterized 3D model of RVABI](image)

The types of constraining kinematic pairs between the parts are defined, including rotating pairs, ball joints, cylindrical pairs, and fixed pairs according to the actual connection points.

3.3. Flexibility analysis and modeling of link

Some parts may deform elastically and affect the force and the motion accuracy due to their different material properties. The flexible body generated by the finite element software replaces the rigid body in the model to analyze the influence of the deformation caused by the component on the motion accuracy. However, all flexible parts in the model will significantly increase the simulation time and reduce the efficiency. The key flexible parts in the model that have the highest impact on the motion accuracy should be found: a comparison of the pure rigid body model with the model considering the flexibility of the link and the model containing the flexibility of the flow control ring. It is concluded that the flexibility of the connecting rod has the most significant influence on the deviation of the motion accuracy, as shown in Figure 3. Therefore, the link is selected for the flexibility treatment. There are two standard methods of flexibilization. The first one is to directly establish the modal neutral file of the component through the Auto Flex module in ADAMS. This operation has a long cycle, and it isn’t suitable for application in the cyclic parametric simulation. Instead, the second one is very convenient for parametric modeling and simulation.
The \textit{x}\_t file of the link, which is built in Solidworks, should be imported into Abaqus, is set with the relevant material properties, the assembly processing, and two steps to analysis: the first step is to extract the natural frequency of the part, and the second step is to generate the substructure which is integrated the discrete elements into a whole. Then, some point should be established to connect other parts in the link. The mesh of the link should be divided into eight-node linear hexahedron elements. Finally, some modified keywords set the interface with ADAMS. The modal neutral file (.mnf) generated by the GUI operation is imported in ADAMS and replaced with the corresponding parts in the model to integrate, as shown in Figure 4.

![Fig.3 The comparison of RVABI displacement between flexible link and rigid link](image)

3.4. \textit{Analysis of collision constraint caused by kinematic pair clearance}

There is a clearance fit caused by manufacturing errors, design tolerances, wear during operation, and other factors of the relative rotating motion pair, and the relative rotation of the shaft and the bushing will produce mutual collision and contact force, which will affect the displacement accuracy. It also can cause the mechanism to vibrate, which will reduce the stability. Contact collision is set between the rotational shaft and the cartridge receiver, as shown in Figure 5.

![Fig.4 The rigid-flexible coupled parametric model](image)

3.4.1. \textit{The contact collision force calculation in ADAMS}

The Hunt-Crossley contact force model is the most effective way of dealing with contact collision, which is an improved model. It uses a nonlinear spring-damper element to compensate for the elastic deformation of the contacting object during the contact process in the Hertz contact force model, which doesn’t take into account the energy loss, to simulate the contact collision deformation process. Its expression is as follows in Equation 1:
\[ F_N = K \delta^n + D \delta_p \]  

(1)

Where, \( \delta \): the contact depth of two parts; \( n \): the force index \( K \): the contact stiffness of two parts, the calculation formula is shown in Equations 2-3 as follows:

\[ K = \frac{4}{3(h_i + R_j)} \left( \frac{R_i R_j}{R_i + R_j} \right)^{\frac{1}{2}} \]  

(2)

\[ h_l = \frac{1 - \mu_i^2}{E_i} \]  

(3)

Where, \( E \): Elastic modulus \( \mu \): Poisson ratio \( R \): contact radius \( i, j \); \( D \): the damping coefficient related to the contact stiffness; the calculation formula is shown in Equation 4 as follows:

\[ D = \frac{3K(1 - e_r)\delta^n}{2\delta v_0} \]  

(4)

Where, \( e_r \): the coefficient of restitution; \( \delta v_0 \): Initial relative contact collision velocity

The built-in IMPACT function is used to calculate the contact impact force generated by the contact impact between the shaft and the bushing in the rotating pair based on the theoretical assumptions of H-C contact theory in ADAMS. It is shown in Equation 5 as follows:

\[ \text{Impact} = \begin{cases} 0, & \delta \leq 0 \\ K\delta^n + \text{STEP} \times \delta, & \delta > 0 \end{cases} \]  

(5)

The normal contact force is proportional to the stiffness coefficient \( K \), and the collision depth is within \( 0 \leq \delta \leq \delta_{\max} \) during the collision. The reaction force caused by the contact is calculated with a cubic approximation Heaviside step function \([6]\) that defines the relationship between the collision depth and the damping coefficient by the damping component to replace Equation 1. The damping coefficient \( C_{\max} \), which is about 0.1%-1% of the contact stiffness coefficient, reaches the maximum value at the same time when the collision reaches the maximum depth: \( \delta_{\max} \). The STEP function of the damping coefficient term in this contact impact force model to respect the relative contact impact velocity in ADAMS is shown in Equation 6. The contact collision process can be simulated more realistically by calculating the normal contact force by this method to some extent.

\[ \text{STEP} = \begin{cases} 0, & \delta \leq 0 \\ C_{\max} \left( \frac{\delta}{\delta_{\max}} \right)^2 \left( 3 - 2 \frac{\delta}{\delta_{\max}} \right), & 0 < \delta < \delta_{\max} \\ C_{\max}, & \delta \geq \delta_{\max} \end{cases} \]  

(6)

3.4.2. The friction model in ADAMS

The shaft and the sleeve in the rotating pair containing the clearance will inevitably generate friction, which is also the component of tangential contact force during the contact collision process. So, the dynamic modeling, which is the RVABI of the rotating pair including the clearance, needs to consider the effect of friction. There are mainly two types of friction in the clearance pair: dry friction and friction considering lubrication. This paper selects dry friction to research to simplify the dynamic model. The modified Coulomb friction model is used in ADAMS to describe the friction from static friction to dynamic friction and the viscous and micro-slip phenomena at low speed. The accuracy of the dynamic friction coefficient must be ensured during simulation calculation because kinetic friction accounts for the main part of the friction. The sliding friction coefficient is set to about 0.55 for the dry frictional contact in titanium alloy materials to ensure that the boundary conditions are consistent with the theoretical numerical calculation. Moreover, setting the parameters of static friction coefficient, static slip velocity, and dynamic slip velocity in the Coulomb friction model is used to calculate the tangential friction force generated during contact motion. A set of collision parameters of this model can be obtained by consulting relevant materials, as shown in Table 1.

| Table 1 The Parameters of the Impact |
|-------------------------------------|
| Name                | Contact stiffness: K | Contact depth: \( \delta \) | Force index: n | Damping coefficient: C |
|----------------------|----------------------|-------------------------------|----------------|------------------------|
| Value                | 2.6E+05N/mm          | 0.1mm                        | 1.5            | 25Ns/mm                |
3.4.3. The analysis of clearance in collision
The wear of the rotating pair with clearance is aggravated due to the continuous movement of the rotating pair. Therefore, the change, which is the more significant gap size, is studied by changing the size of the gap between the shaft and the bushing with the condition that other factors in the function remain unchanged. When setting the gap size: c=0.1mm, 0.08 mm, and 0.05mm respectively, the comparison results with the dynamic characteristics of the mechanism among different gap sizes are calculated as shown in Figure 6. It is found that the size of the gap has a significant effect on the contact collision force-based results. With the continuous increase of the gap, the amplitude of the contact collision force curve is continuously increased, and the fluctuation becomes more severe to cause the motion errors. So, the larger the gap, the more extensive the motion errors.

![Fig.6 The contact collision force with different gap sizes](image)

3.5. The motion simulation and theory verification
The translational drive is applied to the hydraulically driven translation pair. The script is set and carried out the solution analysis that the displacement of the flow control ring is 120.6414mm. The motion relation Equations 7-10 can be solved in MATLAB. The comparison between the obtained results and the simulation results can verify the parametric model’s correctness to ensure the simulated motion’s accuracy.

\[
\begin{align*}
    y_1 + L_2 \sin \theta_2 &= L_1 \cos \theta_1 \\
    L_2 \cos \theta_2 + L_1 \sin \theta_1 &= x_1 \\
    L_3 \cos \theta_2 + x_2 &= L_4 \cos \theta_3 \\
    L_3 \sin \theta_2 - y_2 &= L_4 \sin \theta_3
\end{align*}
\]

Where, \( y_1 \): the projected distance from the drive-shaft to the hydraulic link in the y-direction; \( x_1 \): the projected distance from the drive-shaft to the hydraulic link in the x-direction; \( L_1 \): the length of the hydraulic link; \( L_2 \): the length of the outer rocker arm; \( L_3 \): the length of the internal rocker arm; \( L_4 \): the length of the internal link; \( \theta_1 \): the angle of rotation of the hydraulic link; \( \theta_2 \): the angle of rotation of the outer rocker arm; \( \theta_3 \): the angle of rotation of the internal link.

4. The analysis of the dispersive dimension factor
The size of the parts cannot be guaranteed to be precisely equal or equal to the ideal size, even if the parts are produced in the same batch, due to the existence of machining accuracy errors during the manufacturing process. It’s especially significant on the influence of the dimensional dispersion of some critical parts for the motion accuracy of the mechanism. The parts’ grade of tolerances is determined according to “The Guidelines for Failure Modes, Effects and Hazard Analysis of Aerospace Products”. Furthermore, the maximum displacement deviation of the flow control ring is calculated in Table 2 when each part has the largest tolerance.

The analysis is that the dispersity of the outer rocker arm’s length significantly affects the motion accuracy of the RVABI, and it’s the most constrained in position precision. Therefore, this paper chooses the dispersive dimension of the outer rocker arm to study the degree of influence on motion accuracy.
Table 2 The table of deviations corresponding to tolerance

| Factors of dispersive parts                          | Displacement deviation (mm) |
|------------------------------------------------------|-----------------------------|
| The length of the outer rocker arm                   | 120.64±0.034                |
| The length of the internal rocker arm                | 120.64±0.017                |
| The installation angle of the internal rocker arm    | 120.64±0.020                |
| The length of the internal link                      | 120.64±0.001                |

5. The reliability evaluation of the RVABI

5.1. Establishment of an improved Monte Carlo model based on Latin hypercube sampling

It can avoid the problem that the Monte Carlo method is easy to extract from the distribution area with high probability, which leads to data aggregation and must extract too many sample points based on the Latin hypercube sampling method [7-10]. Firstly, the normal distribution describes the randomness produced by the joint action of many uncertain factors of the same magnitude. It is suitable for characterizing the size of parts. Secondly, writing a size dispersion program for the normal distribution of random numbers. A sampling program of size dispersion is written based on the random numbers of the normal distribution. The program can ensure that random numbers exist in each average distribution interval hierarchically by the LHS method, calculate the expected distribution probability under the current random number through the error function, and compare the probability calculated by the dichotomy method. Finally, the current random number is determined within the error range, and the random array is generated in turn. Then the .c file is embedded in ADAMS for the dynamic connection. The relevant batch commands on the ADAMS commander are executed to act the loop simulation, and the calculation of Equation 11 determines the minimum sampling times of 3500 times.

\[ N = \left( \frac{Z_{\alpha/2} \cdot \sigma}{ME} \right)^2 \]  

(11)

Where, N: The number of sampling points; \( Z_{\alpha/2} \): Confidence level; \( ME \): the margin of error; \( \sigma \): The standard deviation of the part.

5.2. The reliability analysis of motion accuracy considering the influence of dispersive dimension

The result of each simulation is output and saved to a text file by the command in ADAMS, and the text file with 5000 simulation results stored is used for statistical analysis of data in MATLAB. The failure criterion, which is that the translation error exceeds ±0.03mm will be invalid, should be formulated. The read-in text file counts the number of failures in the simulation according to the failure criteria. The statistical analysis is as follows: the number of failures is 32 times, and the number of failures accounted for 0.65% of the total sampling times. It can be concluded that the reliability of RVBA in the case of the randomness of the parameters of the active arm is 99.35%. The frequency distribution histogram of the displacement of the flow control ring is shown in Figure 7.
6. Conclusion
This paper draws the following conclusions for the RVABI, based on the multi-factor simulation analysis and research according to the use of the parametric module design:

(1) The parametric modeling method is used for mechanism design, which can quickly determine the key dimension parameters of the mechanism and better meet the design requirements; the feasibility of the scheme is verified, and the simulation design efficiency is improved while ensuring the accuracy of the results.

(2) The flexible processing of critical parts and the rigid-flexible coupling simulation can more accurately reflect the motion error caused by deformation, which is more in line with the actual working conditions. It also can guarantee the simulation authenticity while ensuring the calculation efficiency and time balance.

(3) The effect of the contact force generated by the clearance rotating pair on the motion accuracy is reflected in the parametric modeling. The difference of motion under different restitution coefficients is analyzed. It plays a vital role in the analysis and prediction of the dynamic behavior of the mechanism.

The reliability mapping the single failure mode based on dimensional dispersion is calculated, laying the foundation for the subsequent reliability analysis and evaluation. It provides reliability analysis and kinematic research support for following research on the RVABI.

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