Dynamic simulation method of adjustable nozzle considering clearance fit

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Abstract. Aiming at the motion stagnation and local damage failure of a 2D needled Cf /SiC adjustable nozzle during operation, the motion performance of the nozzle and the contact stress at the key parts were studied. A dynamic simulation method of the nozzle with adjustable nozzle considering clearance fit was established, and the throat contraction process was analyzed by a simulation example. Firstly, the critical analysis positions of the nozzle were determined by trial calculation, and the model was simplified and the mesh was optimized. Then, the simulation was carried out under the boundary conditions involving multiple fields. The motion characteristics of the nozzle throat during the throat contraction process were analyzed due to the velocity results, and the stress state and failure state at the key position of the nozzle during the impact process were finally determined.

1. Introduction
The adjustable nozzle is an important part of the engine, which can change the working state of the engine by adjusting the nozzle flow through throat contraction. In order to adapt to the high temperature working environment, the parts of a certain type of nozzle are made of 2D needled Cf /SiC composites. Cf/SiC composites have high hardness, brittleness, the worse performance of machining features, resulting in the exhaust components are larger processing error and poor surface morphology, done in by air pressure control mechanism action, easy to place in the key assembly connection and mutual sliding parts produce bigger impact load and high local stress, causing key parts move higher binding and failure risk, seriously affecting the exhaust mechanism reliability.

At present, the research on the simulation of adjustable nozzle is limited, and most of them focus on the control of the nozzle and the gas simulation, etc., and the simulation analysis on the actual kinematic performance, mechanical performance and failure risk of the nozzle is rarely carried out. Zhang Hong, Chen Yuchun et al. performed fluid simulation for an adjustable nozzle of a ramjet\textsuperscript{[1]}. Qiao Zhou et al. analyzed and optimized the thermal performance of a variable section nozzle\textsuperscript{[2]}. Chen Guohua and Liao Ridon from Beijing Institute of Technology proposed a simulation prediction method for the flexibility of adjustable nozzle and studied the influencing factors of its flexibility\textsuperscript{[3]}, but the gap fit of the nozzle structure in the actual situation was not considered. In view of the above situation, a dynamic simulation method is proposed in this paper, which considers multiple field interactions, assembly clearance and vibration, reasonable mesh creation and analysis scale of composite materials.
2. Dynamic Simulation of Nozzle
The dynamic simulation analysis of nozzle throat shrinkage mainly involves the determination of analysis type, the establishment of analysis model, mesh division and optimization, and the determination of composite analysis scale, etc. According to the analysis process, it can be divided into three parts: input, pre-processing and post-processing. The flow of simulation analysis method is shown in Fig.1.

![Simulation analysis method flow](image)

2.1. Validation of Analysis Type
There is a large gap in the key fitting parts of the nozzle, and the contact state is unstable under the action of temperature field and impact condition, which leads to poor convergence of the simulation model, and it is difficult to converge if the statics and implicit dynamics model are used. At the same time, according to the trial calculation, the implicit dynamics occupies a lot of memory and calculation force, so the simulation calculation is difficult to complete. Therefore, the display dynamics, which is suitable for analyzing instantaneous impact, occupies less memory and computing force, is adopted. The explicit algorithm is based on the Newmark method of dynamic equation and adopts the difference scheme of dynamic equation. It does not need to directly solve the tangent stiffness, and does not need to carry out equilibrium iteration, so it has good stability and convergence.
2.2. Establishment of simulation model

The structure of the nozzle can be regarded as the connecting rod slider system on the two-dimensional projection plane, and its schematic diagram is shown in Fig. 2, where A, B and C are the joint pin with clearance fit.

![Figure 2 Principle of nozzle mechanism](image)

The nozzle has two states: large throat and small throat. Switching is completed through throat contraction action. The key pose data is calculated according to the size of the drawing, as shown in Table 1.

| Column 1 Key size and pose data of nozzle | Value (mm) | Angle range of $\alpha$ |
|------------------------------------------|------------|-------------------------|
| Diameter of wide throat state            | 230        |                         |
| Diameter of narrow throat state          | 188        |                         |
| Move Distance of joint pin C             | 10.8       | 136.74°-180°             |
| Distance between joint pin A and joint pin B | 58        |                         |
| Distance between joint pin B and joint pin C | 113       |                         |

Due to the axisymmetric structure of the nozzle, the quarter model of the nozzle is simplified, so that it is easier to obtain a high quality and moderate size mesh in the mesh division of the model, and then obtain a more ideal minimum stability time. PIN improves the calculation efficiency of the model. Through trial calculation, it is determined that Model A, B and C, which are the key analysis positions, bear obvious impact and large stress at the pin shaft. Therefore, the model was simplified for the distal end of the contact parts of other structures.

![Figure 3 Model of nozzle](image)

The main contents of the simplified model are as follows: the main body of the fixed end is removed, and only the key matching parts are retained; for complex fillet transition of non-key parts, small fillet positions of AB and BC pieces are trimmed. Since dynamic analysis is sensitive to mass variation, the mass variation caused by model simplification should be less than 1%[4]. Because the quality change of the model before and after simplification was 0.785%, less than 1%, the model simplification was considered to be within the acceptable range.

In addition, due to the poor machinability of Cf/SiC composites, for the consideration of function realization and processing technology, clearance fit is used at pin axes of A, B and C of the nozzle. In the modeling, the model was modeled according to the intermediate value of pin shaft and shaft hole size to better simulate the influence of assembly clearance on the simulation model.
The overall composition of the nozzle is composite material. Considering the analysis model type, analysis output type and analysis efficiency, the macro-scale analysis of composite material is adopted. The Cf/SiC composite material was regarded as homogeneous orthotropic material, and each part of the nozzle was assigned to it. The material coordinate system was consistent with the actual direction of layup, and the density was set according to the measured value.

The structure of the nozzle mechanism is complex, and there are some problems in the model, such as mesh division, mesh quality and mesh density change. In general, the shorter the minimum stability time is, the longer the simulation time will be. The minimum stability time is directly proportional to mesh size, mesh mass and material density, and inversely proportional to material stiffness. Smaller mesh size will lead to smaller minimum stability time and larger mesh number, which will increase the simulation calculation time. However, larger mesh size can easily lead to poor mesh quality and shorten the minimum stability time, which even exceeds the effect of smaller mesh size on the minimum stability time. In this paper, the methods of simplifying non-critical parts, model splitting and local mesh encryption are adopted to achieve both the simulation accuracy and the simulation efficiency while ensuring the less impact on the simulation results.

In order to ensure the quality of calculation, the structure is segmented. For key contact parts such as A pin, B pin and C pin, the structured mesh division method is adopted. For other non-key parts, tetrahedral mesh is adopted for mesh division. At the same time, mesh refinement operation is carried out for key parts. See Table 3 for grid type and number of each part.

Because of its function, the temperature field distribution of the nozzle has the characteristics of large temperature gradient. According to the actual working conditions, the inner temperature of the nozzle is 1530°C and the outer temperature is 530°C, which changes evenly in the diameter direction of the nozzle.

The nozzle is under the action of gravity field. The gravitational acceleration in the radial direction was applied to the simulation model, and the value was 9800mm/s^2.

The nozzle is driven by the pressure difference to complete the throat narrowing action. The pressure of the closed cavity is 0.12MPa and the size is constant. The pressure inside the nozzle is equal in circumferential direction and changes linearly in axial direction. Node positions and node pressure values are shown in Figure 3. According to the actual working conditions. The uniform distribution pressure of 0.12MPa was applied to the upper surface of the nozzle mechanism to simulate the driving pressure of the closed cavity. The driving pressure was applied instantaneously. The linearly varying pressure field on the lower surface of the nozzle mechanism is defined by analytical field function to simulate the actual movement load of each piece. The pressure at the front-end pin A is 0.16MPa, the pressure at the B-end pin is 0.1MPa, and the pressure at the back-end pin C is 0.04MPa. The pressure value changes linearly along the axis.

Symmetric boundary conditions were applied on the two symmetrical surfaces of the quarter model of the nozzle to limit all the degrees of freedom except the in-plane motion, so that the model could better simulate the whole motion state of the nozzle on the premise of improving the simulation efficiency. According to the actual motion state of the mechanism, all the degrees of freedom of the front end of the nozzle mechanism and the motion limit part are restricted, and all the degrees of freedom of the end of the nozzle except the axial motion are restricted.

3. Result and discussion
As it’s shown in fig.4, axial velocity-time curve of nozzle throat contraction process were drawn according to the simulation results obtained, present the attenuation volatility trend curve, it can be
seen that the nozzle contraction were firstly driven by pressure, then collision rebound happen when it reaches the limit position, the process repeats and decays, until eventually decays to stable state. Obviously, the maximum impact occurred in the process of the first collision and rebound. Therefore, the stress state analysis of joint pins A, B and C was carried out in the time interval of 6.5-8ms when the first collision occurred.

The Mises criterion based on the fourth strength theory is no longer applicable because the nozzle is orthotropic brittle material, and the mechanical properties in each direction are different, the compressive strength and tensile strength in each direction are also not consistent. Thus the failure analysis of pin A, pin B and pin C of the nozzle is carried out by the second strength theory. The curves of maximum tensile and compressive stress and average value of each pin axis in the material coordinate system in X, Y and Z directions (X, Y are 0 degree and 90 degree fiber bundle layer directions, and Z direction is the needle direction) were drawn, and compared with the tensile and compressive strength limits in X, Y and Z directions respectively. In addition, the ratio of tension and compression failure nodes of each pin in X, Y and Z directions was calculated, as shown in Fig. 7-9. In which T stands for tensile stress, C stands for compression stress, Max, min and avg stands for the maximum, minimum and average value respectively.
Figure 5 Curves of maximum and average values of tensile and compressive stresses and failure statistics of joint pin A

Figure 6 Curves of maximum and average values of tensile and compressive stresses and failure statistics of joint pin B
Figure 7 Curves of maximum and average values of tensile and compressive stresses and failure statistics of joint pin C

The simulation results show that the failure modes of A-pin are compression failure in X and Y directions and tensile failure in Z direction, in which the tensile failure in Z direction is the main failure mode. Pin B only has a small amount of compression failure in the Y direction. The failure modes of C-pin are compression failure in X and Y directions and tensile and compression failure in Z direction, of which the tensile and compression failure in Z direction are the main failure modes. Considering the stress and failure modes of the three joint pins, the stress on pin B is smaller than the other two joint pins, the ratio of failure node is less than 0.005% which indicates that almost no failure occurs. The stress on pin C is the largest, and the failure ratio in X, Y and Z directions is obviously higher than that of the other two pins, so there is a larger overall failure risk.

4. Conclusion
According to the dynamic simulation analysis of the composite nozzle with clearance, the stress concentration position is three joint pins A, B and C. According to the analysis of the axial velocity of the nozzle, the impact-rebound process occurs when throat contraction reaches the limit position, and the nozzle basically reaches a steady state after three reciprocating motions. Failure occurred in all three joint pins in the impact process during throat contraction. The failure of pin C was the most serious, followed by pin A, and pin B was the least. Therefore, in the subsequent optimization process, attention should be paid to the control of the stress on pin C to avoid the overall failure of the nozzle due to the serious failure of pin C.

The analysis can be used as the basis for determining the key factors affecting the mechanical properties of the nozzle, controlling of the stress during the working state, and enhancing the reliability of the nozzle.

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