The Coupling Analysis and Research of Temperature and flow Field

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Abstract

To the solid rocket axisymmetric thrust-vectoring nozzle, under the action of flow field and temperature field, Comsol Multiphysics is used for this mechanism to simulate the load deformation and thermal deformation of the convergent plate, sheet, rod expansion regulation and other components, and to analyze the dynamic characteristics of the system in the generator mode under the two field coupling. Simulation and analysis to forecast the deformation of the mechanism accurately have important theoretical significances to the design of the system.

Keywords

Axisymmetric Vectoring Exhaust Nozzle; Dynamics; Coupling; Simulation

Introduction

In this paper axisymmetric jet engine thrust-vectoring nozzle treated as the prototype which is based on axisymmetric vectoring nozzle (AVEN) to model. From the beginning to the maximum swing angle of the swing and then to restoration because of the dual role of flow-temperature field, the divergent flap, the convergence closure disk of nozzle will produce dynamic load. In order to verify if the kinematic parameters (displacement, velocity and acceleration) meet the requirements of the system design, it’s necessary to analyze its multi-field coupling.

Currently, it’s very common to research the solid rocket motor of full swing axis TVC system. Dual Stewart platform driven thrust-vectoring nozzle is developed on the conventional mechanical nozzle and has been applied to the latest foreign aircraft engine (fighter). However, there is no report on the application of Stewart platform driven thrust-vectoring nozzle to the solid rocket motors (Comsol Multiphysics). Authors used Solid works, three-dimensional graphics software, to model and then Comsol Multiphysics was applied for physical field coupling analysis. Comsol Multiphysics an advanced numerical simulation software, developed by the Swedish Comsol and widely used in various fields of science and engineering computing is the first truly multi-physics of any direct coupling analysis software and with its efficient computational performance and outstanding multi-field coupling analysis capabilities, it has achieved an accurate numerical simulation of arbitrary multi-physics highly, which is widely used in the global leader field of numerical simulation (Huang ZhenYu, Xu WenCan, Mao HongYu, 2000); as well, it has a powerful solver for solving multi-field coupling analysis, which differs from other simulation software and can help improve the design accuracy of axisymmetric vectoring nozzle (AVEN).

AVEN Model

There is widely existent large drive torque, contact stress of moving parts, deformation and other issues in the thrust vector control system of domestic solid rocket motor. This subject includes a scheme, simultaneously adjusting the thrust-vectoring and throat diameter of nozzle and the fixed body is guaranteed on the divergent of the nozzle during the process of adjusting the thrust and direction, of dual Stewart platform thrust-vector which is driven by the linear motor. When a small amount of load is distributed in the expansion piece of the nozzle which is driven by a linear motor, moving parts change from a high-load, high-temperature and high-pressure into a relative low-load, low-temperature region. As nozzle is far away from the center of gravity of the rocket, a small deflection angle will produce enough torque deflection (generally the deflection angle requires only 6° ~ 8°), at this time, the impact on the axial thrust is only 10% or so. Therefore, even if the thrust of rocket engine is great, the driving force required for the vector nozzle in this program is very limited, which provided the conditions of directly using the linear motor to driven. Reducing the driving force of the system means to reduce the weight of the system (if
the engine is reduced by 1 kg, the range will be increased by 20 ~ 30 km). Compared with conventional hydraulic drive, Linear motor drive is not only reduces the weight of the rocket nozzle but also improves control accuracy (Comsol Multiphysics). The composition of thrust-vector of dual Stewart platform system driven by linear motor is shown in Fig. 1. The basic structure of the apparatus is: the divergent section of the nozzle (stationary object), A1 regulation ring,A2 steering regulation ring, the convergent flap 1, the expansion closure disk 2, the divergent flap 3, pull rod 4, cross joint 5, the convergence closure disk 6 and other components.

![Diagram of nozzle structure](image)

**FIG. 1 THE COMPOSITION STRUCTURE OF DOUBLE STEWART PLATFORM THRUST-VECTOR SYSTEM**

For the perspective of mechanism, the device is a dual-Stewart platform complex spatial mechanism. Between the dual-Stewart platforms; there are dozen pairs of space hinge mechanism in parallel. The space combined guide convergent flap and expansion space flap is a closed expansion nozzle. The position and orientation of convergent flap are determined by the regulation ring A1; while the position and orientation of expansion flap are determined by steering adjustment ring of A1 and adjustable ring of A2. In order to achieve the oscillating motion of the nozzle, regulation rings A1, A2 are driven by a linear motor. The device consists of the three components which are front, middle and rear.

The front portion connected to the diffuser of nozzle for controlling the area A1, central portion is actuation mechanism for the expansion flap, and rear portion is expansion flap. In order to withstand rocket gas jet effect, the nozzle consists of convergent flap, expansion flap and the convergence closure disk. During the process of adjusting the thrust vector, the flap and the expansion sheet are always subjected to the pressure of the gas and the pressure changes with the nozzle. During the operation, it is the core issue of this new type of nozzle’s development that how to ensure coordinated movement of the convergence (expansion) flap and adjust of thrust vector.

**Coupling Numerical Methods and Turbulence Models of Flow-Temperature Field**

The problem of multi-field coupling in the system, consisting of two or more than two interacting field, is widespread phenomenon in the nature or electromechanical products. Mechanisms in the flow field, temperature field, electromagnetic fields, and force field are affected by all kinds of coupling parameters and have effects on the system dynamic performance. It is necessary to study the coupling mechanism of the physical field parameters, explore the essential rules of multi-field coupling. From the view of the system theory, considering the dynamics performance of the physical field of the system and establishing the partial differential equations which is a unified description of the dynamic characteristics of the system are necessary (Comsol Multiphysics). Flying at high altitude, the motor working temperature generated inside the nozzle and the fluid will produce stress and strain on the part of convergent and expansion section. In the literature (Wang YuXin, 2006), for the flow field of axisymmetric thrust vectoring nozzle is a typical transonic flow field, using Jameson’s finite volume method and three-dimensional Euler/NS equations to solve flow field of vectoring nozzle. In order to overcome the pulsation of the central difference scheme smooth area and oscillation of discontinuous solutions, it used artificial viscosity technique; in order to accelerate the convergence speed of solution, the local time step, enthalpy damping technology, average implicit residual, as well as Runge-Kutta time advance technologies of mixed step are utilized. Comsol Multiphysics is employed for coupling analysis of the mechanism.

When the nozzle at the position of 0°, the high temperature fluid which burst forth by the combustion chamber get to the outside world through the nozzle, the temperature of the fluid decrease from the high to low, the velocity increases gradually. Using the NS equations of time-dependent 3-dimensional Cartesian coordinates conservation to solve the problem of the nozzle in temperature and flow field. Turbulence type using $k-\varepsilon$ model, based on the development of eddy viscosity model contains part of the history effects of eddy viscosity. Specifically, it is associated with the
eddy viscosity and turbulent kinetic energy and turbulent kinetic energy dissipation; and the \( k \) and \( \varepsilon \) can solved by using them (Wang Tao, 1999). The following equations (1)~(6) are the control equations of the coupled field.

\[
\frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \left( \mu + \mu_t \right) \left( \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) - 2/3 \left( \mu + \mu_t \right) (\nabla \cdot \mathbf{u}) I + \nabla \cdot \mathbf{F} \tag{1}
\]

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \tag{2}
\]

\[
\frac{\partial k}{\partial t} + \rho (\mathbf{u} \cdot \nabla) k = \nabla \cdot \left( \left( \frac{\mu + \mu_t}{\sigma_k} \right) \nabla k \right) + P_k - \rho \varepsilon \tag{3}
\]

\[
\frac{\partial \varepsilon}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \varepsilon = \nabla \cdot \left( \left( \frac{\mu + \mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right) + C_{\varepsilon} \frac{\varepsilon}{k} P_k - C_{\varepsilon 2} \frac{\varepsilon^2}{k}, \tag{4}
\]

\[
\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon}, \tag{5}
\]

\[
P_k = \mu_t \left[ \nabla \mathbf{\mu} \cdot (\nabla \mathbf{\mu})^T - \frac{2}{3} (\nabla \cdot \mathbf{\mu}) I \right] - 2/3 \rho k \nabla \cdot \mathbf{\mu} \tag{6}
\]

In the equations:
- \( \rho \) — Flow density
- \( p \) — Stream Pressure
- \( \mathbf{u} \) — Airflow velocity field
- \( k \) — Turbulent kinetic energy
- \( C_p \) — Atmospheric heat capacity
- \( C_\mu \) — Specific heat capacity

Nozzle and air physical parameters in Table I and Table II:

**Boundary Conditions and Mesh Generation**

Boundary conditions of the flow field of nozzle include:

Inlet boundary condition: given total temperature, total pressure and velocity direction of import nozzle. Outlet boundary conditions include: total external pressure. Wall boundary conditions: no penetration, no-slip condition, pressure gradient is zero. Inlet velocity is 150m/s. Pressure is 6e6Pa, outlet velocity is 2000m/s, the outlet pressure is 0.11e6Pa.

**FIG. 2 COMSOL MULTIPHYSICS MESHED**

Temperature field of the nozzle boundary conditions: Inlet and outlet boundary conditions: Temperature of given inlet is 3000K, outlet temperature is 1300K. Calculation parameters: inlet radius of nozzle is 81.25 mm; throat radius is 167mm; convergence length is 123 mm; expansion length is 191mm; vector deflection angle is 0°; airflow inlet total temperature is \( t_0 \); pressure ratio is 2–8. This mechanism is axisymmetric and the one third of model is desirable to do analysis.

**Comsol Flow Field-Temperature Field Coupling to Solver Results**

**Temperature Change Map**

Figure 3 shows Bodies high temperature concentrated at the entrance to the nozzle diffuser in the given constraints. The maximum temperature is 3000 K.

<table>
<thead>
<tr>
<th>steel</th>
<th>density</th>
<th>Viscosity</th>
<th>thermal conductivity</th>
<th>Specific heat ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value (units)</td>
<td>7850 kg/m³</td>
<td>1</td>
<td>46.1</td>
<td>43.53</td>
</tr>
</tbody>
</table>

**TABLE THE RELATION OF ATMOSPHERIC HEAT CAPACITY AND TEMPERATURE OF STEEL**

<table>
<thead>
<tr>
<th>T/C</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>755</th>
<th>900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cp/(J/Kg)</td>
<td>480</td>
<td>498</td>
<td>524</td>
<td>560</td>
<td>615</td>
<td>700</td>
<td>854</td>
<td>1064</td>
<td>806</td>
</tr>
</tbody>
</table>

**TABLE II PHYSICAL PROPERTIES OF DRY AIR**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Density (kg/m³)</th>
<th>Specific heat (kJ/kg°C)</th>
<th>Thermal Conductivity (W/m°C)</th>
<th>Dynamic Viscosity (Pa*s)</th>
<th>Specific Heat Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>(°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1.205</td>
<td>1.013</td>
<td>2.593</td>
<td>1.81</td>
<td>1.4</td>
</tr>
<tr>
<td>300</td>
<td>0.615</td>
<td>1.047</td>
<td>4.605</td>
<td>2.97</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>0.329</td>
<td>1.114</td>
<td>7.176</td>
<td>4.43</td>
<td></td>
</tr>
</tbody>
</table>
Pressure Change Map

In the given constraints, fluid pressure changes within the organization shown in Figure 4. Maximum pressure $p_{\text{max}}=8.2304\times10^{19}$Pa on the side of convergent flap. In Figure 4, the structure shows the Pressure value in Yellow area $p=1$Pa, Minimum pressure is 0 Pa.

Conclusion

Based on the problem of multi-physics coupling of nozzle, it has been researched how to do with the process of multi-physics coupling and delimit on a variety of constraints and boundary conditions of multi-physics problems. Through assembling Three-dimensional model, Comsol Multiphysics three coupling method (Flow field - temperature field - Solid Mechanics) was adopted for solving simulation. Research showed the exact stress in the three coupling method combined effect and heat conditions was clear through using multi-physics coupling analysis software. The operator interface of Comsol Multi-physics Software was simple to understand. Coupling method was directly coupled but not sequentially coupled. This article was significant to study and analyze the axisymmetric vectoring nozzle (AVEN).

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