Stress and deformation analysis of the turbine in liquid rocket engine using fluid-thermal-structure coupling method

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ABSTRACT

The turbine is widely used in the aerospace industry such as liquid rocket engine (LRE). The turbine in LRE is under extreme conditions of high temperature gradient, high pressure and high rotation speed. The safety assessment of the turbine during operation is essential in the design period. In this paper, the stress and deformation analysis of the turbine in LRE based on three-dimensional fluid-thermal-structure coupling method is investigated. First, the unsteady flow and heat transfer analysis of the turbine is performed using Computational Fluid Dynamic (CFD). The time average method is applied to obtain the pressure and temperature results. Then, temperature and pressure results obtained from CFD calculation are assigned as thermal and aerodynamic loads through coupling analysis. Finally, the stress and deformation distributions of rotor are analyzed under different load conditions using Finite Element Method (FEM). The results of this paper can provide some references for the turbine design in LRE.

INTRODUCTION

The turbine is widely used in the aerospace industry such as liquid rocket engine (LRE). In LRE, the turbine is under extreme conditions of high temperature gradient, high pressure and high rotation speed rotating that involves complex aerodynamics, heat transfer, and structural deformation. Considering the characteristics of its complex fluid-thermal-structural coupling, combining the CFD and FEM to obtain the temperature distribution became the research focus. Sun et al. [1] showed the difference between heat transfer computation and experiment of rotating cavity includes a buoyancy model driven. Tian et al. [2] computed on experimental model and the computational results were similar with the experiment. Tian also found the similar circulation flow model, and
the results of tangential velocity and radial Nu distribution were qualitative similar with the experimental data. A.Gunther et al. [3] carried out the CFD/FEM coupling transient analysis of the mid-plate temperature distribution and thermal conductivity of the two-cavities rotating geometries. The results showed that the prediction of surface temperature distribution is quite accurate, but the error of heat flux is relatively large.

The turbine rotor is simultaneously subjected to mechanical and thermal load. The stress analysis for the turbine in LRE is usually necessary for safety and reliability. Some numerical analysis on fluid-thermal-structural coupling of turbine blade have been proposed. Ho and Paull [4] described a method to implement aerodynamic heating models into a finite element code for thermal-structural and thermal-structural-vibrational analyses of a hypersonic engine. A combined effect of varying dynamic pressure and thermal loads was considered, and thermal-structural vibrational response of an engine was studied. Shen et al. [5] conducted a fluid-thermal-structure coupled analysis and an optimization of a turbine mortise/disc. In their work, a complete multidisciplinary method containing fluid-thermal-structure of the mortise/disc was formed, taking influence of the fluid flow and heat transfer into account. Krishnakanth et al. [6] carried out finite element analysis for the structural and thermal analysis of gas turbine rotor blades. They found that the temperature had a notable effect on the overall stress in the turbine blades. Other relevant works involving multidisciplinary analysis and optimization design of gas turbines can be found in references [7–11].

In this paper, the ANSYS software is used for a fluid-thermal-structural coupling analysis the turbine in LRE. At first, an unsteady flow analysis is conducted to obtain temperature distribution and the aerodynamic pressure on the turbine. The time average unsteady method is applied to obtain the pressure and temperature results. After that, the stress and deformation analysis are then conducted considering three cases of loads: thermal load, aerodynamic load combined with centrifugal load, and all the three types of loads. Unlike the previous studies, this paper systematically studied the three cases to ensure the safety and reliability of the rotor in LRE.

**NUMERICAL METHOD AND COMPUTATIONAL MODEL**

**COMPUTATIONAL MODEL AND BOUNDARY CONDITION**

The total pressure and total temperature are applied as inlet conditions. The inlet turbulence intensity is 5%. At the outlet, a static pressure is defined. In the simulation, at the rotor-stator interface frozen rotor method is applied to dealing with rotor-stator interaction. The solid boundaries are assumed to be adiabatic, and a no-slip boundary condition is applied along the solid boundaries. Only conduction and convection are taken into account. Radiation is neglected since differences in surface temperatures are small. The SST turbulence model developed by Menter [12] is used in the computations.

A turbine rotor in LRE has been taken as a study object. The calculation flow chart is shown as Figure 1. In order to simulate the flow and heat transfer in the turbine more accurately, unsteady flow analysis in the turbine is conducted to obtain the pressure and temperature on surface of the rotor. The time average unsteady method is applied to obtain the pressure and temperature results. Then the results are applied to the rotor for structural analysis. Due to the existence of radial gas intake, the computational model is composed of 35 rotor blades, corresponding rotor passage and stator passage. The geometry of the rotor is shown in Figure 2, and the flow domain is
shown in Figure 3. The ANSYS ICEM is used for the structured mesh generation in CFD calculation, hex dominant mesh method is chosen and mid-side node is kept to get hexahedral mesh for structural analysis. The mesh of fluid domain and solid domain is shown in Figure 4.

**Figure 2** Geometry of the rotor in LRE

**Figure 3** Fluid domain of turbine in LRE

**Figure 4** Mesh of fluid domain and solid domain

**LOADS AND MATERIAL PROPERTIES**

The material properties used in the rotor are given in Table 1. Considering the effect of temperature, the material properties under different temperature are listed. The load on the rotor in this paper consists of thermal load resulting from the temperature gradient in the rotor, centrifugal load caused by the rotation speed, and aerodynamic load derived from the aerodynamic pressure. The rotation speed is 16000r/min.

**RESULTS AND DISCUSSION**

**FLOW AND HEAT TRANSFER CHARACTERISTIC**

In this section, the time average unsteady pressure and temperature fields in the turbine rotor are analyzed. The flow pattern and heat transfer characteristics are investigated. Figure 6 shows the dimensionless pressure distribution on the rotor blade. In the rotor blade passage, the gas does work by expansion, leading to a decrease in the pressure along the blade passage. A significant increase in pressure is observed at the pressure surface around the leading edge. The maximum pressure occurs at the shroud of pressure surface.

The analysis of the rotor temperature is very important because it has a notable effect on the thermal stress calculation. Figure 7 shows the dimensionless temperature distribution on the rotor. As observed, the dimensionless temperature on the blade is relatively high because of the convection heat transfer between the blade and hot gas. Because parts of the cryogenic cooling liquid bleed into blade passage, there are low temperature regions around the hub on the suction surface and pressure surface. Meanwhile, there is a large radial direction temperature gradient at the leading edge, especially in the location of blade hub.
### TABLE 1 MATERIAL PROPERTIES OF ROTOR

<table>
<thead>
<tr>
<th>Temperature</th>
<th>°C</th>
<th>20</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>W·(m·K)^{-1}</td>
<td>12.34</td>
<td>12.34</td>
<td>13.93</td>
<td>15.48</td>
<td>17.03</td>
<td>18.62</td>
<td>20.29</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>GPa</td>
<td>226</td>
<td>222</td>
<td>217</td>
<td>211</td>
<td>205</td>
<td>198</td>
<td>192</td>
</tr>
<tr>
<td>Coefficients of thermal expansion</td>
<td>10^{-6} °C^{-1}</td>
<td>11.49</td>
<td>11.49</td>
<td>11.82</td>
<td>12.38</td>
<td>12.80</td>
<td>13.11</td>
<td>13.45</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>/</td>
<td>0.32</td>
<td>0.33</td>
<td>0.32</td>
<td>0.33</td>
<td>0.34</td>
<td>0.35</td>
<td>0.36</td>
</tr>
<tr>
<td>Density</td>
<td>kg·m^{-3}</td>
<td>8300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 6 Dimensionless pressure distribution on the rotor](image1)

![Figure 7 Dimensionless temperature distribution on the rotor](image2)
**FLUID-THERMAL-STRUCTURAL COUPLED ANALYSIS**

The FEM package ANSYS is used for the stress analysis of the rotor blade based on the CFD analysis above. The time average unsteady pressure and temperature results are applied to the rotor for structural analysis. Three cases are considered to analyze the effect of different loads on the total stress of the turbine, as shown in Table 2.

**Stress distribution in different cases**

Figure 8 shows the thermal stress distribution on the rotor blade for Case 1. As observed, a stress concentration region occurs at the blade root of the leading edge. A maximum thermal stress of 1543 MPa occurs at the blade root of the leading edge. This is consistent with the high temperature gradient in this region obtained from CFD analysis. As shown in Figure 7, there is a high radial temperature gradient in the air intake side because of the existence of cryogenic cooling liquid.

Figure 9 shows the mechanical stress distribution for case 2. As observed, a maximum equivalent stress of 663 MPa occurs at the blade root of the leading edge. Besides, there is still a stress concentration region at the blade root of the leading edge. Especially, it is not easy to simulate the true constraint under operating condition. The constraint applied on support surface results in larger stress than reality. However, the constraint have little influence on stress results in the flow path, so the results in the flow path still has a good reference value.

The total equivalent stress distribution for case 3 is shown in Figure 10. The stress distribution is quite similar with that in case 2 and there is a maximum equivalent stress of 989 MPa occurs at the blade root of the leading edge. Through compared with stress results in these three cases, thermal stress is dominant in the total stress. However, the mechanical stress will counteract parts of thermal stress at the location of maximum equivalent stress. The value of maximum total equivalent stress is lower than that of thermal stress.

<table>
<thead>
<tr>
<th>Case</th>
<th>Thermal load</th>
<th>Centrifugal load</th>
<th>Aerodynamic load</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Thermal stress</td>
</tr>
<tr>
<td>Case 2</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Mechanical stress</td>
</tr>
<tr>
<td>Case 3</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Total equivalent stress</td>
</tr>
</tbody>
</table>

Figure 8 Distribution of thermal stress (case 1)
The maximum stress results in three cases are shown in Table 3. As observed, the value of thermal stress is the largest, and the mechanical stress is the lowest. The mechanical stress has a positive effect on reducing the total stress. Figure 11 shows the maximum equivalent stress in different blades for three cases. The rotor blades are numbered from 1 to 35. As observed, the thermal stress for case 1 is maximum. Due to the existence of radial gas intake, the stress fluctuation exists in three cases. The fluctuation of thermal stress is the largest, and the total equivalent stress is the smallest. The change tendency among three cases is similar.

The yield strength of the rotor material in the corresponding temperature is 897MPa, and the maximum total equivalent stress is 989 MPa. The value of maximum total equivalent stress is slight larger than that of yield strength. Therefore, reducing the radial temperature gradient to control the thermal stress is essential to the design of turbine rotor in LRE. On the other hand, increasing the mechanical stress to offset more thermal stress is also a method to reduce the total equivalent stress.

**TABLE 3 STRESS RESULTS IN DIFFERENT CASES**

<table>
<thead>
<tr>
<th>Case</th>
<th>Thermal stress (case 1)</th>
<th>Mechanical stress (case 2)</th>
<th>Total equivalent stress (case 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Result/MPa</td>
<td>1543</td>
<td>663</td>
<td>989</td>
</tr>
<tr>
<td>Location</td>
<td>blade root of leading edge</td>
<td>blade root of leading edge</td>
<td>blade root of leading edge</td>
</tr>
</tbody>
</table>

**Figure 11 Stress distribution in different blades**

**Deformation distribution in different cases**

Figure 12 shows the total deformation distributions for three cases. The total deformation increases gradually with blade height in three cases, and the maximum deformation occurs in the blade shroud. For case 1, the maximum thermal deformation of the rotor is 2.3028mm. For case 3, the maximum total deformation is 2.0397mm. Through compared with deformation results in three cases, thermal deformation is dominant in the total deformation.

The radial deformation distributions for three cases are shown in Figure 13. Similar with the total deformation, the radial deformation also increases gradually with blade height in three cases. For case 1, the maximum radial deformation of the rotor is 1.1217mm. For case 3, the maximum radial deformation occurring in the
blade shroud is 1.129mm. Heat is still the major influence factor on the radial deformation.

CONCLUSION

In this paper, the three-dimensional unsteady flow and heat transfer analysis of the turbine in LRE are conducted. The time average method is applied to obtain the pressure and temperature distributions. The stress and deformation distributions of the turbine are also investigated based on the above results. The main conclusions are summarized as follows.

1. For the rotor blade passage, the maximum pressure occurs at the shroud of pressure surface. A significant increase in pressure is observed at the pressure surface around the leading edge. Because parts of the cryogenic cooling liquid enter blade passage, there are low temperature regions around the hub on the suction surface and pressure surface. There is a large radial temperature gradient at the leading edge, especially in the location of blade hub.

2. With a consideration of thermal load, centrifugal load, and aerodynamic load, a maximum total equivalent stress of 989 MPa is obtained. A maximum thermal stress of 1543 MPa is obtained when only considering the thermal load, indicating that the effects of thermal stress is dominant in the total stress. When considering the effect of centrifugal load and aerodynamic load, a maximum mechanical stress of 663 MPa is obtained. Meanwhile, the mechanical stress will counteract parts of thermal stress at the location of maximum equivalent stress. Therefore, reducing the radial temperature gradient or increasing the mechanical stress is available to control the total equivalent stress.

3. The total deformation increases gradually with blade height in three cases, and the maximum total deformation occurs in the blade shroud. Through compared with total deformation results in three cases, thermal deformation is dominant in the total deformation. These results of this paper can provide some references for the turbine design in LRE.

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