NUMERICAL ANALYSIS OF EFFECTS OF TIP CLEARANCE ON COMPRESSOR PERFORMANCE AND NOISE CHARACTERISTICS

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The effects of tip clearance on compressor performance and noise emission are numerical analyzed in this paper. The compressor steady flow characteristics with different tip clearances are calculated under three different operating speeds, the compressor unsteady flow simulations are subsequently completed to obtain the noise sources, then the compressor noise is calculated through acoustic boundary element method (BEM). The results indicate that the total-to-total pressure ratio and efficiency of the compressor decrease with the tip clearance increasing, the trend is more obvious in high compressor rotating speeds. However, the compressor performance improves when the tip clearance increases in a small range 0-0.15mm. The analysis of compressor noise spectrum shows that the tip clearance has little influence on compressor tonal noise but there is a great influence on compressor broadband noise. The compressor noise has obvious acoustic directivity in the area of compressor inlet in all calculation cases, but the sound pressure level varies with the tip clearance changing.

Keywords: tip clearance, compressor, performance, noise, numerical analysis

1. Introduction

Turbochargers are widely used in internal combustion engines due to their capability in increasing efficiency [1]. With the development of design methods and materials, although turbochargers have high flow rate and pressure ratio in nowadays, but they also induce annoying noise, which has attracted the attention of the researchers. As the main component of turbocharger, the compressor noise significantly increases the turbocharger noise level. Raitor and Neise [2] completed an experimental study to explore the dominant sound generation mechanisms of the centrifugal compressors, they found that the discrete tonal noise (a series discrete peaks appear at blade passing frequency and its harmonics), tip clearance noise and Buzz saw noise (a series discrete peaks appear at rotor shaft frequency and its harmonics) are the main sources of noise. Therefore, experimental and numerical study on tip clearance noise have been conducted by many researchers. Booth [3] found that the loss due to leakage flow in the turbine can be as high as one-third of the turbine-level loss. Andrew [4] studied the three-dimensional flow at the tip clearance of a linear turbine through experiments and gave the velocity field of the tip clearance. J. Tallman et al. [5-6] used numerical simulation to illustrate the mechanism of leakage flow, they found the relationship between fluid parameters, turbine rotation, Reynolds number
and leakage flow. Senoo [7] found that the leakage flow loss is proportional to the gap size of centrifugal and axial impellers through theory and experiment.

The above researchers have many useful conclusions of compressor tip clearance, but their researches are only aiming at the effect of tip clearance on compressor conformance. As shown in Ref [2], the tip clearance also has significant influence on compressor noise. In this paper, six numerical models with different impeller gap sizes are simulated to study the effect of tip clearance on compressor performance and noise emission.

2. Numerical simulation

2.1 Numerical model

In this paper, the steady flow field is calculated first, then the results will be used as the initial flow field in the unsteady flow field. The pressure fluctuation on every grid nodes of the rotor inlet surface is extracted as the sound source information, which is used in the numerical calculation of compressor aerodynamic noise. The prediction process based on computational fluid dynamics (CFD) and boundary element method (BEM) is shown in Fig. 1.

![Flow field simulation](time domain) → Sound field simulation (frequency domain)

- Compressor steady flow field simulation
- Compressor transient flow field simulation
- Compressor dipole sound source (CGNS)
- Sound field calculation and analysis
- Acoustic boundary definition
- Sound source information import and data transfer

Figure 1: Noise prediction process

The centrifugal compressor of JTH150 turbocharger was selected as the research object, there were 8 main blades and 8 splitter blades, as well as 11 diffuser blades. Six different models were established, the tip clearance of the impeller was set to 0mm, 0.15mm, 0.3mm, 0.45mm, 0.6mm, 0.75mm, respectively, but the blade number, blade profile and other components of the compressor remain unchanged. The three-dimensional compressor model and numerical model (0mm) are shown in Fig. 2.

![3-D model](a) The 3-D model ![Numerical model](b) Numerical model (0mm)

Figure 2: Compressor model
Single flow passage and periodic boundary were used in compressor steady flow calculation, in order to reduce the calculation amount. The full computational fluid domain including inlet pipe, rotor, stator and volute, the domain was meshed with 1.2 million polyhedral cells approximately. Navarro [8] performed a mesh independence analysis, showing that a mesh twice as fine does not provide significant differences in terms of global variables and noise predictions.

2.2 Numerical simulation

In this paper, ANASYS CFX was employed for flow field calculation. In order to adapt to the complicated flow field of the compressor, the implicit $k-\varepsilon$ double equations turbulent model was used. Each numerical model was calculated under three operating speeds, including 36,000 r/min, 54,000 r/min and 64,800 r/min. The fixed inlet pressure, inlet temperature, and outlet pressure boundary conditions were employed, but when the operating conditions moved toward the surge line, the fixed inlet mass flow rate and temperature were applied to ensure the convergence of the numerical computation [9-10]. The residual was set to $10^{-6}$ to gain reliable flow field results. Several monitor points was used to obtain compressor performance in all cases.

2.3 Results of flow field

The effects of tip clearance on compressor performance are shown in Fig. 3. It is obvious that the change of tip clearance has obvious influence on compressor performance. It can be seen that in a relatively large range (0.15mm-0.75mm) of tip clearance, the increase of tip clearance will reduce the compressor flow range and the pressure ratio, big tip clearance will impact pressure ratio greatly as rotating speed increasing. However, for extremely small one like 0mm, the compressor performance becomes better at low rotating speed and small flow range, although the performance gets worse at high rotating speed and large flow range. The effect on isentropic efficiency is the same as pressure ratio.

It can be explained that due to the existence of tip clearance, there will be leakage flow in the flow field. When it meets the flow from impeller inlet, leakage vortex will be generated, resulting in energy loss. The increasing of tip clearance and rotating speed will deteriorate the phenomenon. But when the gap is too small, the internal flow field will be difficult to adapt to the change of boundary, which is especially obvious under high rotating speeds and large flow conditions.

(a) 36000r/min
3. Noise prediction

3.1 Acoustic model

In this paper, the compressor noise was calculated through BEM. Lee [11] introduced BEM to study the discrete tonal noise of centrifugal fans. The specific idea of BEM for solving the sound field was as follows, the BEM method transformed the differential equation of the computational acoustic field domain to the discrete integral equation of the domain boundary, and used the weighted method to calculate the integral value on the boundary [12]. The maximum calculation frequency was set to 22000Hz in order to show the noise peaks at BPF and its first two harmonics. It was usually assumed that there are at least 6 mesh cells in the minimum wavelength range, thus the maximum size of the boundary element was set to 2mm according to Eq. (1).

\[ l_{\text{max}} \leq \frac{c}{6f_{\text{max}}} \]  

(1)

Where, \( l_{\text{max}} \) is the maximum size of boundary element; \( c \) is the sound speed; \( f_{\text{max}} \) is the maximum calculation frequency.

This paper mainly studied the aerodynamic noise radiation characteristics under natural intake conditions, so the compressor inlet in the boundary element was set as open boundary. The rotor outlet surface was set as non-reflecting boundary in order to avoid effect of acoustic reflection. The field
point mesh was a spherical envelope surface with a radius of 1m at the compressor inlet. There was a monitor point in front of the compressor inlet. The acoustic mesh is shown in Fig. 4.

3.2 Numerical simulation

LMS Virtual. Lab was used for noise analysis in this paper. The sound field was calculated at a selected compressor operating condition, the rotating speed and the pressure ratio is 54,000r/min and 2.8, respectively. The time step in unsteady flow field calculation was set to 2.5e-6s, thus the impeller mesh turned no more than 1° per time step, this time-step is sufficient to accurately resolve pressure spectra within human hearing range [8]. 4000 time-steps were calculated to obtain periodicity pressure fluctuation, the results of the last 2500 time-steps were used for sound field analysis. The BPF of this case was calculated by Eq. (2).

\[ f_{BPF} = \frac{nZ}{60} \]  

Where, \( f_{BPF} \) is the blade passing frequency; \( n \) is the rotating speed; \( Z \) is the number of main blades.

3.3 Results of sound field

![Figure 5: Effect of tip clearance on compressor noise emission](image-url)

Figure 5: Effect of tip clearance on compressor noise emission
The noise spectrum obtained at the monitor point is shown in Fig. 5. As can be seen, the noise spectrum of each model has a series of noise peaks at 7200Hz, 14400Hz and 21600Hz. It also indicates that the change of tip clearance has little influence on compressor tonal noise but there is great influence on compressor broadband noise. Then, with the data of noise spectrum, total sound pressure level is calculated by Eq. (3). The results are shown in Table 1. The results of total sound pressure level show that the noise level increases when the tip clearance increasing.

\[
SPL_{total} = 10 \lg \left( \sum_{i=1}^{n} 10^{\frac{SPL_i}{10}} \right)
\]  

(3)

Where, \(SPL_{total}\) is the total sound pressure lever; \(SPL_i\) is the sound pressure lever at a certain frequency.

Table 1 Effect of tip clearance on total sound pressure level of the monitor point

<table>
<thead>
<tr>
<th>tip clearance (mm)</th>
<th>0</th>
<th>0.15</th>
<th>0.3</th>
<th>0.45</th>
<th>0.6</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>total sound</td>
<td>127.5</td>
<td>128.1</td>
<td>128.1</td>
<td>128.8</td>
<td>129.9</td>
<td>130.5</td>
</tr>
<tr>
<td>pressure level (dB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For further analysis, acoustic directivity at BPF was calculated, the result is shown in Fig. 6. We can see that the compressor noise has obvious acoustic directivity in the area of compressor inlet in all calculation cases, but the sound pressure level varies with the tip clearance changing.

Figure 6: Effect of tip clearance on acoustic directivity at BPF

4. Conclusion

In this paper, the effect of tip clearance on compressor performance and noise emission is numerical analysed. The main conclusions are as follows.

1) In a relatively large range of tip clearance (0.15mm-0.75mm), the increase of tip clearance will reduce the flow range, pressure ratio and isentropic efficiency, the trend becomes more obvious with rotating speed increasing. For the model without tip clearance (0mm), the performance becomes better at low rotating speed and small flow range, although it gets worse at high rotating speed and large flow range.
2) The change of tip clearance has little influence on compressor tonal noise, but the change has great influence on compressor broadband noise. When the tip clearance increases, the noise emission gets greater.

3) The compressor noise has obvious acoustic directivity in the area of compressor inlet in all calculation cases, but the sound pressure level varies with the tip clearance changing.

**REFERENCE**