Critical Speed Analysis of the Turbocharger Rotor System Based on ANSYS Workbench

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ABSTRACT

It is rather important to calculate the critical speed of high speed turbocharger rotor system in the design process of the turbocharger. Based on SolidWorks software, the solid model of the turbocharger rotor system was established, then the finite element analysis was carried out in the Workbench software, and the critical speed of turbocharger rotor was calculated. The finite element analysis of the compressor blade and rotor shaft of the turbocharger rotor system showed that the designed rotor system can achieve the requirements of the turbocharger. This conclusion provides a reference value for the design and analysis of turbocharger.

INTRODUCTION

The critical speed is a rather important performance which must be calculated in design process of the rotor system, the rotor system security and stability can be presented be from critical speed calculation results. At present, critical speed calculation are decided by two methods, as the transfer matrix method and finite element method [1]. The transfer matrix method can calculate the critical speed with high order of matrix number, and the order will not change easily even if free system changed. Compared with transfer matrix method, finite element method also has its own characteristics, such as longer calculation time, larger computer storage, and rather higher computation accuracy and precision. The expression of profile in place can completely avoid the transfer matrix of peripheral portion of the computational defects, very suitable for the analysis and calculation of the rotor system. Completeness and accuracy of the calculated can be guaranteed [2].

In this paper, the critical speed of the turbocharger rotor system was calculated by the finite element method, and the natural frequency of the turbocharger rotor system was obtained by modal analysis.

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MATHEMATICAL MODEL OF ROTOR SYSTEM

The rotor structure should be simplified before rotor system calculation, the discrete analysis can be considered as the best method for mathematical model, and discretization separates continuous whole or part into subunits to calculating.

Wanting to more close to the actual value in the model, it should increase the number of the simplified segmentation. But the number of discrete can not be too great, and too many parameters will be difficult to the calculation. So the simplify model must be appropriate.

The relationship between the disc and the shaft is established by the finite element method, and the dynamic differential equation of the rotor system is obtained by the finite element method, being showed as the following:

\[
\begin{bmatrix}
M_1 & 0 \\
0 & M_1
\end{bmatrix}
\begin{bmatrix}
q_1 \\
q_2
\end{bmatrix} + \Omega_1
\begin{bmatrix}
0 & J_1 \\
-J_1 & 0
\end{bmatrix}
\begin{bmatrix}
q_1 \\
q_2
\end{bmatrix} +
\begin{bmatrix}
k_1 & 0 \\
0 & k_2
\end{bmatrix}
\begin{bmatrix}
q_1 \\
q_2
\end{bmatrix} =
\begin{bmatrix}
F_1 \\
F_2
\end{bmatrix}
\]

Type: \( M_1 \) is for the overall quality of the matrix, \( \Omega_1 \) is rotation matrix, \( K_1 \) is stiffness matrix, \( K_1 \) and \( \Omega_1 \) are all \( 2n \times 2n \) order symmetric sparse banded matrix, \( q_1, q_2 \) are displacement vectors \( F_1, F_2 \), are for system load force.

MODAL ANALYSIS OF TURBOCHARGER ROTOR SYSTEM

D Modeling and ANSYS Workbench Pretreatment

The main premise of the analysis software is to simplify the model and ensure accuracy. According to the mathematical model of the rotor system of turbocharger, the SolidWorks software is used to established the turbocharger rotor system model as shown in Figure 1.

The model was imported into ANSYS Workbench, solid 187 unit of the analysis was used to discrete, it is a high-order derivable tetrahedral structural unit, with special quadratic displacement vector form.

Material of The Rotor System

The impeller of the compressor is made of aluminum alloy, and the material of the rotor shaft section is alloy of 40CrNi, and the impeller of turbine is made of the K-13 iron and the gold. The performance parameters of these materials are shown in Table 1.
Table 1. Material performance of the rotor system.

| Name               | Elastic modulus (GPa) | Density (kg/m³) | Poisson ratio |
|--------------------|-----------------------|-----------------|---------------|
| Compressor impeller| 72                    | 2680            | 0.33          |
| Turbine impeller   | 176                   | 8000            | 0.30          |
| Shaft section      | 200                   | 7820            | 0.30          |

**Rotor System Grid Division**

Based on the rotor system’s modeling and the consideration of bearing support stiffness, the rotor is divided by elements. In particular, the shape of the blade is very complex, so the mesh of finite element is divided into 62727 nodes and 34109 elements. The finite element model of the rotor system after meshing is shown in Figure 2.

![Figure 2. Mesh generation of turbocharger rotor system (finite element model).](image)

**Inherent Model Analysis of Rotor System**

In analysis of the rotor system’s natural frequency, it needs to draw the rotor system of front five order vibration diagram and to determine the dynamic characteristics of the rotor system, the front five vibration modes are calculated by the software of Ansys as shown in Figure 3.

![Figure 3. Turbine rotor five order formation diagram.](image)
The above figures shows overall around an axis of rotation (Fig.4a) and the graph in the vertical direction of the second order bending vibration (Fig.4b), graph illustrates the horizontal direction of the three order bending vibration (Fig.4c), the diagram explains vertical direction of four order bending vibration (Fig.4d), graph shows a horizontal direction of the fifth order bending vibration (Fig.4e). By the calculation of the workbench software the natural frequencies of the rotor system are obtained to determine the formation of the natural frequency, the inherent frequency. Based on the natural frequencies of the above modes, the Vibrate problem should be avoided when designing and manufacturing.

Rotor Critical Speed Analysis

When analyzing the critical speed, Campbell diagram is a very practical and direct graph. Horizontal coordinates representing speed, longitudinal axis of coordinates that represents natural frequency, a slope line was made from the origin in the graph, the node in this slope line corresponding to the intersection of horizontal and vertical coordinates is the critical speed. In this paper, the Campbell diagram of the rotor system obtained by the Ansys software for the finite element model (Figure 3) is shown in Figure 4.

![Campbell diagram of the rotor system.](image)

In the Campbell diagram, the overall slope curve is the curve representing the rotor eddy forward precession, 45 degrees straight intersecting abscissa corresponds to the forward precession of the critical speed, the overall slope is a negative curve representing the rotor vortex precession reversed curve and 45 degrees straight intersecting abscissa corresponds to the reverse precession of the critical speed. In this paper, the critical speed is generated when the forward vortex, so the actual critical speed must be considered in practical design, the solution of this study was shown in Table 2.

| order | first   | second  | third   | fourth  | fifth   |
|-------|---------|---------|---------|---------|---------|
| speed (rad/s) | 1288.3  | 1451.1  | 3082.2  | 3620.4  | 10119   |
| speed (r/min)  | 12302   | 13857   | 29433   | 34381   | 96629   |

Table 2. Five critical speeds of rotor.
CONCLUSIONS

This study established an entity model of the rotor using SolidWorks software, and the model was imported to ANSYS Workbench to conduct the grid division, then the system was analyzed with the Campbell diagram module in the workbench, acquiring the results of the critical speed analysis. Based on these results, the model of the first critical speed was calculated, and the relevant conclusions of the critical speed and the order of formation were obtained.

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