Modal Analysis of Rail Transit Gearbox

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Abstract. Modal analysis is an important method to study the dynamic properties of structures. In order to explore the effect of prestress on the dynamic characteristics of rail transit gearboxes, in this paper, a three-dimensional solid model of the rail transit gearbox was established, and the bearing reaction force of the transmission system was obtained by multi-body dynamics method. Considering the force transmitted by transmission system through the bearing seat to the case, the prestressed modal analysis of the rail transit gearbox casing was conducted by utilizing a finite element method, and the prestressed modal of the case was obtained. The modal parameters of the model were compared with the model of the case without prestress. The results manifested that the prestress has a significant on the modal characteristics of the gearbox casing, and the prestress of gearbox casing should be taken into account when conduct modal analysis.

1. Introduction
With the rapid development of urban rail transit and increasing passenger flow, growing requirements are imposed on the carrying capacity, reliability and bulkfactor of the rail transit drive system. In the process of transmission, the gearbox system has to withstand large load, thus resulting in large deformations and stresses [1]. In the application process, it also puts higher requirements on the reliability and life of the rail transit gearbox, minimizes the size and weight, and reduces the vibration and noise, which prompt the academic and industrial circles to conduct in-depth research on the dynamic characteristics and structural optimization of rail transit gearboxes.

Rail transit gearbox casing resonance can lead to large vibration and noise [2]. In addition, Xu & Shao [3] research demonstrated that about 90%~95% of the radiated acoustic energy of the gearbox is transmitted to the case in the form of solid sound through the gearbox casing vibration radiate to the outer space of the gearbox. Nevertheless, the modal analysis of the gearbox casing can identify the modal characteristics of the case, avoiding the phenomenon that the natural frequencies of the case and the meshing frequency of the transmission gear or the rotational frequency of the shaft is close to each other, which leads to the resonance of the case [4], analyzing the sensitive area of gearbox casing vibration. Therefore, an important research content of the vibration reduction and noise reduction of the gearbox is to optimize the design of the gearbox casing. According to the identified modal parameters of the gearbox casing by modal analysis, it is able to optimize the design of the gearbox casing. In recent years, many scholars have carried out extensive research work on modal analysis of gearbox casing [5-7], which mainly concentrates on computational modal analysis and experimental modal analysis.

However, there is little information available in literature about prestressed modal analysis of gearbox casing. In order to explore the effect of prestress on the dynamic characteristics of rail transit gearboxes. Based on the principle of multi-rigid-body dynamics, this paper obtained the supporting force
at the bearing seat of the gearbox, after that loaded the supporting force into the rail transit gearbox casing of FEM model and conducted the prestressed modal analysis, and compared the modal parameters of the rail transit gearbox casing with and without prestress.

2. Modal analysis theory
Modal analysis transforms the physical coordinates of the linear time-invariant system vibration differential equations into modal coordinates, decoupling the equations into a set of independent equations described by modal coordinates and modal parameters, which in order to obtain the modal parameters of the system [8]. The ultimate goal of modal analysis is to identify the modal parameters of the system, and to provide the basis for the analysis, fault diagnosis and prediction of the vibration characteristics of the structural system and the optimization design of the structural dynamic characteristics [9].

3. Transmission system dynamics simulation

3.1. Transmission system multi-rigid body dynamics model
As show in Figure 1, rail transit gearbox is composed of three-stage gear transmission, input stage is bevel gear transmission, intermediate stage and output stage is helical gear transmission. A three-dimensional solid model of the rail transit gearbox was built in SOLIDWORKS.

![Gearbox](image1)

![Transmission system](image2)

Figure 1. Rail transit gearbox solid model

The three-dimensional solid model of rail transit gearbox transmission system was imported into the ADAMS, which conducted multi-rigid body dynamics simulation. In order to obtained the supporting force of the transmission shaft in the transmission system dynamics simulation, a dummy object was established in the ADAMS, the rotating pair of the transmission shaft was defined, and the contact was set to transmit the interaction force between the gear teeth.

3.2. Transmission system multi-rigid body dynamics simulation
The input shaft was applied a constant input speed of 2100 r/min, and the output shaft was applied a constant load of 3000 N⋅m. The total time of the simulation was 0.5 s. Besides, the reaction force data of the nine support points of the drive shaft can be obtained, and the reaction force data of 0.2~0.5 s in the stable phase was taken. Figure 2 shows the supporting force of the position of bearing 1.
4. Gearbox Modal Simulation Analysis

4.1. Gearbox casing finite element model

The gearbox casing solid model imported into ABAQUS needs to be simplified, which helps to reduce the difficulty of meshing, improve the quality of meshing and improve the computational efficiency of finite element software. The simplified gearbox casing solid model was imported into ABAQUS. Due to the simplified case model have large curved surfaces and irregular geometric shapes, it is impossible to directly use the structured and swept grid to quickly divide the hexahedron mesh. The use of hexahedral meshing is not only difficult but also takes a lot of time. Therefore, the tetrahedral free meshing technique was used to directly mesh the case, with 206679 elements and 332435 nodes.

4.2. Gearbox casing constrained modal analysis

The finite element modal analysis of the rail transit gearbox casing was to obtain the modal parameters of the gearbox under constrained condition. So that the case avoids the external excitation
frequency and prevents the generation of the case resonance phenomenon. According to Figure 1, the gearbox was fixed to the outside by bolts. In the process of constrained modal analysis of the gearbox casing, the gearbox casing surface connected to the outside was selected to apply a fixed constraint to simulate the actual restraint of the case. Figure 3 shows the 3D FEM constraint model. The Lanczos method was used to analyze the modal of the gearbox casing, and the first 15 natural frequencies of the gearbox casing were extracted, and Figure 5 shows the first 8 model shape of the rail transit gearbox casing under constrained condition.

Mode 1: 196.63 Hz  
Mode 2: 263.58 Hz  
Mode 3: 555.18 Hz  
Mode 4: 658.18 Hz  
Mode 5: 716.52 Hz  
Mode 6: 846.95 Hz  
Mode 7: 937.50 Hz  
Mode 8: 1200.10 Hz

Figure 5. The mode shapes of the gearbox casing

4.3. Gearbox casing Prestressed modal analysis
At present, gearbox casing constrained modal analysis is mostly adopted to fully constrain the contact surface, which neglect the influence of the prestress caused by the gearbox working. This leads to a large error in the calculated simulation results. Therefore, the finite element modal analysis of the prestress of the gearbox casing has positive significance for obtaining accurate modal data.

The prestressed modal analysis of gearbox casing was carried out in ABAQUS. Nine reference points was established at the center of the bearing seat, which established coupling constraints with the bearing seat round surface. The supporting force data of gearbox transmission system obtained by multi-rigid-body dynamics simulation analysis was loaded into the corresponding reference points of FEM model of gearbox casing. Figure 4 shows the 3D FEM prestress model. Setting up two simulation analysis steps, the first one was static analysis step, and the second one was frequency analysis step. The first 15 natural frequencies of the prestressed modal analysis of gearbox casing was extracted, and Figure 6 shows the first 8 modal shape under prestressed condition.

Mode 1: 235.75 Hz  
Mode 2: 307.81 Hz  
Mode 3: 645.08 Hz  
Mode 4: 803.94 Hz  
Mode 5: 950.16 Hz  
Mode 6: 1092.30 Hz  
Mode 7: 1130.50 Hz  
Mode 8: 1491.40 Hz

Figure 6. The mode shapes of the gearbox casing
4.4. Comparison of case modal analysis

Figure 7 shows the first 15 natural frequencies comparison of the rail transit gearbox casing in the presence or absence of prestress. The natural frequencies of the case under the prestress state are significantly higher than the natural frequencies of the case without prestress, and this trend becomes increasingly obvious as the modal order increases. In addition, there are also obvious differences in the mode shapes, and the vibration sensitive area of the rail transit gearbox casing has changed.

According to the theory of modal analysis, the modal of the structure is only affected by the stiffness distribution, mass distribution and damping. The prestressed state of the gearbox casing changes the boundary conditions of the case, further affecting the stiffness distribution of the case. From the modal analysis data of the gearbox casing, result indicated that the rigidity of the case is increased after the prestressed was applied. Therefore, in the constrained modal analysis of the rail transit gearbox casing, the influence of the stress applied to the case during the operation of the gearbox transmission system should be considered. The modal analysis of the rail transit gearbox casing under the prestressed state should be performed.

![Figure 7. Natural frequency comparison](image)

5. Conclusions

(1) The multi-rigid body dynamics model of the rail transit gearbox transmission system was established, and the dummy object was used to define the rotating pair of the rotating shaft of the transmission system, which solved the problem of over-constraint of the rotating pair and obtained the reaction force data of transmission shaft.

(2) The FEM model of the rail transit gearbox casing was established, and the modal analysis of the gearbox casing under prestress and no prestress was conducted, and the modal characteristics of the case in two states were obtained. The results show that the prestress generated in the working condition of the gearbox leads to the dynamic characteristics change of the rail transit gearbox casing.

(3) Modal analysis of the rail transit gearbox casing needs to take into account the role of prestress, which can get more accurate modal parameters, and help to optimize the structural design of the gearbox casing, reducing vibration and noise of the gearbox. It has reference significance for gearbox design optimization.

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