Noise Prediction of Traction Gear of High-Speed EMU Base on Acoustic-Structural Coupled Method

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Abstract. The dynamic characteristics of traction gear transmission system have great influence on the safety, comfort and reliability of EMU. Base on acoustic-structural coupled theory, the noise radiation characteristics of gear transmission system in high-speed train CRH380A are studied by finite element-boundary element method. The acoustic radiation analysis model is built by using acoustic BEM. The radiated noise is predicted by Helmholtz boundary integral equation. The research results can provide a theoretical basis for the optimization design of the low noise gear in EMU.

Keywords: traction gear of EMU, dynamic characteristics, acoustic BEM, noise prediction.

1. Introduction
Traction transmission system is the core of power source for high-speed electric multiple unit (EMU) running. To study the dynamic mechanical characteristics and acoustic response characteristics in gear meshing process, furthermore to analyze and predict the magnitude and the origin of noise is the key for improving the transmission performance of traction gear and reducing vibration and noise.

The internal excitation is the characteristic that distinguishes gear transmission from other mechanical systems, also the origin of gear transmission system noise. Xue et al. [1] established the Spur Planetary Gear model by using the parametric method, simulated and analyzed the gear meshing process, and obtained the contact pressure and stress in a meshing period. Tang et al. [2] established finite element model of traction gear transmission system for the high-speed train CRH380A, and based on transient dynamics, analyzed the distribution and variation of equivalent stress and contact pressure on the gear tooth surface. Taking the dynamic meshing force along the meshing line, away from the meshing line, the dynamic tooth force and the bearing force as measure, Ghosh and Chakraborty [3] evaluated the vibration and noise of gears under different conditions.

The noise of gear transmission is not only about transmission error fluctuation, tooth surface stress distribution, dynamic meshing force change and other mechanical characteristics, but also about the structural characteristics, vibration characteristics of gear and transmission characteristics of meshing
force. Hou[4] studied the test vibration data of CRH2 EMU gearbox, made some comparison on the vibration frequency characteristics of gearbox under different working conditions, and explored the standard for vibration test and analysis of EMU gearbox. Through modeling and simulation test of the carriage of inter-city EMU CJ-1, Jia et al.[5] analyzed the generation, propagation, as well as acoustic-vibration relationship between propagation rule and bodywork, and found the main noise origin parts of EMU. Li[6] constructed the finite element simulation model for EMU gearbox, avoided resonance by modal analysis, meanwhile, measured the transmission noise by load test method.

The noise analysis and prediction of gear transmission system was achieved indirectly by studying the impact vibration and dynamic load on gear teeth [7-8], however, further acoustic study on gear transmission system is rare. The main reason is that it is difficult to build a noise analysis model for system, which is also much more complicated [9]. In this paper, based on acoustic-structural coupled system, by the finite-element boundary method, the dynamic characteristics and vibration response characteristics of the gear meshing has been analyzed for EMU (high-speed train CRH380A) under continuous traction.

2. Parametric Modeling of Gear Transmission System in Emu

In this paper, using software PRO/E, a parametric solid model is constructed for helical gear transmission system.

2.1. The Basic Parameters of Gear Pair

The basic geometric parameters of traction gear pair of high-speed train CRH380A are shown in Table 1.

| Name                    | Driving gear | Driven gear |
|-------------------------|--------------|-------------|
| Teeth \( Z \)           | 29           | 69          |
| Modulus \( m_n \) (mm)  | 7            | 7           |
| Helix Angle \( \beta \) (°) | 20          | 20          |
| Tooth face width \( B \) | 70           | 70          |

2.2. Establishment of Parametric Model

Considering the workload of computation in simulation, to ignore parts such as the transmission shaft, bearing and spline, the simplified gear pair is taken as the research object model (Fig.1).

3. Dynamic Characteristics Analysis of Gear Transmission System

By analyzing and solving the dynamic characteristics of gear pair, the accurate origin of noise and acoustic boundary conditions are provided for the acoustic radiation study of the system.

3.1. Dynamic Simulation in Gear Meshing Based on RecurDyn

The built model of gear pair in PRO/E is imported into the multi-body system dynamics simulation software RecurDyn and the dynamic meshing force of gear pair is solved. The main steps are as follows:
1. To define the transmission mode.
2. To define material properties. These properties are shown in Table 2.

Table 2. Material properties of gear pair

| Material properties  | Driving gear | Driven gear |
|----------------------|--------------|-------------|
| Elastic modulus E / (MPa) | $2.06 \times 10^{11}$ | $2 \times 10^{11}$ |
| Poisson's ratio $\mu$ | 0.31 | 0.29 |
| Density $\rho$ / (kg/m$^3$) | 7850 | 7800 |

3. To define boundary conditions. The speed and torque are respectively 841.5N.m and 434rad/s for traction gear pair of high-speed train CRH380A under the continuous working condition.

4. To simulate and solve. The dynamic meshing force is solved by finite element method.

It can be seen from Fig. 2 and Fig. 3, the overall trend of the meshing force in each meshing period is stable and presents a periodic variation law although the meshing force of the gear pair fluctuates with time.

Figure 2. Time domain diagram of gear pair meshing force

Figure 3. Frequency domain diagram of gear pair meshing force

3.2. Modal Analysis

By the modal analysis, the any ordered natural frequencies and modal characteristics of the transmission gear pair in a certain frequency range can be solved. On this basis, the vibration response of the gear pair under various excitations in a certain frequency range can be predicted.

The modal analysis can be realized through the workbench module in ANSYS. The finite element structures were solved, and the results are shown in Table 3. The mode of the first order is shown in Fig. 4, and the others are omitted.

Table 3. Natural frequency of gear pair in the first six order

| Order | Frequency (Hz) |
|-------|----------------|
| 1     | 507.34         |
| 2     | 769.1          |
| 3     | 882.65         |
| 4     | 1457.6         |
| 5     | 2186.7         |
| 6     | 2603           |
3.3. Dynamic Harmonic Response Analysis of Transmission Gear

The harmonic response analysis include vibration displacement, vibration velocity and vibration acceleration. In the analysis, the peak value and the corresponding frequency should be emphatically observed as to avoid fatigue and resonance. The forced vibration equation of undamped system is:

\[ [M][\ddot{u}] + [K][u] = [F] \]  

(1)

In the equation, \( u \) is vibration displacement. \( \ddot{u} \) is vibration acceleration, \( M \) represents systematic mass matrix. \( K \) represents stiffness matrix.

According to formula 1, the vibration response characteristics are calculated and the frequency response output curve is gotten (Fig. 5).

![Figure 5. Gear pair frequency response curve](image)

According to Fig.5, the frequency response curve has a peak at frequency 500Hz, and there is no significant peak near the following order natural frequencies, it shows that the vibration generated in the process of gear transmission which is mostly concentrated in the low frequency band. It is completely consistent with the actual situation, and the reliability of the model and method is verified.

4. Noise Analysis of Gear Transmission

The above dynamic characteristics analysis can provide boundary conditions for acoustic noise analysis of gear transmission system.

4.1. To Select the Numerical Computation Methods for Acoustic

In dealing with the acoustic radiation issue in unbounded sound field, if the whole model entity is meshed by the finite element method, the computational complexity is often too high to calculate. However, by the boundary element method based on Helmholtz boundary integral equation, the acoustic radiation can be calculated with one pattern by extracting the surface mesh of the structure[10]. The expression is as follows:

\[ p = [A_e(w)]^T v_e(w) \]  

(2)

\[ p(r_s) = \sum_{i=1}^{\infty} N^i_i^*(r_s) \cdot a_{pi}, \hspace{1cm} r_s \in \Omega_{ac} \]  

(3)
In these equations, \( p \) is sound pressure. \( \mathbf{A}_n(w) \) is acoustic transfer vector. \( v_n(w) \) is the normal velocity of vibration on structural surface unit. \( n_n \) is the number of nodes on the \( \Omega_{ae} \) unit. \( a_{pn} \) is sound pressure on the boundary element nodes. \( a_{ui} \) is normal velocity on the unit nodes. \( N'_n \) is shape function of unit.

Then, the normal velocity \( v_n \) and sound pressure \( p \) at a distance of \( r \) from the origin of noise in the gear transmission system are satisfied as equation (3) and equation (4).

### 4.2. Noise Analysis Based on Boundary Element Method

The obtained results of the vibration response from the analysis in Section 3 are imported into the noise vibration analysis software LMS, the noise of the gear transmission system can be simulated and predicted.

The sound field medium is defined as the air fluid property, and the action of the field point is similar to the acoustic sensor, where it needs to calculate the noise level in the sound field [11]. The distance is about 1m from each point to the center of the gear pair on the ISO spherical acoustic field. Taking the positions of passengers are right above the gear pair into consideration, in the sound field, as marked in Fig.6, the four appropriate points is selected. To check the sound pressure level at those points, and the corresponding sound pressure level curves are plotted (Fig. 7).

![Figure 6. Pictorial view](image)

![Figure 7. Sound pressure level curve at various points](image)
4.3. To Predict the Noise
In the paper, the sound power level of the radiated noise will be solved, and it will reflect the radiated energy of the origin of noise in a time unit. The average sound power is the average sound energy passing through the plane and being perpendicular to the plane in the unit time. The expression is shown as follows:

\[ W = \xi c_0 S \]  
\[ \xi = \frac{E}{V_0} - \frac{1}{2} \rho_0 \left( v^2 + \frac{1}{2} \rho_0 c_0^2 \right) \]  

In the equation, \( c_0 \) is the speed of sound propagation. \( S \) is the area of acoustic diffusion direction. \( \xi \) is energy density.

Through the sound pressure level contour obtained in the upper section (Fig. 8), according to the equation (5)-(6), the sound power level curve of the transmission gear pair and the root mean square (RMS) of the sound power level of the transmission noise can be obtained as Fig. 8. It can be seen from the figure that the corresponding RMS in the whole scanning frequency band is 114.44 dB.

![Figure 8. Sound power curve](image)

5. Conclusion
Through the simulation analysis of the dynamic mechanical properties and acoustic response characteristics of the traction gear transmission system in high-speed train CRH380A, the noise of the gear transmission system is predicted by using of the finite element-boundary element method, which can provide reference for the optimization design of low noise gears for high-speed EMUs and the modification design of vibration and noise reduction. The main conclusions are shown as follows:

(1) Based on the parametric model of traction gear transmission system of high-speed EMU, the dynamic characteristics are analyzed, including dynamic meshing force, natural vibration characteristics and dynamic vibration response. The research results show that the generated vibration is mainly concentrated in the middle and low frequency band in the running process of the gears, and the peak value of frequency response curve appears at 500 Hz, which is just at the first order natural frequency.

(2) The vibration characteristic curve obtained from harmonic response analysis of gear transmission system, can establish boundary conditions for solving the noise response by boundary element method. The results show that the corresponding RMS of power level of the traction gear in the whole scanning frequency band is 114.44 dB.

Acknowledgements
This project is supported by National Natural Science Foundation of China (Grant No.51765015) and supported by the Natural Science Foundation Project of Jiangxi Province (Grant No.20171BAB206027).
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