Design and Dynamic Analysis of The Gear Contact Fatigue Testing Machine

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Abstract. For gear contact fatigue testing, a new gear contact fatigue testing machine structural based on closed mechanical power-flow was proposed and the structural model was established. A set of power balance of the system was given according to theoretical calculation and mathematical deduction of the system transmission efficiency. In addition, statics and dynamics simulation analysis of the power transmission circuit was carried out, and the structural strength and stability under normal operating frequency was checked. The simulation results showed that the design and theoretical calculations had been confirmed.

1. Introduction

The gear fatigue test is the most effective method in studying the gear fatigue, which is of great significance to improve the gear performance. In US, the closed running gear test rig was first designed by Dr. Lewis, which could save 90% energy consumption than open system. Therefore, the closed running gear tester had been widely applied in the US [1]. In the 80s of last century, the gear test rig of JGl50 type closed flow mechanical lever was used to test the gear of various materials, and the gear contact fatigue life curve was drawn. The accuracy of the gear fatigue test results depends greatly on the accuracy of the gear fatigue testing machine and the rationality of its structure. Therefore, it is very important to develop the gear testing machine with high reliability and high dynamic loading accuracy [2].

2. Design of gear contact fatigue testing machine

According to the difference of the power transmission principle and the loading method of the testing machine, the gear test can be divided into two categories: open power and closed power. The closed power testing machine has not energy dissipation devices, and is suitable for long-term operation fatigue testing. Therefore, closed model is adopted by most gear testing machines [3].

In order to save the energy, a torque converter was added to the middle closed loop. This design scheme is simple in structure and low in energy consumption, and the torque size can be precisely controlled by controlling the hydraulic pressure of hydraulic rotary cylinder, and this scheme can also be used to measure the transmission efficiency of a single test gearbox. Based on the testing machine structure, the three dimensional solid model is constructed according to the requirement of design parameters, including gear pair, gearbox, transmission shaft, gear shaft, intermediate shaft, coupling
and rack. The complete assembly of the gear fatigue testing machine's structural assembly is shown in Figure 1.

![Figure 1. Structural assembly ligands for gear fatigue testing machine](image)

3. **Analysis and calculation of transmission efficiency**

The power losses include the friction loss between gear and bearing, the oil loss of gear, the friction loss on shaft seal, and the power loss of torque converter. Therefore, ignoring the power losses of the bearing, torque converter and other non-gear box, there exists a balance in the whole system. When the oil temperature is constant and the whole system is in thermal equilibrium, the heat power of the tank is equal to the power loss of the gears and the input power of the motor. Then, the losses of power on the bearing and torque converter can be integrated into the loss in the two gearboxes, and the torque load diagram of the whole power cycle system can be drawn, as shown in Figure 2.

![Figure 2. Torque load diagram of the power cycle system](image)

As shown in Fig.2, the torque equations can be derived as follows:

\[ M_{1A} = M \]
\[ M_{2A} = \left( M_{1A} - (M_{PVB} + M_{PCB}) \right) i = \left( k_A M_{1A} - M_{PCA} \right) i \]  
\[ M_{2B} = M_{2A} = \left( k_A M_{1A} - M_{PCA} \right) \]  
\[ M_{1B} = \frac{M_{2B}}{i} - (M_{PVB} + M_{PCB}) = \frac{M_{2B}}{i} - \left( \frac{M_{2B}}{i} \left( 1 - k_B \right) + M_{PCB} \right) = k_B \frac{M_{2B}}{i} - M_{PCB} \]

Due to the two gear boxes have the same size and same lubrication conditions, the constant power loss can be considered to be the same. That is:

\[ M_{PCB} = M_{PCA} = M_{PC} \]  

The efficiency expression of gear box A and B can be derived from the above relations.
\[ \eta_A = \frac{W_{2A}}{W_{1A}} = M_{2A} \omega_2 = \frac{M_{2A} \omega_2}{M_{1A} \omega_1} = \frac{(k_A M_{1A} - M_{PC})i}{M_{1A}i} = k_A \frac{M_{PC}}{M_{1A}} \] (6)

\[ \eta_B = \frac{W_{2B}}{W_{1B}} = \frac{i M_{2B} \omega_2}{M_{2A} \omega_1} \frac{i}{i} = \frac{(k_A M_{1A} - M_{PC})i}{i} \frac{(k_A M_{1A} - M_{PC})i - M_{PC}}{(k_A M_{1A} - M_{PC})i} = k_B \frac{M_{PC}}{M_{1A}} \] (7)

Note that there is a moment balance for the high speed shaft 1:

\[ M_{4B} = M_{1A} - M_{m} = M - M_{m} \Rightarrow k_B (k_A M - M_{PC}) - M_{PC} = M - M_{m} \] (8)

For the gear box A, because of the heat balance, the mechanical power loss is equal to the heat dissipation power, so it can be obtained:

\[ M_{1A} \omega_1 (1 - \eta_A) = K \alpha T_A \Rightarrow M (1 - K_A) + M_{PC} = K_A T_A \] (9)

Also, for the gearbox B:

\[ M_{2B} \omega_2 (1 - \eta_B) = K_B T_B \] (10)

When \( \omega_1 \) is integrated into \( K_B \):

\[ Mk_A (1 - k_B) + M_{PC}k_B = K_B T_B \] (11)

\[ M - [k_B (k_A M - M_{PC}) - M_{PC}] = K_A T_A + K_B T_B \] (12)

\[ M_m = K_A T_A + K_B T_B \] (13)

From the above, it can be concluded that the cooling power of the tank is equal to power loss of the gear and the input power of the motor.

In the above formula: \( i \) represents the gear train speed ratio; \( M \) represents the torque measure of the driving motor; \( M_{PV} \) represents variable torque loss; \( 1-k \) indicates variable torque loss coefficient; \( M_{PC} \) means constant torque loss; \( T \) indicates the temperature difference between the heat balance of the gearbox and the external temperature. \( K \) represents the heat power conversion coefficient; \( \omega \) represents the speed of the shaft.

4. Modal Analysis of Power Transfer Loop

The power load of the testing machine is mainly applied to the closed circuit by hydraulic torque loader. And the whole circuit is rotated at high speed driven by motor. Power transfer loop includes torque loader, intermediate shaft, size coupling, gear wheel and two pairs of gears. The power transfer loop is fixed to the frame by bearing. In order to verify the stability of the system, it is necessary to do modal analysis on the whole power transfer loop.

In the project module in ANSYS Workbench, the Modal program is selected, the CAD model is entered, and the model is constrained and loaded. It is worth noting that modal analysis is only related to the mass distribution and stiffness of the system, so for some smaller oil holes, the ring groove and so on are omitted, and the coupling and other components are directly replaced by the mass blocks fixed on the shaft.

4.1 Modal Analysis

The model is divided into grids and the boundary conditions are set. The modal analysis results of the power transfer loop from ANSYS are shown in Fig. 3.

As can be seen from the figure, the modal frequency of system stability is about 290 Hz. It is much less than the operating frequency of the system 3000Hz, so there is no risk of resonance in the system.
4.2 Modal Analysis of Power Transfer Loop Considering Prestress

It is necessary to calculate the modal analysis of the system under load, because the power transmission loop is subjected to a torque load of 4000 Nm in practice, which means that the stiffness matrix of the power transmission loop may change under prestressed condition.

By establishing the modal analysis model of power loop under prestressed condition, the load and boundary conditions of the model are set up as shown in Figure 4. Then the model is solved, and the modal analysis and calculation of the model under the prestressed state are carried out as shown in Fig. 5 and Fig. 6.
From the analysis results, it can be seen that the maximum stress of the whole circuit appears in the position of gear contact, and the stress is 2057.6 MPa, which is consistent with the previous calculation of gear pair contact stress. Compared with the absence of prestress, the modal analysis results of the power transfer loop are slightly higher, but the difference is not great and the difference with working frequency (3000 Hz) is still very large, therefore, it meets the requirements.

5. Conclusions

In this paper, a mechanical closed power flow testing machine for gear contact fatigue is designed, including the overall structure scheme design and the 3D virtual assembly design. By means of theoretical calculation and mathematical deduction, the transmission efficiency of gear contact fatigue testing machine is analysed. The simulation of statics and dynamics of the whole power transmission circuit is carried out, and the correctness of theoretical design and calculation is verified. Though, the hydraulic system of power transmission circuit is not analysed, the hydraulcic system of gear lift fatigue testing machine can be used as a follow-up research direction.
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