A New Design of the Test Rig to Measure the Transmission Error of Automobile Gearbox

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Abstract. Noise and vibration affect the performance of automobile gearbox. And transmission error has been regarded as an important excitation source in gear system. Most of current research is focused on the measurement and analysis of single gear drive, and few investigations on the transmission error measurement in complete gearbox were conducted. In order to measure transmission error in a complete automobile gearbox, a kind of electrically closed test rig is developed. Based on the principle of modular design, the test rig can be used to test different types of gearbox by adding necessary modules. The test rig for front engine, rear-wheel-drive gearbox is constructed. And static and modal analysis methods are taken to verify the performance of a key component.

1. Introduction
Gearbox is a critical component in mechanical transmission, which is widely used in automobile to transform the power generated from engine. It can be regarded as a self-excited vibration source[1], which affects the performance of the entire vehicle. Generally, gearbox is a complicated assembly including gears, shafts, bearings, synchronizers and housings. Above all components, gears plays an significant role in the process of power transmission. Gear transmission error (TE) has been considered as a main source of noise and vibration in gear system, which has been corroborated by several investigators[2-5]. TE is defined as the deviation between the theoretical position and the actual position of the output shaft if the gear drive were perfectly accurate and rigid[6]. However, because of the existence of manufacturing error and teeth deformation, TE is unavoidable in gear system. Current research is mainly concentrated on the measurement of the TE for single gear drive[7-9]. And TE measurement in a complete automobile gearbox under actual operating conditions were rarely conducted[4,10].

To accurately measure the TE of automobile gearbox and investigate the origin of TE, a kind of electrically closed test rig is developed. Due to the adoption of energy-recycling technology, the cost of operation and maintenance is relatively more economic compared with open test rig. The test rig can be used for TE and vibration measurement of gear pairs or complete gearbox. Besides, the system can work flexibly on testing for several types of gearbox by adding necessary modules. The overall structure and operation principle of the test rig are described subsequently.

2. Design of the test rig
Generally, the gearbox test rig can be divided into two types: open system and closed system, according to the energy cycling methods. The limitation of open system is that the energy generated
by power source is consumed without recirculation, and loading on gearbox requires additional energy. Although the expenditure of construction for open test rig is relatively lower, subsequent operation and maintenance need further investment. As for the closed system, the energy can be recirculated via feedback device. The energy consumption is much lower than the open system, especially for high-power and long-time testing. Therefore, the closed testing method is chosen, more specifically, electrically closed method.

Based on the principle of modular design, the test rig can satisfy the test requirement for various types of gearbox. And the features of the measurement object determine the structure of the test rig.

**Figure 1.** The structure of the test rig for TE measurement of FR gearbox

The front engine, rear-wheel-drive (FR) gearbox includes one input shaft and one output shaft. Accordingly, the overall arrangement of the traditional FR gearbox test rig is linear type, which means occupying a larger floor space. And the output power of the gearbox has high speed and low torque. In order to match the output power of the gearbox and the mechanical characteristic of the load motor, a single speed reducer or back-to-back slave gearbox is always employed to transmit the power or choose a high-power load motor directly. Thanks to the using of self-designed double speed reducer and universal coupling, the TE detection test rig can be installed on a smaller iron floor, which measures 4 by 2 meters. Specifically, the input and output shaft of the reducer are on the same side, so the transmission route of the test rig can be folded. And the gear ratio of the reducer is designed to meet the needs for power matching.

**Figure 2.** The structure of the test rig for TE measurement of FF gearbox

The front engine, front-wheel-drive (FF) gearbox includes one input shaft and two output shafts. The input shaft and a output shaft locate on one side, and the other output shaft situates on the contrary side. Thus, the structure of FF gearbox test rig is ‘h’ type. Compared with FR gearbox, the output power of FF gearbox has relatively lower speed and higher torque because of the integration of a main reducer. In order to shorten the length of the test rig, a synchronous belt transmission device is used to fold the transmission route. The synchronous belt transmission device can transmit the output power
of the gearbox with an accurate transmission ratio. Therefore, the FF gearbox test rig can be installed on the same iron floor, which increases the universality of the gearbox test rig.

The structures of the test rig for TE measurement of FR and FF gearbox are shown in figure 1 and figure 2 respectively. And the test rig for TE measurement for FR gearbox is built based on the existing conditions of laboratory, which is shown in figure 3. The detailed structure and working principle of the FR test rig will be introduced subsequently.

The working principle of the test rig are shown in figure 4. The test rig includes two alternating current (AC) motors, serving for driving and loading respectively. The gearbox is powered by the driving motor capable of speeds up to 3000 rpm, and the input torque can arrive at about 150 Nm. The load motor serves as a dynamometer to simulate the load. The driving speed and loading torque can be regulated within a certain range. Electricity comes from AC power is transformed into direct current (DC) by active line module (ALM), and transmitted into the DC bus. The power of the driving motor comes from the DC bus via frequency inverter and electric reactor, and the electricity generated by the load motor is fed back to the DC bus through electric reactor and frequency inverter. In this way, the energy can be recycled in the system. The overall power consumption of the test rig depends on the transmission efficiency, and the test rig can be operated much more economically. The ALM and frequency inverters are controlled by the industrial personal computer (IPC) via control module.
The detection of angular motion and torque is achieved by the input and output test module. The structure of the two modules are identical in structure, as is shown in figure 5. Taking the output test module as an example, the angular motion and torque of the output shaft of the gearbox are measured by the Heidenhain angle encoder (ERA4280C) and HBM T40B torque sensor respectively. The Heidenhain angle encoder is consisted of reading head, circular grating and protective cover. The circular grating is mounted on the flange shaft and rotates with the shaft. The reading head and protective cover are fixed on the encoder support. In order to simplify the structure and save space, HBM T40B torque sensor is chosen to measure the torque. The torque sensor is composed by a rotor and a stator, and they are non-contact. The rotor is a torque flange with strain gauges inside, while the stator is used to receive the signal transmitted by the rotor. All the rotating components are supported by two bearing blocks to enhance the rigidity of the module and prevent sensors from damaging. The output signal of angle encoder is received by MSE1000 data acquisition module, and transmitted to MSE software to get angle motion data. Voltage or frequency signal can be chosen as the output signal of torque sensor. Limited to the sampling frequency of the data acquisition card, voltage signal is chosen. The angle motion and torque signal are imported into LabVIEW software for post-processing.

![Figure 5. The structure of the TE test module](image1)

Figure 5. The structure of the TE test module

A reducer is designed to match the output speed of the gearbox with the speed of load motor, figure 6 presents the structure of the reducer. The reducer includes two speeds which is realized by using double step sliding gear. And the double step sliding gear is driven by the shifting fork and guide bar, which is shown in figure 7. The transmission ratio of the reducer can be selected manually according the output speed of the gearbox to match the mechanical characteristic of the load motor. Thanks to the using of the reducer, the load motor can operate at the best working point. Gear 5 and 6 are always in constant mesh. In low-speed mode, gear 1 and 2 are engaged, and the overall reduction ratio is 1.2. In high-speed mode, gear 3 and 4 are engaged, and the overall reduction ratio is 4.

3. Analysis of the reducer

The reducer is the key power conversion device of the test rig, and the performance of the reducer affects the measurement of the TE. As is shown in figure 8, the reducer is modeled in Romax Designer software to realize static analysis and modal analysis under actual loads. And the finite model of reducer housing is shown in figure 9.

![Figure 6. The structure of the reducer](image2)

Figure 6. The structure of the reducer

![Figure 7. The shifting mechanism of the reducer](image3)

Figure 7. The shifting mechanism of the reducer

![Figure 8. Romax model of the reducer](image4)

Figure 8. Romax model of the reducer

![Figure 9. FE model of the reducer housing](image5)

Figure 9. FE model of the reducer housing
3.1. Static analysis

Figure 10 and figure 11 present the deflection of transmission components and the distribution of von Mises stress on the housing respectively. The peak value of shaft deflection magnitude is located on shaft B at 1st speed, and the peak stress is 5.75 Mpa, which is much less than allowable stress. The maximum of von Mises stress is located on the ribs of bearing hole for shaft B, and the peak stress is about 5.81 Mpa, which is also a safe value compared with the yield limit 200Mpa. Thus, the structural strength of the reducer can satisfy the requirement for gearbox loading.

![Figure 10. Deflection of transmission components](image1)

![Figure 11. Distribution of von Mises stress on the housing](image2)

3.2. Modal analysis

The inherent characteristic of the housing has an important influence on the vibration and noise performance of the reducer. The modal analysis can be used to analyze the inherent frequency and modal shape of the housing to avoid resonance. The modal analysis of the reducer housing result in 20 inherent frequencies in the frequency range 510-1699Hz. Boundary conditions for housing are fixed. Generally, the low-order modes are more commonly used in modal analysis than high-order modes[11]. Because the high-order modes would attenuate sharply with the effect of damping. And it means that high-order vibrations can hardly generate resonance.

![Figure 12. First four order modes of the housing](image3)

The first four order modal shape and inherent frequency of the housing are shown in figure 12. In the first mode, the upside and the bottom of the housing vibrates along Y axis in positive direction. In the second mode, the bottom of the housing vibrates along Y axis in positive direction, too. In the third mode, the upside of the housing twists around X axis, and the left and right sides of the housing vibrate along Z axis in positive direction. In the fourth mode, the upside and bottom of the housing twists around X axis, and the left and right sides of the housing vibrate along Z axis along negative direction.

The mesh frequencies (MF) of the gears in the reducer are listed in table 1. And the MF of the six gears do not coincide with the inherent frequencies of the housing, thus avoiding housing resonance. Therefore, the performance of the reducer can satisfy the dynamic matching task.

Table 1. Mesh frequencies of the gears in the reducer
4. Conclusion
In this paper, a test rig is designed to measure the TE of automobile gearbox, which is based on electrically closed method. The detailed structure and working principle of the test rig is introduced. The test rig can be used to measure different kinds of gearbox via adding necessary modules. And FR gearbox test rig is constructed based on the existing conditions of the laboratory. The FR gearbox test rig includes a two speed reducer to match the output speed of gearbox and the input speed of load motor. Static and modal analysis methods are taken to validate the performance of the reducer. The analysis result indicates that the reducer can satisfy the dynamic matching task for TE measurement.

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