Research on Test Method and Sensor of Engine Mount Transmission Force

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Abstract. The engine mount transmission force can be used as an important basis to evaluate the vibration isolation performance of the engine mounting system. However, there is a lack of testing equipment and methods for the transmission force. The force sensor and the test method of the transmission force is studied. The finite element model of the mounting element is established to analyze the arrangement position of the sensor. The force sensor is developed based on the resistance strain gauge. The sensor is arranged in the middle of the intermediate bolt. The test system of mount transmission force is established at the same time. The driving force of driving wheel is obtained through the chassis dynamometer test. The force sensor is calibrated based on the test data. The results of mounting transmission force are obtained through the vehicle road test.

1. Introduction

At present, the vibration isolation performance of engine mounting system is mainly evaluated by vibration acceleration. The vibration acceleration of the vehicle is measured by arranging the acceleration sensors at different positions of the engine and chassis under different working conditions [1]. Then the transmissibility of vibration is obtained by processing the test data. This method has been widely used in the research and evaluation of vehicle vibration. But there is a defect: it is not suitable to evaluate the vibration isolation performance of engine mounting system in the road test. The acceleration sensors are installed at the active and passive sides of the mounting elements [2]. The acceleration of the passive side of the mount is usually affected by the road excitation. Therefore, the transmissibility cannot reflect the vibration isolation performance of engine mounting system under road test.

It is the most direct and effective evaluation method to use engine mount transmission force. Because this method can avoid the influence of vehicle body side vibration on the evaluation results. However, due to the compact structure of the engine mounting system, it is difficult to arrange the force sensor. The test methods of transmission force are as follows [3, 4]: (1) direct measurement method, (2) dynamic stiffness method of mount method, (3) inverse square of Frequency Response Function matrix method [5].

In this paper, the layout, basic structure and application of the engine transmission force sensor are studied. The layout position of the sensor is determined by theoretical analysis. The sensor is made of
the sensitive elements suitable for the transmission force test. The sensor is calibrated by chassis dynamometer. The results of the transmission force are obtained through the vehicle road test.

2. Analysis of sensor arrangement

2.1. Analysis of Engine Mounting System Structure

The engine mounting system of the sample vehicle adopts four-point layout. The left and right mounts mainly bear the vertical load and vibration of the engine. The front and rear mounts are mainly used to restrain the pitching and horizontal motion of the engine. When the engine works, the engine excitation is transmitted to the vehicle body or subframe through the path of mounting bracket (engine side) - mounting element body - mounting bracket (body/ subframe side)-body/ subframe. Therefore, it is necessary to select the appropriate position in the transmission path and arrange the sensor for measuring the force transmitted by the engine to the body or subframe. Since there are usually multiple connection points between the mounting bracket and the engine or body. Therefore, it is not suitable to place the sensor in this position [5]. It can avoid the difference of the test results and improve the accuracy of the test results by placing the sensors on the mounting body.

The structure of mounting element mainly consists of mounting bracket, colloid, steel sleeve and bolt. Because of the large deformation and irregularity of the colloid part, it is not suitable to arrange the sensor. Due to the large volume of the mounting bracket and many connecting points, it is not easy to measure the accurate transmission force by placing the sensor. The bolt in the mounting center is the only way to transfer the mounting force, and it is small and single in structure, so it is easy to obtain the accurate engine mount transmission force.

2.2. Finite Element Analysis of Mounting Element

In order to verify the effectiveness of the scheme of arranging sensors on the bolts, the finite element model of the mounting element is established. The engine mount transmission force is calculated by applying the load on the mounting bracket.

2.2.1. Meshing: Firstly, the 3D model of the mounting element is imported for pre-processing. Through the main steps: geometry cleaning, mesh generation and mesh inspection, the main components such as bracket, colloid, bolt and rubber core steel sleeve are meshed. Then import the mesh file into ANSYS [6], as shown in Figure 1. There are 37212 elements in the mount finite element model.

![Figure 1. Finite element model of mount.](image)

2.2.2. Material settings: The bracket, bolt and steel sleeve are made of steel. The bolts are made of 0.45% carbon steel and the rest are made of structural steel. The parameters of the steel is shown in
Table 1. The Mooney-Rivlin model is used to fit the constitutive characteristics of rubber materials according to the structural characteristics of mount rubber [7].

| Material          | Density(kg/m³) | Elastic Modulus(Pa) | Poisson's Ratio |
|-------------------|----------------|---------------------|-----------------|
| structural steel  | 7800           | $2.06 \times 10^{11}$ | 0.3             |
| 0.45% carbon steel| 7850           | $2.09 \times 10^{11}$ | 0.269           |

2.2.3. Mounting load: The displacement excitation is applied to the mount bracket on the engine side in vertical direction. The frequency of the excitation is the same as the 2nd order excitation vibration frequency of the engine idle speed. The frequency of the engine can be given as follows:

$$f = \frac{ni}{30\tau}$$

Where: $n$ is the speed of the engine, $i$ is the number of engine cylinders, $\tau$ is the number of strokes, and $v$ is the order of the engine vibration.

2.2.4. Simulation result: The simulation results are shown in Figure 2 and Figure 3. The excitation and response have the same change rule, and they are all sine wave. It shows that there is a fixed proportional relationship between the strain of intermediate bolt and the mounting displacement. It is proved that the mounting load can be analyzed by measuring the strain in the middle of the bolt.

Figure 2. Displacement excitation curve.

Figure 3. Strain in the middle of bolt.
3. Manufacture and calibration of force sensor

3.1. Manufacture of Force Sensor

Resistance strain gauge is a kind of sensor whose resistance value changes with its own deformation. The strain of the resistance strain gauge can be measured by measuring the resistance change.

The fabrication method of the sensor is as follows: firstly, turn the hole at the head of the bolt with a diameter of 2 mm, which is used to arrange the connecting wire of the resistance strain gauge. A groove is milled in the middle of the bolt to arrange the resistance strain gauge. The structure form, size, resistance value, service temperature, creep characteristics need to be considered in the selection of resistance strain gauge. The main parameters of the resistance strain gauge selected are shown in Table 2. Then, the machined surface is polished and cleaned, and the strain gauge is glued into the bolt groove. Finally, the white silica gel is used as the protection of the resistance strain gauge. The force sensor is shown in Figure 4.

| Size       | Resistance value | Temperature range | Creep model |
|------------|------------------|-------------------|-------------|
| 3.0×2.3mm  | 120Ω             | -30°C-150°C       | T0          |

3.2. Construction of Test System

The test system of transmission force mainly includes: force sensor, bridge, amplifier, filter, data collector, laptop, etc.

The resistance strain gauge should be equipped with electric bridge when it is used. The structure of the bridge includes: single arm bridge, half bridge and full bridge. The half bridge is selected because the certain temperature compensation ability and the size limitation of intermediate bolts. \( R_1, R_2, R_3, R_4 \) is the resistors of the bridge. Resistance \( R_1 \) and \( R_2 \) are usually connected to the test part. When the strain is occurred, the corresponding resistance changes to \( R_1+\Delta R_1, R_2+\Delta R_2 \). Suppose \( R_1=R_2=R_3=R_4=R \) and \( \Delta R_1=-\Delta R_2=\Delta R \), The output of the bridge is given as follows [8]:

\[
U_b = \frac{R_1R_2 - R_3R_4}{(R_1 + R_2)(R_3 + R_4)} U_s = \frac{(R_1 + \Delta R_1)R_3 - (R_3 + \Delta R_3)R_1}{(R_1 + \Delta R_1 + R_2 + \Delta R_2)(R_3 + R_4)} U_s = \frac{\Delta R}{2R} U_s
\]

Where: \( U_s \) is the supply voltage.

3.3. Calibration of Force Sensor

The force sensor needs to be calibrated to determine the proportional relationship between the voltage signal of the sensor and the transmission force. The calibration method is based on the principle of torque balance. The torque generated by the transmission force of the mount is balanced with the output torque of the engine. The output torque of the engine can be obtained by converting the driving force of
the driving wheel. The driving force of driving wheel is tested by double hub chassis dynamometer [9]. During the test, the vehicle speed is 30km/h. The transmission is in 2nd gear, and the engine load is full load.

The relationship between driving force of driving wheel $F_t$ and engine output torque $T_{tq}$ is as follows:

$$F_t = T_{tq} \frac{i_g i_0 \eta_T}{r}$$  \hspace{1cm} (3)

Where: $i_g$ is the transmission ratio, $i_0$ is the main reducer ratio, $r$ is the tire rolling radius, $\eta_T$ is the mechanical efficiency of the transmission system.

The driving force curve measured in the test is converted to the output torque curve of the engine according to equation (3). The curve is shown in Figure 5.

![Figure 5](image)

**Figure 5.** Engine output torque curve.

Because the signal measured by the force sensor is a broadband signal, which is not conducive to the calibration of the sensor. It is necessary to process the test signal. The method of wavelet analysis is used to process the signal. The signal is processed by db wavelet in MATLAB software [10], as shown in Figure 6. The fundamental wave of the front and rear mount test signal is obtained by wavelet analysis, as shown in Figure 7 and Figure 8.

![Figure 6](image)

**Figure 6.** Wavelet decomposition of force signal.
According to Figure 7 and Figure 8, the ratio of the absolute value of the first peak amplitude of the front and rear mounting curves is 2.63. Therefore, the ratio of the front and rear mounting forces is approximately 2.63. The relationship between the transmission force and engine output torque is given as follows:

\[ F_1 l_1 + F_2 l_2 = T_{eq} \]  \hspace{1cm} (4)

Where: \( F_1 \) is the transmission force of the front mount, \( F_2 \) is the transmission force of the rear suspension, \( l_1 \) is the vertical distance from the front mount to the center line of the crankshaft of the engine, which is 0.35m, \( l_2 \) is the vertical distance from the rear mount to the center line of the crankshaft of the engine, which is 0.25m.

According to the ratio of the front and rear mount transmission forces and equation (4), the relationship between transmission force and engine output torque is given as follows:

\[ F_1 = 0.9948 T_{eq} \]  \hspace{1cm} (5)

\[ F_2 = 2.6163 T_{eq} \]  \hspace{1cm} (6)

The engine torque curve is processed according to equations (5) and (6), and the theoretical calculation results of the transmission force of are obtained.
Finally, the calculated amplitude of front and rear transmission force analysis curve is taken as the ordinate, and the amplitude of the test signal curve processed by wavelet method is taken as the abscissa to draw the scatter diagram, as shown in Figure 9 and Figure 10.

![Figure 9. Calibration curve of front mount.](image)

![Figure 10. Calibration curve of rear mount.](image)

After fitting, the sensor calibration formula is obtained:

\[
F_1 = -9.01A_1 + 1117 \quad (7)
\]

\[
F_2 = 10.21A_2 - 1370 \quad (8)
\]

4. Vehicle test of transmission force

In order to obtain the transmission force under the actual working condition, the force sensor is used in the vehicle road test. The test conditions include idle and 3rd gear driving, as shown in Table 3. The test equipment mainly includes: force sensor, dynamic strain gauge, and signal conditioning instrument, data collector, inverter, and laptop.

| Test condition | Engine speed(rpm) |
|----------------|------------------|
| Idle           | 800   1000 1500 2000 2500 3000 |
| 3rd gear       | --    1000 1500 2000 2500 3000 |
The test results of idle condition are shown in Figure 11. The test curve has obvious periodicity, which corresponds to the periodic operation of the engine under the idle condition. The amplitude of the engine mount transmission force does not change significantly at different engine speeds, which is mainly due to the fact that the engine has almost no load under the idle condition, so the engine power changes little. At the same time, it also shows that the vibration isolation performance of the mount has little change under the idle condition.

![Figure 11. Mount transmission force at idle condition.](image)

The test results of 3rd gear driving condition is shown in Figure 12. The test results show that the transmission force of the powertrain mount basically increases with the increase of the engine speed. This is consistent with the change trend of engine output power. However, when the mounting speed is 2000 rpm, the transmission force of the mounting is large, which may be due to the poor dynamic stiffness of the connection position between the mounting bracket and the vehicle body and the existence of local modes.

![Figure 12. Mount transmission force at 3rd gear condition.](image)

5. Conclusion
The middle of the intermediate bolt is suitable to place the force sensor according to the analysis. The engine mounting element model is established, and the response of the middle part of the mounting bolt is obtained by adding displacement excitation on the mount bracket. The results show that the strain of the intermediate bolt is in direct proportion to the excitation. The feasibility of the method is proved
The transmission force sensor is made by arranging the strain gauge on the intermediate bolt of the mounting element. The driving force of driving wheel is measured by chassis dynamometer. The engine torque is obtained by conversion. According to the proportional relationship between the peak signal of the force sensors, the theoretical curve of the transmission force is obtained. The force sensor is realized by combining the sensor voltage signal with the transmission force. The test results of the mounting force are obtained by the vehicle test, which provides an effective basis for the evaluation and analysis of the engine mounting vibration isolation performance.

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