Simulation and Experimental Verification of Sweep Frequency Vibration Fatigue for Motor Controller of Integrated Electric Drive System for Electric Vehicle

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Abstract. The motor controller of the integrated drive system for electric vehicles has the risk of sweep frequency vibration fatigue (SFVF) failure in the frequency range of 100 ~ 440 Hz. In this paper, a finite element simulation method of SFVF for an integrated motor controller is introduced. The failure position of the motor controller component is predicted using this simulation method, which is consistent with the fracture position of the sweep frequency vibration fatigue test (SFVFT). This indicates that the simulation method is accurate. And the structural optimization suggestions are also put forward using this method. The optimized motor controller meets the requirements of SFVFT. This indicates that it is feasible to use this method during the design process of the motor controller for integrated drive system.

1. Introduction

With the increasing awareness of global energy saving and environmental protection, countries have successively released the development strategy of electric vehicles, and formulated a timetable for the suspension of sales of traditional fuel vehicles [1-3].

The electric drive system is the core system of electric vehicles, which is mainly composed of drive motor, motor controller, and reducer. The components of the early electric drive system were dispersed and individually arranged, and connected by connectors such as wire harnesses, which brought many problems such as large layout space and high cost [4]. To solve these problems, major vehicle manufacturers began to develop integrated electric drive system [5], but it also brought new challenges to the strength design of integrated electric drive system motor controller. Lei Hou [5] made an introduction to the design and structural simulation of an integrated electric drive system, but the research on each simulation item was insufficient. In particular, when analyzing the SFVF of the controller, the vibration fatigue of the motor controller of the integrated electric drive system was tested for 8 hours using the SFVF standards for the motor controller of the single installation specified in the standard QC/T413-2002 [6]. This standard can only be applied to the vibration fatigue test of a separately installed motor controller. For the motor controller of integrated electric drive system installed with motor and reducer, the specified working conditions of the standard cannot fully cover...
the severe working conditions in actual use. According to the standard ISO 16750-3-2007 [7], the reducer of passenger cars will be subject to vibration excitation in the frequency range of 100 ~ 440 Hz. The design of the reducer must meet the requirements of the 22 hours SFVF standard in the frequency range of 100 ~ 440 Hz. The modal frequency of some components of the motor controller is low, and there is a risk of vibration fatigue failure in this frequency range. Therefore, during the design process of the motor controller of the integrated electric drive system, it is necessary to ensure that all parts of the motor controller meet the SFVF requirements specified in the standard ISO 16750-3-2007, just like the reducer. In this paper, a finite element simulation method of SFVF for the motor controller of integrated electric drive system is studied. Using the simulation method, the fracture position in SFVFT of the motor controller is accurately predicted, and the advanced design scheme of the motor controller meeting the requirements of SFVFT is given.

2. Simulation and test

2.1. SFVF simulation method

As we all know, vibration fatigue failure is a major factor leading to the failure of auto parts. In the vehicle design process, the vibration fatigue simulation method is used to predict the failure risk of the structure and put forward optimization suggestions, which can effectively shorten the research and development cycle and cost. There are many parts of the electric vehicle motor controller, and some of them have the risk of SFVF. Therefore, it is necessary to perform SFVF simulation analysis on the motor controller during the design stage.

As the control unit of the electric drive system, the motor controller directly affects the performance of the entire electric drive system. There are many components of the motor controller, and it is difficult to replace them individually. Once a component is damaged, it is necessary to replace multiple or even all the components connected to it, which brings problems such as high maintenance cost and inconvenient maintenance. At the same time, it is difficult to obtain the S-N curve of the material because the parts of the motor controller of the electric drive system are mostly provided by foreign suppliers, which is a general problem faced by domestic vehicle manufacturers. Considering the above factors comprehensively, the infinite life design method is used in the SFVF design of the motor controller in this paper [8], that is, the stress of each component of the motor controller should be less than its fatigue limit under sweep frequency vibration (SFV) condition. According to the standard ISO 16750-3-2007 [7], the load of SFVFT is sinusoidal vibration excitation, which belongs to a kind of symmetrical cyclic load. Therefore, the strength condition of SFVF simulation can be simplified as follows [8],

\[ n_s = \frac{\sigma_{-1}}{\sigma_s} \geq [n] \]  

(1)

Where, \( n_s \) is the working safety factor under the excitation of SFV, \( \sigma_{-1} \) is the fatigue limit of the material, \( \sigma_s \) is the response stress under the SFV, \([n]\) is the allowable safety factor. According to experience, \([n]=1\) is taken in the simulation method of SFV of motor controller introduced in this paper, formula (1) can be written to,

\[ n_s = \frac{\sigma_{-1}}{\sigma_s} \geq 1 \]  

(2)

\[ \sigma_s \leq \sigma_{-1} \]  

(3)

That is, the component meets the sweep vibration fatigue requirements when the response stress of each component of the motor controller under the sweep vibration is less than the fatigue limit of its material.
2.2. SFVFT
The SFVFT of the motor controller was carried out according to the standard ISO 16750-3-2007 [7]. As shown in Fig.1, the motor controller is installed on the test tooling which is fixed on the test bench. Restrain the installation point of tooling and apply vibration excitation at the installation point. The amplitude versus frequency is illustrated in Table 1. A sweep rate of 0.5 octave/minute is used. The SFVFT was carried out in three directions of X, Y, and Z for 22 hours respectively.

![Figure 1. SFVFT diagram of motor controller.](image1)

![Figure 2. The finite element model of motor controller.](image2)

### Table 1. Values for maximum acceleration versus frequency.

| Frequency (Hz) | Maximum acceleration (m/s²) |
|---------------|-----------------------------|
| 100           | 30                          |
| 200           | 60                          |
| 440           | 60                          |

3. Results and discussion

3.1. Simulation results

3.1.1. Model description. The geometric model of the motor controller is established in CATIA. The finite element model is established in Abaqus. The busbar and cover of the motor controller are built with the shell elements. Other components are built with tetrahedral elements, with a total of 2695424 elements. The material parameters of each component are shown in Table 2. Restrain the installation point of tooling and apply vibration excitation at the installation point. The amplitude versus frequency is illustrated in Table 1. The complete finite element model of SFVFT simulation of the motor controller is shown in Fig.2.

![Image of finite element model](image3)

### Table 2. Material parameter table for main components of the motor controller.

| Components          | Material | Elastic Modulus (GPa) | Poisson's ratio | Density (Kg/m³) | Fatigue limit (MPa) |
|---------------------|----------|-----------------------|-----------------|-----------------|---------------------|
| Cover               | DC04     | 206                   | 0.3             | 7850            | 81                  |
| Case                | ADC12    | 71                    | 0.28            | 2680            | 93                  |
| Busbar              | T2       | 118                   | 0.343           | 8890            | 73.5                |
| Capacitor housing   | PPS      | 19.1                  | 0.35            | 1830            | 43.5                |
| DC terminal guide   | PPO      | 12.3                  | 0.35            | 1670            | 48                  |
3.1.2. Result of Fatigue Finite Element Simulation of SFVF. As described in Section 3.1.1, the vibration excitation is loaded at the installation point. The amplitude versus frequency is illustrated in Table 1. The response stress curve (RSC) of SFV of each component of the motor controller is shown in Fig. 3. As shown in the figure, the sweep vibration response stress of most components increases with the increase of frequency. However, the RSC of DC terminal guide and case has a peak value near the frequency of 350 Hz. This is because 350 Hz is close to the first-order natural modal frequency of the DC terminal guide structure, which causes the resonance of the structure in the process of frequency sweep vibration, thus a maximum value of response stress appears near the 350 Hz frequency. The DC terminal guide is installed on the case, and the resonance of DC terminal guide causes a large deformation, resulting in a local maximum stress at the installation point of the case.

![Response stress curves](image)

Figure 3. RSC of Z-direction SFV of the motor controller’s components.

The maximum response stress value of each component caused by SFV excitation is shown in Table 3. The maximum response stress of the cover, case, capacitor housing, and DC terminal guide are all below the fatigue limit of its material. According to Section 2.1, these components meet the requirements of SFVF. The maximum response stress of Z-direction SFV of the busbar is 106.1 MPa, which is higher than the fatigue limit of 73.5 MPa. Therefore, it does not meet the requirements of SFVF. The maximum stress is near the installation point of the busbar on the insulated gate bipolar transistor module (IGBTM). The SFV response stress nephogram of Z-direction SFV of the busbar is shown in Fig. 4. The red area in the figure is the failure risk area predicted by SFVF simulation. The two busbars with the largest response stress are located at both ends of IGBTM, which are the two positions with the worst structural strength. The maximum response stress values are 106.1 and 94.7 MPa respectively, which are higher than the fatigue limit of its material. Therefore, they don't meet the requirements of SFVF.

| Table 3. The maximum response stress value of SFV of the main components of the motor controller. |
|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Direction of sweep vibration | Cover (MPa) | Case (MPa) | DC terminal guide (MPa) | Capacitor housing (MPa) | Original busbar (MPa) | Optimized busbar (MPa) |
|-----------------|--------------|-------------|------------------------|-----------------------|------------------------|------------------------|
| X               | 2.1          | 5.6         | 3.6                    | 9.2                   | 58.9                   | 23.9                   |
| Y               | 1.6          | 4.4         | 12.3                   | 11.3                  | 59.9                   | 32.4                   |
| Z               | 3.3          | 6.8         | 39.0                   | 9.7                   | 106.1                  | 41.2                   |
3.2. Discussion of test results and optimization

3.2.1. Discussion of test results. According to the steps shown in Section 2.2, the SFVFT of the motor controller was carried out in three directions of X, Y, and Z for 22 hours respectively. After the X-direction and Y-direction test, the components of the motor controller have no visible damage and normal function. It is consistent with the simulation results in Section 3.1.2, which verifies the accuracy of the simulation method. During the 22h SFVFT in the Z direction, the test was forced to stop due to the fracture failure of the components of the motor controller. The fracture location is shown in Fig. 5. Two busbars at both ends of IGBTM are broken, which was consistent with the failure position predicted by finite element simulation. The accuracy of the finite element simulation method of SFVF of the motor controller introduced in this paper is proved again.

3.2.2. Optimal design. According to the results of simulation and test, there is a risk of fatigue failure near the installation point of the busbar on IGBTM. To solve this problem, the commonly used optimization methods include increasing the thickness of the busbar, replacing the material of the busbar, and adding reinforcement ribs on the busbar. This time, the first method is used to increase the thickness of the busbar on IGBTM from 0.8 mm to 1.5 mm. Using the method described in Section 3.1, the SFVF simulation of the optimized motor controller is carried out. The RSC of SFV of the optimized busbar is shown in Fig. 3 (b). As shown in Table 3, its maximum stress is 41.2 MPa, which is less than the fatigue limit of 73.5 MPa. Therefore, the optimized controller meets the requirements of SFVF.

The SFVFT of the optimized motor controller was carried out in three directions of X, Y, and Z for 22 hours respectively. After the fatigue test, there is no damage was observed in the components of the motor controller, and its function was normal. This shows that the optimization motor controller meets the requirements of SFVF. This indicates that it is feasible to use the SFVF simulation method introduced in this paper in the design of motor controller.
4. Conclusion
In this paper, this design suggestion is put forward that the motor controller of the integrated drive system should meet the requirements of 22h SFVFT in the frequency range of 100 ~ 440 Hz. This can provide a reference for the design of other similar motor controllers.

In this paper, a finite element simulation method for SFVF of the motor controller of the integrated drive system is introduced. Using this simulation method, the fracture position of the motor controller SFVFT is accurately predicted, and an optimization scheme that meets the SFVFT requirements is proposed. These indicate that the SFV simulation method of the motor controller is accurate and feasible.

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