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FAILURE ANALYSIS AND OPTIMIZATION DESIGN OF SUSPENSION SUPPORT HOLES FOR GEARBOX CASES

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The suspension hole of a gearbox case was cracked after the mining test vehicle has covered 7000 km. In order to analyze and solve this problem, in this paper, based on the modal analysis of the suspension system and failure analysis of the faulty parts, the finite element model of the powertrain system was established using Ansys, and strength analysis of the gearbox case was carried out. According to the analysis results, improvement and optimization measures were proposed. The analysis results show that the maximum stress of the optimized gearbox case was reduced by 6.9%, and the test vehicle could operate for 50 000 km without failure after the improvement, which verified the effectiveness of those measures. Accumulating experience in the gearbox case design and simulation, modal analysis and finite element analysis were combined to quickly identify the failure causes of the suspension support hole, and targeted improvement measures were taken, which effectively shortened the research and development cycle and saved production costs.

Keywords: gearbox case, modal analysis, failure analysis, optimization design, suspension support holes

1. Introduction

The gearbox is mainly composed of gears, bearings, shafts, and case among other parts. It is an important component of the vehicle powertrain and is widely used in machinery (Vilan *et al.*, 2010). As the main supporting part of the gearbox, the case is bolted to the motor externally and supported on the vehicle frame by a suspension structure. The gearbox case of a complex structure and large size is subjected to loads such as shock and vibration from complex road conditions, as well as torque and gear meshing reaction forces applied to the bearing holes by the internal drive shaft of the gearbox through bearings (Dong, 2011). Once the gearbox case ruptures under complex loads, it will affect the performance and life of the vehicle and, in serious conditions, it may cause accidents and generate significant economic losses (Li and Chen, 2017; Liu, 2018; Fu *et al.*, 2010; Hu *et al.*, 2017; Wilk *et al.*, 2011). Therefore, it is necessary to analyze and study the strength of the gearbox case to ensure its reliability and structural strength.

Xue (2019) conducted appearance analysis, metallographic structure analysis, hardness testing, macroscopic fracture analysis and SEM analysis on a fractured part of the gearbox suspension. Chen *et al.* (2018) carried out testing, diagnosis and finite element analysis, and found that the mounting bracket at gearbox surface exhibited a high resonance at the corresponding frequency, which negatively affected the mounting stability and increased interior noise of the vehicle. Xiao established a dynamic model for the suspension system of the EV powertrain. Through experiments, the researcher obtained inertia parameters of a pure EV powertrain and a static stiffness curve of the suspension. He also examined the excitation force on the EV powertrain (Xiao, 2021). Wang *et al.* (2018) studied the influence of polygonal wear of wheels on the dynamic performance of the gearbox housing of a high-speed train. Wu *et al.* (2019) established a three-dimensional multibody system (MBS) railway vehicle model by considering the flexibility of the gearbox shell and wheel set as well as nonlinear wheel rail contact, and studied the effect of wheel polygonization on the fatigue of a gearbox shell installed on the wheel set of a high-speed train. In order to reduce the radiated noise of the gearbox of agricultural electric vehicles, Son *et al.* (2020) optimized the shape of the gearbox shell. There is great space for optimization of the gearbox housing (Jin *et al.*, 2021; Huang *et al.*, 2021), but there are few literatures items that specify or analyze suspension support holes of gearboxes. Therefore, in this study, we carried out failure analysis and optimization design for the suspension support hole of the gearbox housing. In this paper, upon the analysis of failure causes of suspension holes of a gearbox, improvement and optimization measures are proposed, and the strength analysis of the gearbox case is carried out by employing a simulation analysis method to verify the effectiveness of the improvement measures, which is of great significance to promote vehicle research and development.

2. Fault description and detection

During the durability test of a pure electric mining test vehicle, when the vehicle covered 7000 km, the problem of rupture of the suspension hole of the gearbox case appeared. The inspection of the powertrain found that there were oil stains on the surface of the gearbox shell, and the support holes on the left side of the shell (flange direction) were damaged. Two support holes were broken in the middle of the screw thread, with the fracture not structurally loose. Figure 1

Fig. 1. Rupture position of the support hole

shows the lower left and upper right support holes. One support hole steel wire thread sleeve and the inner wall of the hole were damaged in the middle of the thread against the lower end. Figure 1 shows the lower right support hole. The thread of the broken support hole measured up to 10 mm in depth, and the damaged support hole wall measured up to 10 mm in depth. Still, 1/2 was unscrewed as shown in Fig. 2.

Fig. 2. Support hole thread the gearbox case

The inspection of the threaded holes was passed. The technical requirements of the four-hole thread were M14, 20 mm of thread depth, 25 mm of hole depth; the outer circle of the tab was ∅30, and the height of the tab was 30 mm. The support hole without damage was tested as: M14, thread depth being 20 mm, hole depth 27 mm; the outer circle of the small end of the tab 30.7 mm, and the height of the tab 15.3 mm (to the rib), which passed. After physical and chemical analysis of the shell, the structure was free of defects, and the measured hardness was 105 HB, which met the technical requirements (Liu *et al.*, 2021).

The current bolt specification used is M14×25, with the actual screw-in size at about 15 mm. The effective thread connection length of aluminum alloy material is required to be 1.5-2 times of the outer diameter of the thread. The preliminary judgment of the failure phenomenon is that the cause of the failure is that the upper left and lower right bolts are loose and missing, leading to a sudden increase in the load on the single bolt hole, which in turn leads to rupture of the shell. In addition, there is a slight collision trace at the position of the suspension limit, which can be determined that there was a rigid collision at the suspension limit during the operation.

3. Materials and methods

The gearbox housing is made of cast aluminum alloy with the modulus $6.9 \cdot 10^4$ MPa, Poisson's ratio $\nu = 0.3$, and density 2.7 g/cm^3. The suspension bracket is made of Q235, with the modulus $2.5 \cdot 10^5 4$ MPa, Poisson's ratio $\nu = 0.28$, and density 7.7 g/cm^3. All parameters have been set in the material properties of Ansys.

Compared with traditional fuel vehicles, vibration of electric vehicles, which is produced by the power transmission system, has significantly decreased. However, there are still various vibration problems with the motor operation due to limitations of processing technology and precision constraints. To analyze causes of cracking in the connection hole between the gearbox of a mining vehicle and the suspension bracket, this article conducts modal analysis of the powertrain suspension bracket. It analyzes the frequency and mode of vibration of the bracket and performs finite element loading analysis on the overall model. By obtaining strength of each component, it identifies the causes of problems for further optimization of the design.

4. Results of finite element analysis

4.1. Modal analysis of the suspension bracket

The modal analysis is mainly used to determine dynamic characteristics of structural systems to clearly calculate frequencies and vibration patterns of each order, and to further optimize the performance of products in use. Currently, there are wide applications of modal analysis for improvement of vehicle frames, power systems and other components (Fan and Pan, 2010; Guo *et al.*, 2015; Korka and Gillich, 2017; Liu and Gao, 2017; Wang *et al.*, 2022; Walunj *et al.*, 2015); Zhang *et al.*, 2022).

The powertrain suspension bracket is simulated by PSHELL unit, and the basic size of the unit is 4 mm. The finite element modal analysis models of gearbox suspension bracket 1 and 2 are established as showm in Fig. 3a and 3b, respectively.

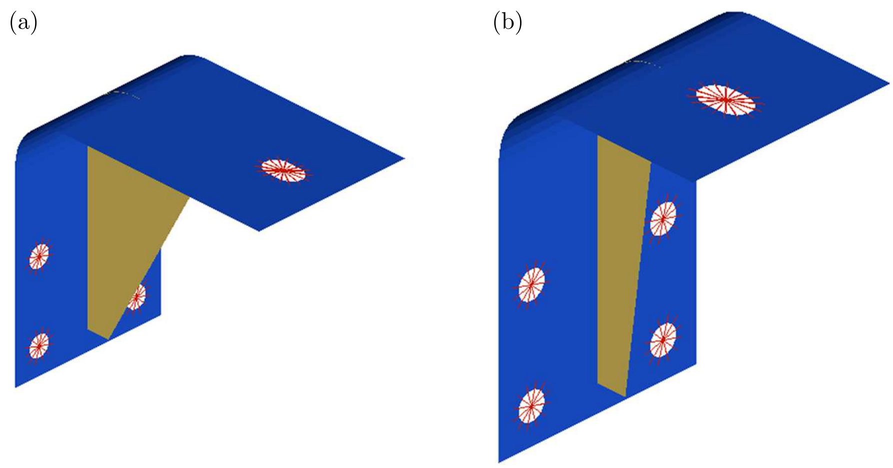

Fig. 3. The finite element model of the bracket: (a) gearbox suspension bracket 1, (b) gearbox suspension bracket 2

To constrain the six degrees of freedom at the connection between the bracket and the powertrain, the third-order constrained modes of vertical vibration, advection and torsion are solved. The first 3 order frequencies of each model are shown in Table 1, and the first 3 order modes and vibration patterns of each model are shown in Fig. 4.

Table 1. The inherent frequency of the first 3 orders of each model

No.	Vibration type	Frequency of gearbox bracket 1 [Hz]	Frequency of gearbox bracket 2 [Hz]	Target value [Hz]
1	Vertical vibration	382.3	583.2	$\geqslant 350$
2	Horizontal vibration	521.3	704.7	
3	Torsional vibration	1089	1332	

From Table 1 and Fig. 4, it can be seen that differences in the inherent frequencies of each order of different models are significant, indicating that the working conditions of different frequencies have a large impact on the modal characteristics of the bracket, and the inherent frequencies of each model under torsional working conditions peak. The inherent frequencies of each order of suspension bracket 1 and 2 are greater than the target value of 450 Hz. The analysis shows that the cracking problem of the connection hole between the gearbox and the suspension bracket of the mine car is not caused by vibration of the bracket (Yang *et al.*, 2022).

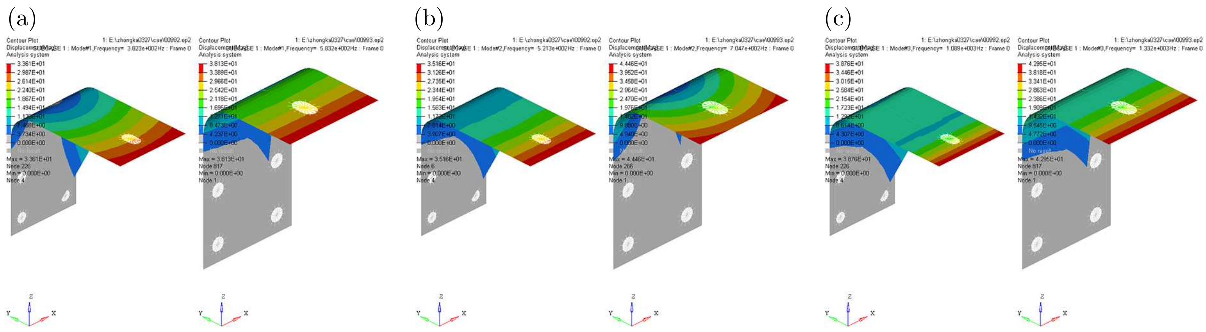

Fig. 4. (a) 1st order, (b) 2nd order and (c) 3rd order of each model

4.2. Powertrain strength analysis

For the problem of cracking of the connection hole between the gearbox case and the suspension bracket, it is proposed to conduct strength analysis of the powertrain, focusing on the stress distribution of the gearbox case to provide a basis for design of the optimized structure of the case. Therefore, a finite element analysis model is established for the whole powertrain as shown in Fig. 5.

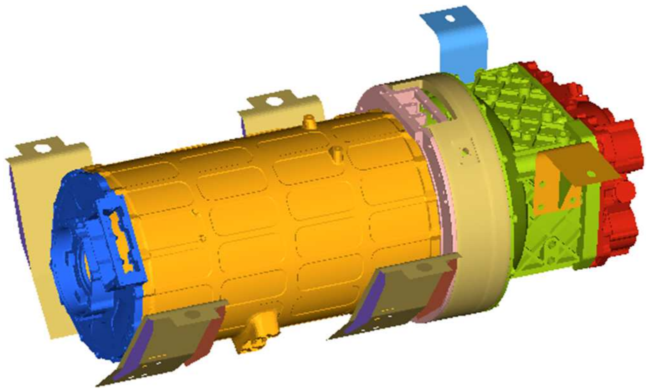

Fig. 5. Finite element analysis model of the powertrain

In this paper, the finite element analysis is based on Ansys, and the suspension bracket of the powertrain is simulated by PSHELL unit with a basic unit size of 4 mm. The bolts and welds are simulated by RBE2 unit; the suspension is simulated by CBUSH unit; mass of the powertrain is 670 kg, and is simulated by CONM2 unit (Fu *et al.*, 2010; Li and Wang, 2008; Shen etal, 2014). The gearbox case, suspension bracket and support arms are all made of cast aluminum alloy, and the bolt is made of steel. If linear elastic properties of the materials are considered alone in the model calculation, the materials are isotropic (Zhang *et al.*, 2014; Zhang and Wang, 2020).

In the powertrain finite element model, 6 degrees of freedom are constrained at the connection between the bracket and the body end, and 9 normal and 4 extreme conditions are selected based on strength analysis. When the finite element method model is calculated, the maximum bolt preload force needs to be considered, and the load information of specific working conditions is shown in Table 2. All working conditions are considered for the self-weight of the powertrain. The yield strength of the gearbox case material is 120 MPa, tensile strength 295 MPa, fatigue strength 126 MPa, and the stress results are shown in Table 3 as follows.

As can be seen from Table 3, the cracking areas of the support holes are smaller than the yield limit, and the stress clouds under each working condition are shown in Figs. 6 and 7 down below. The maximum von Mises stress of the gearbox shell is concentrated at the bolt hole under each working condition, and the maximum value is 69.153 MPa in working condition 9.

Table 2. Strength working conditions

No.	Description	Loading			Target value [MPa]
		$X(G)$	$Y(G)$	$Z(G)$	
1	To the right $1G$		1	−1	⩽ 126 MPa (general working conditions)
2	Vertical downward $3G$			−3	
3	Vertical downward $3G$, forward $1G$	−1		−3	
4	Vertical downward $3G$, backward $1G$	1		−3	
5	Forward $3G$	−3		−1	
6	Backward $3G$	3		−1	
7	To the left $3G$		−3	−1	
8	To the right $3G$		3	−1	
9	Peak torque (12000 Nm)		3	−1	
10	Vertical backward $3G$, upward $4G$			4	
11	Vertical downward $6G$			−6	⩽ 295 MPa (extreme work. cond.)
12	Vertical downward $6G$, to the left $3G$		−3	−6	
13	Vertical downward $6G$, to the right $3G$		3	−6	

Table 3. Strength stress results

No.	Description	Loading			Transmission case maximum stress [MPa]	Target value [MPa]	Maximum deform. of suspension [mm]	Target value [MPa]
		$X(G)$	$Y(G)$	$Z(G)$				
1	To the right $1G$		1	−1	10.044	⩽ 126 MPa (general working conditions)	0.462	⩽ 5 mm
2	Vertical downward $3G$			−3	14.843		1.814	
3	Vertical downward $3G$, forward $1G$	−1		−3	19.618		2.271	
4	Vertical downward $3G$, backward $1G$	1		−3	16.135		1.686	
5	Forward $3G$	−3		−1	27		2.815	
6	Backward $3G$	3		−1	24.134		2.369	
7	To the left $3G$		−3	−1	28.636		3.718	
8	To the right $3G$		3	−1	22.511		3.882	
9	Peak torque (14406 Nm)		3	−1	69.153		5.908	
10	Vertical backward $3G$, upward $4G$			4	19.791		2.418	
11	Vertical downward $6G$			−6	29.696	⩽ 295 MPa (extreme working conditions)	3.627	
12	Vertical downward $6G$, to the left $3G$		−3	−6	52.743		4.847	
13	Vertical downward $6G$, to the right $3G$		3	−6	42.072		5.566	

The maximum stress of the gearbox shell is less than the fatigue strength of the material in each working condition, which meets the design requirements. The deformation of the suspension pad is larger in working condition 9 and 13, and the deformation is 5.908 mm and 5.566 mm respectively, which is larger than the target value. Therefore, working condition 9 is selected for further optimization.

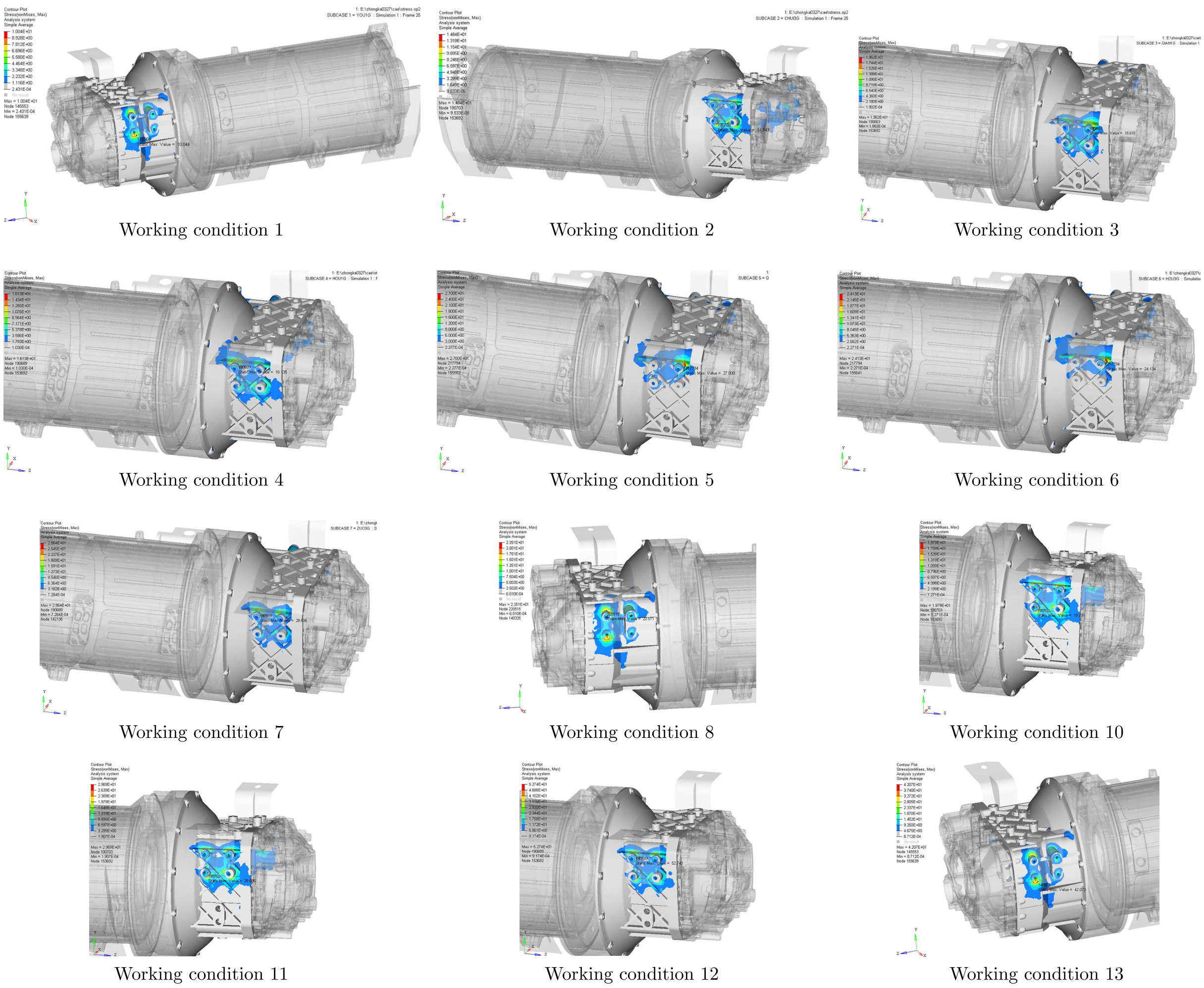

Fig. 6. Stress cloud for each working condition except for 9

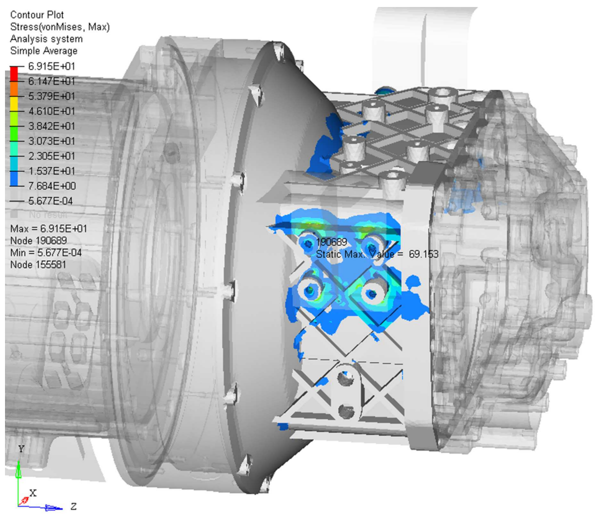

Fig. 7. Stress cloud for working condition 9

In working condition 9, if the suspension rubber pad at the suspension bracket of the gearbox is rigidized, the simulated suspension rubber pad is compressed to the limit, and the "iron touching iron" situation occurs. As it can be seen from stress cloud 9, the maximum stress of the original gearbox shell is 69.153 MPa, and the maximum stress of the gearbox shell after rigidization is 267.075 MPa, which exceeds the allowable target value for the material. Therefore, the limit gap size must be adjusted to avoid the collision between the rubber pad and the limit block, as shown in Fig. 8.

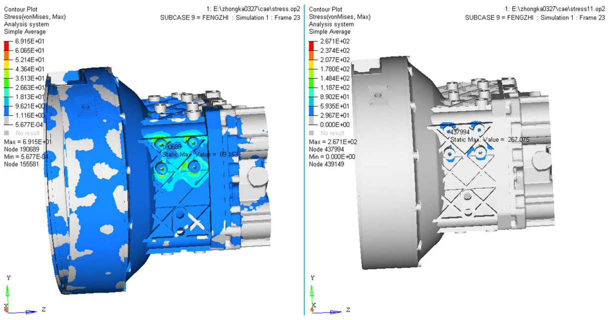

Fig. 8. Stress cloud before and after rigidization of the suspension rubber pad under working condition 9

Under working condition 9, the effect of increased length of the bolt on the case stress is analyzed. The bolt is simulated with RBE2 rigidity, the length of the bolt is increased (by about 10 mm), and the maximum stress of the gearbox case is compared and analyzed. The maximum stress of the original case is 77.064 MPa, and after the bolt is increased by 10 mm, the maximum stress of the case is 69.153 MPa, which is reduced by about 11.4%, which is shown in Fig. 9.

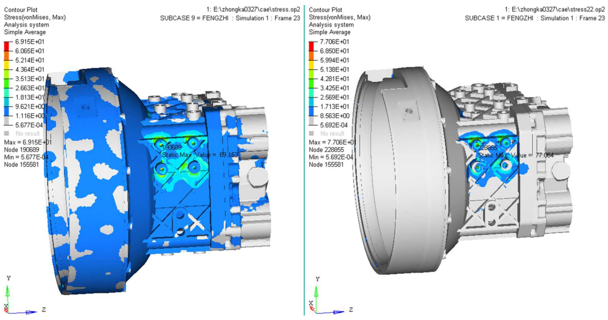

Fig. 9. Stress cloud before and after reducing the bolt length under working condition 9

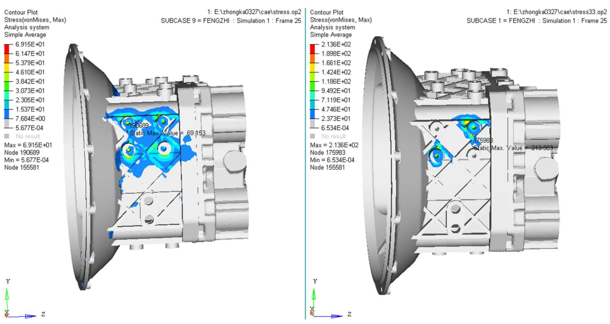

Fig. 10. Stress cloud before and after cancellation of diagonal bolts under working condition 9

The case stresses are compared and analyzed by simulating working conditions with the loss of diagonal bolts at the gearbox cases under working condition 9, as shown in Fig. 10. The maximum stress in the gearbox case when the diagonal 2 screws were not lost was 69.153 MPa, and the stress in the gearbox case after the loss of the diagonal 2 screws was 213.563 MPa, which all exceeded the allowable target value of the material.

In summary, the limit size of the mount foot pads, the connection length of the bolts, and the number of bolt connections have a greater influence on strength of the bolt hole area of the gearbox housing. According to the simulation analysis of the limit size of the suspension foot pad, connection length of the bolts, and the number of bolt connections, these three factors have a great influence on strength of the bolt hole area of the gearbox housing.

4.3. Validation of the optimized solution

Through fault tree analysis, problems such as material defects and machining process of the gearbox shell were excluded. The causes of cracks, based on preliminary analysis of the cracking location, testing data and bracket modal analysis of the integrated support holes of the gearbox case, are: (1) the bolt length and screwing depth are not enough; (2) the bolt is loose and lost, which results in an increase of individual bolt load-bearing beyond the limit; (3) the suspension spacing is limited, resulting in "hard contact" in between.

In response to the aforementioned test and cause analysis, the following improvement and optimization measures were taken: (1) bolt length increased by 10 mm; (2) reinforcement bars at the suspension position of the shell increased; (3) height of the limit block adjusted to 8 mm, which is greater than the maximum runout under normal working conditions.

The improved scheme was imported into the model of the original scheme and strength analysis was performed. According to the results shown in Table 3, only the case under the most severe working condition 9 is compared and analyzed.

Under working condition 9, the support holes of the gearbox case were reinforced with additional ribs, and the maximum stress of the case before and after the reinforcement was compared, see Fig. 11. The original maximum stress of the gearbox case was 69.153 MPa, and the maximum stress of the gearbox case after optimization was 64.364 MPa, which was reduced by 6.9%.

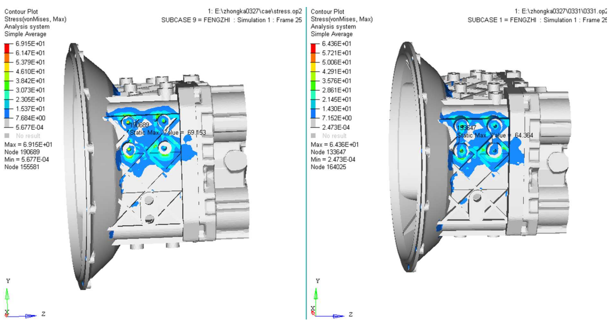

Fig. 11. Stress cloud before and after installation of additional reinforcing ribs under working condition 9

Fig. 12. Before the verification

Fig. 13. Loaded status

Figures 12 and 13 show the gearboxes before and after loading verification, respectively. The improved gearbox case has successfully completed the loading test and undergone a 50 000 km road durability test, indicating that the optimized gearbox case meets the requirements of the design target.

5. Conclusion

This paper adopts a simulation analysis method to determine the specific cause of the cracking problem at the connection hole between the gearbox case and suspension brackets by establishing a finite element analysis model for the powertrain to carry out strength analysis. According to the cause of failure, an optimization strategy of the gearbox case was proposed, and the optimized gearbox case was verified to comply with the design requirements by simulation. With the solution to this problem, we come to the following conclusions accordingly:

- The modal analysis of the suspension bracket was carried out with the help of a finite element analysis software, and the results showed that the working frequency of the bracket was staggered with the intrinsic frequency, so that the resonance could be avoided, thus excluding the cause of cracking at the connecting holes caused by non-bracket vibration.
- Based on the modal analysis of the bracket, strength analysis of the powertrain was carried out by means of finite element simulation. Inspection and testing accurately identified the cause of failure and the structure of the gearbox case was optimized. By comparing the stress of the gearbox case before and after the improvement, the effectiveness of optimization measures was verified, and the R&D cycle and cost were effectively reduced.
- The improved gearbox case the completed a road durability test of 50 000 km and reached the design target. The method proposed in this study solved practical problems for enterprises and reduced their economic losses. Currently, the product is widely used and accepted by the industry.

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