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Vibration Fatigue Analysis and Optimization Design of a Light-truck Urea Box Bracket

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Abstract

In order to solve the cracking problem of a light truck urea box bracket, firstly, the time domain - acceleration signal of the excitation end is collected and converted to frequency domain - acceleration signal, and the frequency response of the urea box bracket is analyzed based on the frequency - acceleration curve of the washboard road, the results show that the maximum stress of the urea box bracket exceeds the yield strength of the material. Then based on the power spectral density curve to do vibration fatigue analysis, the analysis results show that the fatigue life of the urea box bracket does not meet the design requirements and is the same as the cracking position. Furthermore, based on the neighborhood cultivation multi-objective genetic algorithm, the multi-objective optimization analysis of the thickness value of each bracket of the urea box is carried out. The optimum thickness is obtained, the maximum stress of the urea box bracket is lower than the material yield strength, the fatigue life value exceeds the engineering requirement value, and the total weight of the urea box bracket is reduced, achieved the purpose of light weight design. Finally, the bench test of the urea box bracket was carried out, the actual life is close to the simulation value. While it carries on the vehicle road durability verification, the test results show that the vibration amplitude of the urea box bracket is obviously reduced and no cracking after the test, so the cracking problem of the urea box bracket is solved successfully.The method of vibration fatigue analysis and the idea of structural optimization are provided.

Keywords: the urea box support bracket, acceleration spectrum, frequency response, vibration fatigue, optimization;

1. Introduction

In accordance with the provisions of the new state regulations, in order to reduce the content of nitrogen and oxygen compounds in the exhaust gas, to achieve environmental protection purposes. The existing light truck type vehicle needs to install the Urea box [1], and as the key support part of the urea box, the urea box support bracket plays a key role in the safety of the vehicle in the driving process. The random excitation of the road in the driving will usually cause the forced vibration of the structure, so among the automobile components and weld crack damage in the road test and the user feedback, most of them are fatigue damage [2,3].

The cracking phenomenon of a light truck urea box bracket occurs during the road test (the cumulative mileage is 39845 km), as shown in Fig. 1, it can be known from Figure 1 that the cracking position is located at the transition of the circular tube, where is easy to occur stress concentration, and the crack source is gradually formed under the joint action of the alternating force torque and the gravity field, with the increase of the excitation frequency, the crack expands, the final cracking occurs, and the crack location of the section color is deep, the test mileage is long, so the preliminary judgment is fatigue cracking, it is urgently needed to find the cause of cracking, and put forward feasible optimization scheme.

Bao Xiaodong et al. [4]Through collecting road load spectrum and finite element static strength analysis of heavy truck urea box bracket, put forward the bench test method of bracket fatigue verification. However, no finite element method for vibration fatigue analysis is proposed which has certain one sideness. Liu Longtao et al. [5] analyzed the modal and strength characteristics of an airborne structure by using finite element software ANSYS. The vibration fatigue was calculated by using finite element analysis results and empirical formula, but no more theoretical optimization method was proposed. Li Minhao et al. [6] carried out the random vibration fatigue analysis of the vehicle body auxiliary bracket, and carried out the experimental benchmark, which was consistent with the experimental results. Finally, the structure was optimized to effectively improve the fatigue life of the structure under random vibration.

In this paper, frequency response analysis and vibration fatigue analysis to the urea box bracket is carried out, and also optimization analysis based on optimization platform is carried, finally to carry out bench test and vehicle road durability test for the optimization scheme, through which to provide theoretical method for future new product development.

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Figure 1. Cracking of urea box bracket

2. Frequency response analysis principle

Frequency response analysis adopts the array superposition method [7]. The main idea is to transform and coordinate of the dynamic equations of the n degree-of-freedom system, replace the original finite element nodal coordinates with the matrix coordinates, and then obtain the uncoupled n single degree-of-freedom equations through the modal matrix transformation, and solve them individually, and then superimpose the solution to get the results of the dynamic response.

The general solution of displacement of each node in free vibration is:

$$\delta=\delta_{01}\cos(\omega_1 t+\varphi_1)+\delta_{02}\cos(\omega_2 t+\varphi_2)+...+\delta_{0n}\cos(\omega_n t+\varphi_n) \quad (1)$$

In the formula ω_n is the nth natural frequency of the structure, δ_{0n} is the relative vibration amplitude, φ_n is the phase angle.

After solving the natural frequencies and the natural array of undamped free vibration, the displacement vector $\delta(t)$ is regarded as a linear combination of the array δ_{0i}, that is, the transformation is introduced:

$$\delta(t)=\delta_{01}x_1(t)+\delta_{02}x_2(t)+...\delta_{0n}x_n(t)=\Delta X(t) \quad (2)$$

In the formula Δ is array matrix:

$$\Delta=[\delta_{01}\delta_{02}\delta_{03}...\delta_{0n}] \quad (3)$$

$X(t)$ is the array matrix amplitude vector:

$$X(t)=\{x_1(t)x_2(t)x_3(t)...x_n(t)\}^T \quad (4)$$

Substitute it into dynamic equation, the equation can be simplified into n uncoupled single degree-of-freedom vibration formula by using the orthogonality of eigenvector:

$$m_i\ddot{x}+c_i\dot{x}+k_i x_i = f_i (i=1,2......n) \quad (5)$$

Solve each equation, and substitute x_i into it, superimpose n array, then can get the dynamic response of the structure.

3. Collection of acceleration of excitation end

An acceleration sensor is arranged at the front and rear ends of the connection position between the frame longitudinal beam and the urea tank bracket respectively. The acceleration sensors direction X, Y and Z are in the same direction as the vehicle, that is, the front end of the whole vehicle points to the rear end is X positive direction, the main driving side points to the co-driver side is the Y positive direction, and the bottom points to the roof is the Z positive direction. According to the vehicle road durability test specifications, road tests were carried out on short slope road, washboard road, stone road and convex road, to collect the vibration acceleration of the fame longitudinal beam excitation end of each road. By comparing and analyzing the time-domain acceleration curves of each road surface, it can be seen that the acceleration of the washboard road is the largest, as shown in Figure 2. Based on Ncode software, it is converted to frequency-domain acceleration curve, as shown in Figure 3. From the figure 3, it can be seen that the maximum vibration acceleration in X, Y and Z directions is 1.21 g, 1.03 g and 0.24 g respectively. The collected road acceleration is a time-domain load and belongs to a dynamic load, which is different from simply applying a static load such as a force to the urea box bracket, which can better reflect the real working load of the urea box bracket.

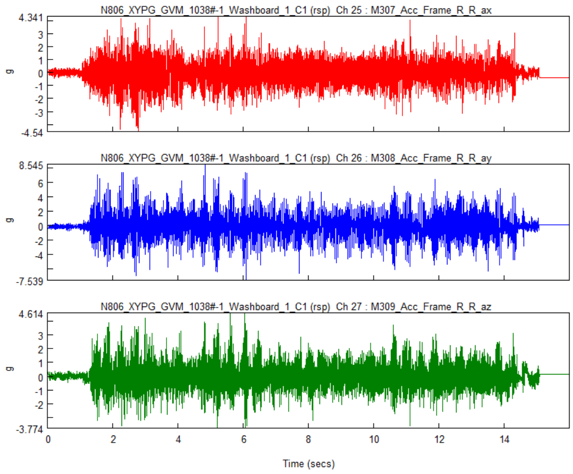

Figure 2. Time domain - acceleration curve of the frame longitudinal end on washboard road

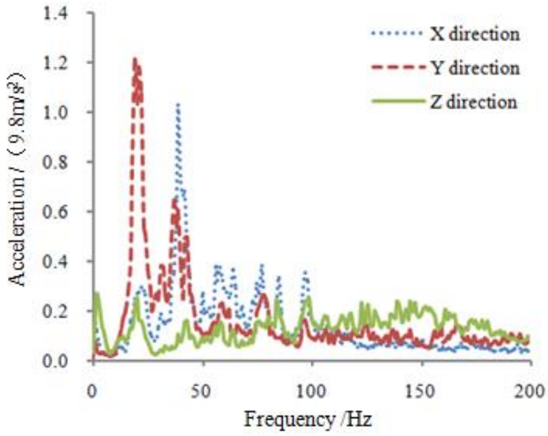

Figure 3. Frequency domain - acceleration curve of frame longitudinal end on washboard road

4. Frequency response analysis of urea box bracket

4.1. Establishment of finite element analysis model

Based on finite element pretreatment software Hypermesh [8] Import the three-dimensional model of frame longitudinal beam, the urea box and the Urea box bracket, among which the urea box bracket includes the bottom plate, the front bracket 1, the front bracket 2, the medium bracket, the rear bracket, the circular tube and the reinforcing plate bracket, and so on, according to the vehicle road spectral acceleration gathering point position section the corresponding frame longitudinal beam, clean the middle surface of the longitudinal beam, the urea box and the urea box bracket of the frame at the same time, and use the 3 mm shell element to divide it into grid. The bolt Connection adopts RBE2+BEAM+RBE2 element to simulate, and the welding connection is simulated by HEXA (ADHESIVE) element. The material of urea box is plastic, its elastic modulus is 2.1E+5 MPa, Poisson ratio is 0.28, density is 7.01E-9 Ton/mm^3, the quality of urea box is 20.8 kg, the material of urea box bracket is Q235, its yield strength is 235 MPa, tensile strength is 375 MPa, The material of the pipe is 20#, its yield strength is 245 MPa, the tensile strength is 410 MPa, based on above to establish the finite element analysis model of the Urea box support, as shown in Figure 4.

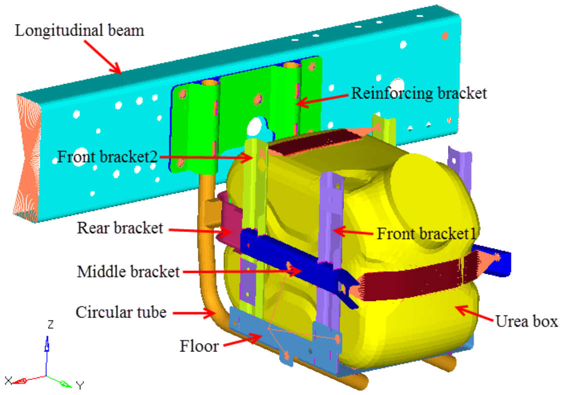

Figure 4. Finite Element analysis model of Urea box bracket

4.2. Analysis results

Taking the frame longitudinal beam, the rear ends as the excitation source, the frequency-acceleration curve of X, Y and Z direction of the frame longitudinal beam on the washboard road is imported into the Nastran software, the frequency range is set to 0-80 Hz and to do frequency response analysis based on it, and the frequency-stress curve of the urea box bracket is obtained, as shown in Figure 5. It can be seen from Figure 5 that when the excitation frequency is 19.6 Hz, the stress of the urea box bracket reaches the maximum. As shown in Figure 6, which is the stress cloud diagram of the urea box bracket at 19.6 Hz. For Figure 6 we can know that the maximum stress of the urea box bracket is 332.4 MPa, and the maximum stress position is in accordance with the actual crack position, exceeding the material yield strength (235 MPa), which is not meeting the strength design requirement and there is the fatigue cracking risk. The strength analysis results can help us find the weak position of the urea tank bracket on the real working load .

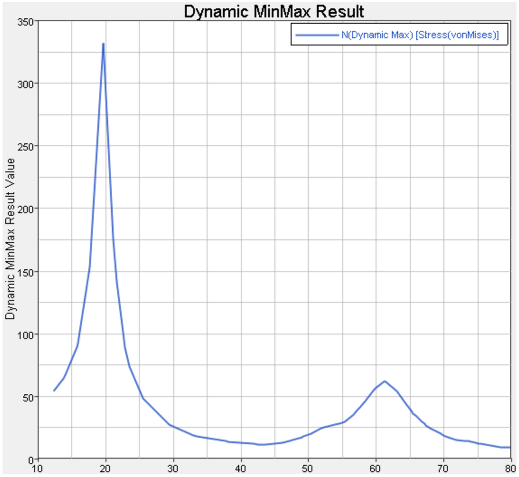

Figure 5. Frequency-stress curve of urea box bracket

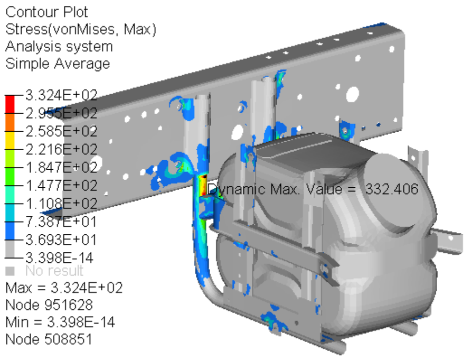

Figure 6. Stress cloud diagram of urea box support

5. Random vibration fatigue analysis theory

The power spectrum density function is the frequency domain description of stable random process, based on the spectral distance of which can obtain statistical information [9, 10], the i order spectral distance is:

$$m_i = \int_0^{+\infty} f^i G(f) df \tag{6}$$

In the formula, f is the vibration load frequency, $G(f)$ is the vibration load function.

According to Miner linear cumulative damage theory [11, 12], the fatigue damage value of the structural part is:

$$D = \sum D_i = \sum \frac{n_i}{N_i} \tag{7}$$

In the formula: n_i is the cycle times of stress level S_i, N_i is the life of the structural part under stress level S_i, when the cumulative damage reach 1 it become invalid.

For continuous state, the stress gcycle times in stress range $(S_i, S_i + \Delta S_i)$ within time T is:

$$n_i = E(P) T P(S_i) \Delta S_i \tag{8}$$

In the formula, $E(P)$ is expected value of peak value of random response signal, T is action time of random response, $P(S_i)$ is probability density function of stress amplitude S_i.

Based on Dirlik probability density function [13, 14] and Miner linear cumulative damage theory, the random vibration fatigue damage of the structure is:

$$D = E(P)\frac{T}{S}\int S^b P(S)dS \quad (9)$$

In the formula, D is the vibration fatigue dame of the structure, $E(P)$ is the expected value of stress peak value, $P(S)$ is the stress amplitude probability density function, b, k, T are the relevant parameters of material and load travel.

6. Vibration fatigue analysis of urea box bracket

In order to obtain the fatigue life of urea box support bracket more truly, the vibration fatigue analysis was carried out based on the theory of vibration fatigue analysis and the acceleration load spectrum of different road. The yield strength and tensile strength of Q235 and 20# steels are input by Ncode software, and the S-N fatigue curves are fitted automatically. At the same time, the time-domain acceleration load curves of short slope road, washboard road, stone road and convex road are converted into PSD load curves based on Ncode.Since the time domain-acceleration load curve is a dynamic load, the PSD load curve is also a dynamic load.PSD curve of short wave road as shown in Figure 7.

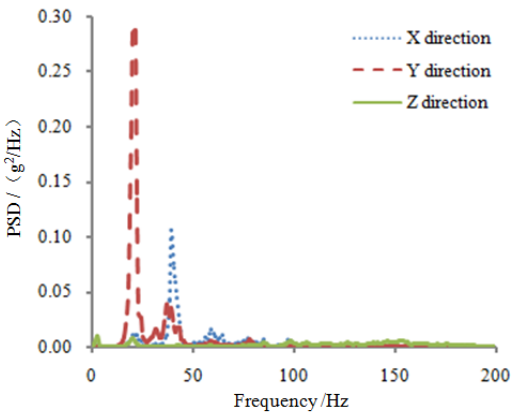

Figure 7. PSD curve of short wave road

Based on Nastran software, the unit load is applied at both ends of the longitudinal beam of the frame to obtain its frequency stress transfer function, and then the PSD dynamic load curves of four kindroads are imported into Ncode software to carry out vibration fatigue analysis. As shown in Figure 8, which is fatigue life cloud diagram of the urea box bracket, its life is 9.23E+4 times,this reflects the times that the urea boxt bracket can work normally under actual road loads, which is lower than the engineering requirement of 3.0E+5 times. It does not meet the fatigue design requirements, and the maximum stress position of the frequency response analysis is consistent with the actual cracking position. In summary, the cracking of urea box bracket is caused by vibration fatigue, which has reshowed its failure mode.

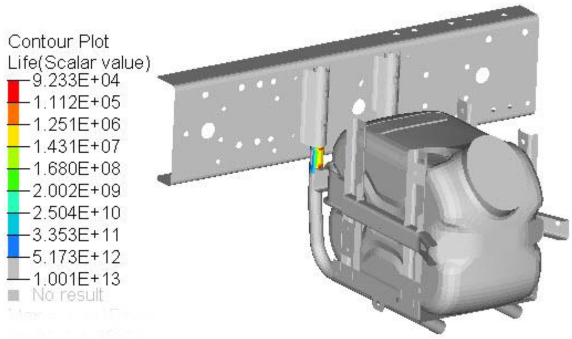

Figure 8. Fatigue life cloud diagram of urea boxt bracket

7. Multi-objective optimization design

7.1. Optimization model

In order to improve the fatigue and strength properties of urea box bracket and reduce its weight at the same time, take the thicknesses of the bottom plate of urea box bracket, front bracket 1, front bracket 2, middle bracket, rear bracket, circular tube and reinforcing plate bracket as design variables, take the minimization of urea box bracket maximal stress, maximization of vibration fatigue life and the minimization of its weight as target functions, take the bracket life bigger than 5.0×105, bracket stress lower than 235 MPa and bracket total weight smaller than 7.2 kg as constraint condition, to build the optimization model as:

Maximum Life (a,b,c,d,e,f,g)
Minimum Stress (a,b,c,d,e,f,g)
Minimum Mass (a,b,c,d,e,f,g)
Subject to Life (a,b,c,d,e,f,g)>3.0E+5 (10)
Subject to Stess (a,b,c,d,e,f,g)<210
Subject to Mass (a,b,c,d,e,f,g)<2.3
$1.0\le a\le 4.0$, $1.0\le b\le 4.0$, $1.0\le c\le 4.0$, $1.0\le d\le 4.0$,
$1.0\le e\le 4.0$, $1.0\le f\le 4.0$, $3.0\le g\le 6.0$

In the formula *Life* is the life of urea box bracket, *Mass* is the urea box bracket total weight, *a* is the thickness of bottom plate, *b* is the thickness of front bracket 1, *c* is the thickness of front bracket 2, *d* is the thickness of middle bracket, *e* is the thickness of real bracket, *f* is the thickness of circular tube, *g* is the thickness of reinforcing plate bracket.

7.2. Optimization methods

Isight software [15] is used to integrate Hypermesh software, Nastran software and Ncode software, as shown in Figure 10. In the Hypermesh module, the command flow of grid cell division of urea box bracket is imported, and the thickness of the bottom plate, the front bracket 1, the front bracket 2, the middle bracket, the rear bracket, the circular tube and the reinforcing plate of the urea box bracket are parameterized as input variables. In the Frequency Response module, the command flow of frequency response analysis based on the collected load spectrum and frequency response analysis based on the unit load is imported. The vibration fatigue command flow based on the actual acceleration signal is imported into the Vibration Fatigue module. The urea box bracket optimization problem belongs to multi-objective problem. Neighborhood cultivation multi-objective genetic algorithm [16,17] deems each objective function as equally important, and crosses each other by grouping after sorting, so as to realize adjacent propagation, enhance the cross-propagation probability of the optimal solution set, and accelerate the convergence to the maximum extent and reduce the calculation time. Therefore, in the Optimization module, neighborhood culture multi-objective genetic algorithm is selected to carry out multi-objective optimization analysis of urea box bracket.

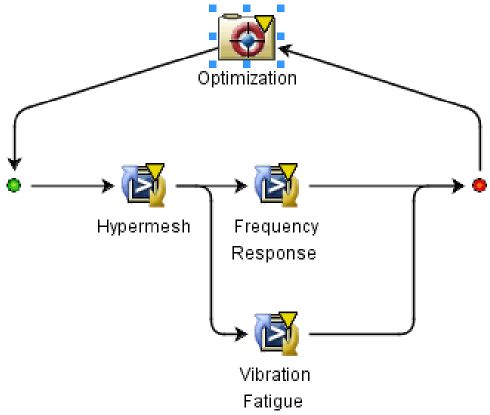

Figure 9. Isight Optimization Platform

7.3. Optimization result

After 158 times of iterations, the optimal thickness of each bracket in the urea box was obtained, as shown in Table 1, the comparison of the parameters before and after optimization. According to table 1, the best thickness of urea box bottom plate is 1.6 mm, the best thickness of front bracket 1 is 1.4 mm, the best thickness of front bracket 2 is 1.4 mm, the best thickness of middle bracket is 1.6 mm, the best thickness of rear bracket is 3.0 mm, the best thickness of circular tube is 3.2 mm, and the best thickness of reinforcing plate bracket is 4.2 mm. At the same time, after optimization, the total weight of the urea box stent is 5.8 kg, which is 23.7% less than that before optimization, achieving the goal of lightweight and saving production costs.

Table 1. Parameters comparison before and after optimization

	Before optimization	After optimization
Floor *a*/mm	2.0	1.6
Front bracke1*b*/mm	2.0	1.4
Front bracke2 *c*/mm	2.0	1.4
Middle bracke *d*/mm	2.0	1.6
Rear bracket *e*/mm	3.5	3.0
Circular tube *e*/mm	2.0	3.2
Reinforcing bracket *e*/mm	4.5	4.2
Mass *m*/kg	7.6	5.8
Stress σ/MPa	332.4	188.4
LifeN_f/cycles	92334	302958

As shown in Figure 10, which is the maximum stress distribution cloud diagram of the urea box bracket, after optimization the maximal stress of urea box bracket is 188.4 MPa, which is 43.3% lower than that before optimization, and less than the yield strength of the material and meets the strength performance requirements.

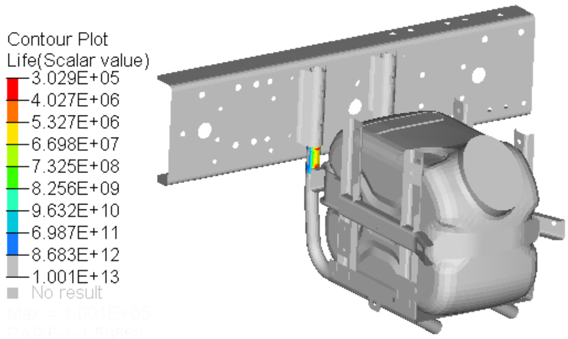

Figure 10. stress cloud picture of urea box bracket after optimization

As shown in Figure 11, which is the vibration fatigue life cloud diagram of the urea box bracket after optimization, it can be known from Figure 11 that the life of the urea box bracket reaches 3.03E+5 times, which is larger than the engineering requirement. Compared with that before the optimization, the life of the urea box bracket is increased by 2.28 times, and its fatigue performance is significantly improved meeting the fatigue design requirements.

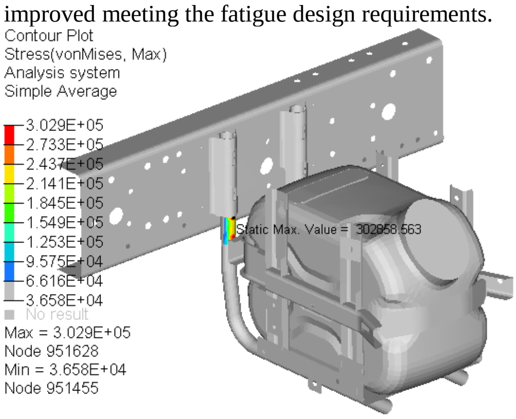

Figure 11. the fatigue life cloud diagram of urea box bracket after optimization

8. Bench test verification

The structure of the urea box bracket optimized by frequency response analysis was used to estimate its fatigue life through vibration fatigue analysis.. In order to verify the accuracy and reliability of the analysis results, a vibration bench test was carried out on the optimum structure of the urea box bracket (Figure 12). The PSD load of the bench test is consistent with the fatigue analysis load. When the bench vibration frequency is 3.64E+5, a crack was found in the urea box bracket. The error rate between the bench test times and the fatigue simulation analysis value is 16.7%.The results of the bench test show that the vibration fatigue analysis method has high accuracy.

Figure 12. bench test of urea box bracket

9. Vehicle road durability verification

In order to verify the reliability of urea box bracket optimization scheme in real road work, the samples were made according to optimization value, the samples before and after optimization were installed on two test vehicles as shown in Figure 13. In order to better compare the urea box bracket vibration situation before and after optimization, a vibration acceleration sensor is installed on the outside of urea box bracket to collect the acceleration signal. According to durability test provision, the road tests were done on short slope road, washboard road, stones road, convex road, by comparing the acceleration signal on each road we can know, the acceleration of the urea box bracket in the Z direction on washboard road is the largest, as shown in Figure 14, which is the frequency domain – acceleration curve of urea box bracket in Z direction on washboard road before and after optimization. It can be known from Figure 14 that before optimization the acceleration of urea box bracket in Z direction maximum is 1.92 g, after optimization it is 0.98 g, which decreased by 48.9% compare to that before optimization, the vibration amplitude is reduced significantly. After the vehicle road durability test (the cumulative test mileage is 10000 km), the urea box bracket has not cracked after optimization, therefore, the optimization scheme of the urea box bracket has high reliability, and the whole analysis and optimization method has high accuracy, and solved the cracking problem successfully and effectively.

Figure 13. optimization scheme of urea box bracket

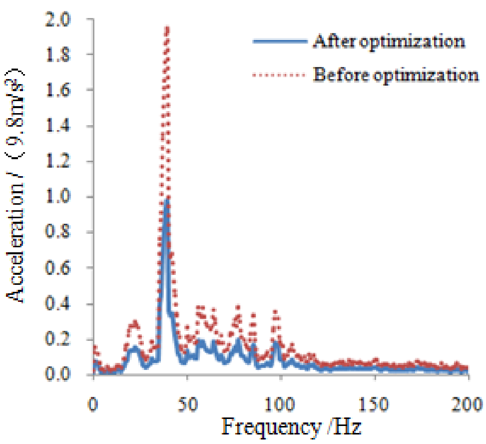

Figure 14. frequency domain acceleration curve of urea box bracket before and after optimization

10. Conclusion

In this paper, concerning the cracking problem of a light truck urea box bracket, the vibration acceleration of the longitudinal beam end is collected, then the frequency response is analyzed, and then the vibration fatigue is analyzed based on the power spectral density, and meanwhile the multi-objective optimization is carried out on the basis of the optimization platform, and finally the bench test and the vehicle road durability verification are carried out.

(1) The acceleration signal of the frame longitudinal end is collected on short slope road, washboard road, stone road and convex road, in which the maximum acceleration of X, Y and Z direction of washboard Road is 1.21 g, 1.03 g and 0.24 g respectively.

(2) Based on Ncode, the measured time domain - acceleration curve is converted to the frequency - acceleration curve, which is used as excitation to analyze the frequency response of the urea box bracket, the urea box bracket achieves the maximum at 19.6 Hz, the maximum stress is 332.4 MPa, which is greater than the material yield strength, and does not meet the strength design requirement, and it is the same as the actual cracking position.

(3) The time domain - acceleration curve of each road is converted into power spectral density curve, and the vibration fatigue analysis of the urea box bracket is carried out, its life is 9.23E+4 times, which is less than the engineering requirement value and is consistent with the actual cracking position.

(4) Based on Isight optimization platform, the optimum value of each bracket thickness is obtained by multi-objective optimization of the thickness of the urea box bracket. After optimization, the maximum stress of the urea box bracket is 188.4MPa, the life of the urea box bracket is 3.03E+5 times. Compare to that before the optimization, the stress value is reduced by 43.3%andits life expectancy has been increased 2.28 times; The total weight of the urea box bracket is 5.8 kg, the weight of which has been reduced by 23.7% compare to that before the optimization, and the aim of lightweight is achieved, the optimization effect is obvious, and it can meet both the fatigue and strength design requirements.

(5) After bench test of the optimization scheme of the urea box bracket, it cracks at vibration times of 3.6E+5, which is close to simulation value. Meanwhile after vehicle durability test, the urea box has not crack, the acceleration in Z direction of urea box bracket is reduced by 48.9% comparing to that before optimization, the vibration amplitude decreased obviously, which successfully solves the cracking problem.

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