Optimization of New Energy Vehicle Road Noise Problem Based on Finite Element Analysis Method

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Abstract—In the use of new energy vehicles, user experience has always been the key project of major manufacturers. At present, the research on user experience focuses on the posture performance of the vehicle itself, and less attention is paid to road noise. Therefore, this study takes the road noise problem of new energy vehicles as the object. The finite element analysis method is chosen for modeling. And the research on the optimization of road noise is carried out. After modeling, the correctness of the model was tested, and all four modes were controlled within the modal error range of 5%. When the new energy vehicle based on this model ran at 80 km/h, the peak road noise was reduced by about 11 dB(A). In addition, after optimizing the tire, the peak value decreased by 4 dB(A). After optimizing the transverse stinger of the rear suspension, the Z-bending mode was increased by 22.3 Hz. Compared with the previous basic scheme, the optimization effect was obvious. When the optimized new energy vehicle ran at a speed of 60 km/h, the peak value is reduced by about 5 dB(A) on the rough road with a frequency of 65 Hz. The results showed that, under the proposed method, the road noise problem was improved, the peak value of the problem was eliminated, and the expected acceptable range was reached.

Keywords—New energy vehicle; Road noise problem; Finite element analysis; Modal error

I. INTRODUCTION

NOWADAYS, new energy vehicles gradually have been used and promoted, and most new energy vehicles are driven by electric motors. Because of the lack of engine cover, this driving method is very likely to cause problems such as tyre/road noise, [1]. Tyre/road noise is the main manifestation of noise in the car. And this noise is low-frequency noise, with a frequency distribution in the range of 30-300 Hz. It is the vibration and noise caused by the unevenness of the road, easily causing anxiety and irritation, greatly affecting the sensory experience of the user, [2]. In addition, in real life, people's requirements for cars are not only limited to safety and transportation needs but also the pursuit of low vibration, quiet and comfortable experience based on this, [3]. The overall model of the vehicle is built based on the finite element method, and the key noise-related modules of the new energy vehicle are optimized and upgraded. In addition, the simulation and optimization results of the rear suspension lateral thrust rod, lateral thrust rod, and tire road noise are tested and analyzed, [4]. At present, the research on new energy vehicles focuses on the performance and energy consumption of the vehicle itself. While research on user experience is scarce, especially for road noise. This study not only provides more direction for the user experience upgrade of new energy vehicles. On the other hand, the study innovatively uses finite element analysis to provide a new solution for the road noise problem of new energy vehicles, which has good practical application value.

II. LITERATURE REVIEW.

The solution to the road noise problem would bring better development to new energy vehicles. Therefore, a large number of scholars at home and abroad had researched road noise and made some progress. Scholars such as Baker argued that the need for road noise and component noise modification was greater when new energy vehicles were automated. The focus on road noise caused by the structure needed to be addressed early in vehicle development to avoid a large number of subsequent problems. The research designed a tyre-wheel system model for virtual road noise development that enabled optimization of the road noise problem. In experimental tests, it outperformed other vehicle models and was able to predict the road noise caused by the structure more accurately, [5]. [6], concluded that the generation of road noise problems was strongly correlated with tyre noise. Therefore, it was important to predict and reduce tyre noise. A hybrid model was developed to predict tyre noise by non-coherently superimposing the sounds emitted by texture impact, tread impact, and air cavity resonance. The results showed that the error of noise prediction was less than 1.7 dBA, providing a valuable method for reducing tyre noise, [6]. [7],. argued that in new energy vehicles, road noise was becoming increasingly evident and a major concern for users due to the lack of masking of engine noise. The sound quality of road noise was investigated through objective and subjective evaluations. The research proposed a group matching pair comparison method to evaluate the noise sample set. And the research analyzed the correlation between sound quality indicators and the subjective distress caused by road noise. The method was validated in real vehicles and outperformed other algorithms in terms of accuracy and robustness, [7]. [8], concluded that active noise control technology would be a solution to reduce the internal noise of new energy vehicles. The active noise control system included a set of acceleration sensors to capture the vibrations that cause road noise. By using the correlation analysis and the Fisher information matrix, the research proposed a method for determining the sensor data set. The results showed that the method was within 0.2 dBA of the target noise reduction results and the road noise was reduced by about 7 dBA, [8]. [9], concluded that tyre and road sound emissions were the main sources of noise caused by vehicles at high speeds. And the tyre and road sound data could be obtained by testing on different roads. However, traditional testing methods were susceptible to environmental influences and lack reproducibility. Therefore, this research introduced a new alternative test method. A comparison of the results revealed that the method yielded a more stable sound spectrum, which was valuable for road noise reduction, [9].

Some scholars had argued that the choice of pavement material could have a significant impact on road noise, [10], and argued that the correct design of the road surface could improve the quality and safety of the ride. And the generation of road noise was also reduced. Therefore, the acoustic performance and surface characteristics of road surfaces were studied. And the mixture of stone asphalt and rubber chips was designed to evaluate the vertical acceleration frequency of road surface and vehicle system in driving. The results showed that the mixture was effective in mitigating road noise and had a significant impact on low-frequency acoustic performance, [10]. [11], suggested that the main source of road noise generated by new energy vehicles was the interaction between tyres and the road surface. Therefore, the ground noise pavements were the best solution to mitigate road noise. This research explored the correlation between road texture and tyre-pavement noise from an experimental perspective. This was addressed by analyzing two existing tyre envelope algorithms, a restricted algorithm based on the second-order derivative of the profile signal, and an indentation method. The correlation analysis showed that the method deepened the tyre-road interaction and effectively reduced the noise generated by tyre rolling, [11]. [12], had developed a new method that effectively reduced the input force from the road surface to the vehicle chassis, thereby reducing the generation of road noise. To predict the dynamic stiffness correction factor of the vehicle chassis, the vehicle beam and coupling point were modeled based on the substructure method of the frequency response function. In a feasibility validation, the model proposed in this research could significantly reduce the generation of road noise, [12]. [13], found that road noise could cause serious environmental health problems. To reduce noise, the research applied a proximity method to characterize the noise levels of different pavement textures using a road measurement trailer. The results showed that the porous friction layer had the lowest noise index compared to other pavements. And the micro-texture of the dense mixed material had a significant effect on the generation of road noise, [13].

In summary, a large number of scholars had worked on road noise reduction. However, most of these scholars' studies were limited to the design of tyres and road surfaces, which were not adapted to new energy vehicles. Therefore, under the finite element method, this research constructed an overall model of the vehicle. And the key modules involved in the noise of new energy vehicles were upgraded. It was aimed at finding a solution to the road noise problem of new energy vehicles.

III. Optimized Design for Vehicle Road Noise Problems

A. *Finite Element Analysis Modeling*

The application of finite elements in automotive and mechanical fields is very extensive. They are automotive safety performance analysis, automotive structural analysis, automotive vibration and noise analysis, automotive fatigue durability performance analysis, etc. All aspects of automotive research are penetrated, [14]. The basic steps of the finite element analysis method for automotive road noise problems are generally divided into six steps, [15]. Firstly, a discretized operation needs to be performed on the continuous structure. Secondly, an effective displacement function is constructed. Then, the unit stiffness matrix is established. And the relationship between the stress, strain, and position of the units can be expressed by Equation (1).

$$\{\varepsilon\} = [B]\{\delta\}^e \tag{1}$$

Equation (1), $[B]$ represents the strain matrix in the cell, and the strain array of any node in the cell is represented by $\{\varepsilon\}$. Equation (1) is substituted into the physical equation. And the relationship between the nodal displacement on the cell stresses is obtained and represented by Equation (2).

$$\{\delta\} = [D][B]\{\delta\}^e = [D]\{\delta\} \tag{2}$$

Equation (2), $[D]$ refers to the elastic matrix on the material and $\{\delta\}$ represents the stress array of any node in the cell.

The equation of equilibrium on the unit can be obtained by combining the principle of virtual work. So it can find the relationship between displacement and stress of the node on the unit, as shown in Equation (3).

$$[K]\{\delta\}^e = \{R\}^e \tag{3}$$

Equation (3), $\{R\}$ represents the equivalent load array, and the stiffness matrix in the cell is represented by $[K]$.

Next, after the discrete structure of the continuous elasticity, the equivalent still needs to be combined with the principle of virtual work. The next step is to assemble the stiffness matrix of each node and establish the equilibrium equations under the discrete structure, as shown in Equation (4).

$$[K]\{\delta\} = \{R\} \tag{4}$$

Finally, the unit stresses and displacement of the discrete nodes are calculated and solved.

Finite element analysis is a method to simplify complex problems. In the finite element analysis, the real continuous structure is divided into discrete elements connected by nodes. By solving discrete element structures separately, the approximate continuous structure is obtained. Error control is one of the most important problems in finite element analysis because finite element analysis is an approximate solution. Generally speaking, the more discrete units, the closer the approximation is to the true value. Therefore, it is necessary to minimize discrete units' number while ensuring accuracy. In theory, the smaller the basic size of a finite element model cell, the finer the mesh that can be divided, and the higher the accuracy of the resulting model (Table 1). Given that the cell size is small to a certain extent, the accuracy of the model is negligible at this time. So the requirements of the finite element cell size are different to maximize the computational efficiency and guarantee the model accuracy.

Table 1. Mesh quality parameters of finite element model

Mesh quality parameters	Aspect Ratio	Jacob	Warpage	Skewness	Maximum angle	Minimum angle
Triangular units	<5	>0.6	<15°	<40°	<100°	>30°.
Quadrilateral units	<5	>0.6	<15°	<40°	<130°	>45°.

Finite element modelling of the complete vehicle is a key basis for solving road noise problems. The Hypermesh finite element pre-processing software is used to build a complete finite element simulation model of the vehicle. The basis of vehicle analysis is first to establish a new energy vehicle model, including two aspects: building a vehicle chassis model and modeling a vehicle body with interior trim. The focus of vehicle modeling is vehicle chassis modeling. The model includes the steering system, sub-frame, front and rear suspension systems, and other modules in the vehicle. It can provide the necessary support for the overall shape of the vehicle, [16]. The specific modelling flow chart is shown in Fig. 1. After the finite element modelling of the car is completed, alignment work is also required. So the necessary preparations can be made for the optimization of the car's road noise problem.

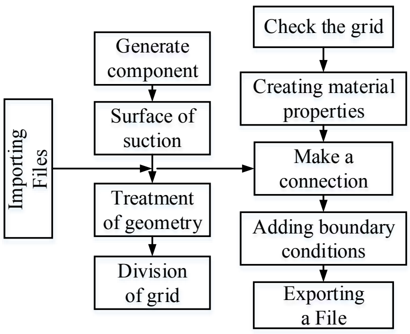

Figure 1. Flow chart of CAE modeling

B. *Vehicle Transfer Path Optimization*

There are many complex ways of generating transmission paths (TPA) for road noise in new energy vehicles. By nature, road noise is divided into two categories: structure-borne noise and airborne noise, [17]. According to the vibration transfer perspective, a complete vehicle is a closed-loop system consisting of a transmitter, a vibration excitation source, and a generator, [18]. The functional relationship between the input and output quantities represents the transfer function. If the system is selected as a linear system, the input quantity is set to $x_0(t)$, which is represented by pull transformation as $x_0(S)$. $x_1(t)$ is the assumed output, which is represented by the pull transformation as $X_1(S)$. $G(S)$ is the assumed transfer function, which is represented by Equation (5).

$$X_1(S) = G(S)X_0(S) \tag{5}$$

For the extraction of the TPA excitation force in multiple transfer paths, as shown in Fig. 2, the acceleration data is collected based on different working conditions. And the main components are analyzed with the help of the singular value decomposition method. At the same time, the separate main components are extracted. The excitation force is extracted by combining the experiments and the frequency response function generated by the inverse matrix method. The excitation force can be obtained in different transfer paths. And the contribution in different transfer paths is calculated to determine the main transfer path.

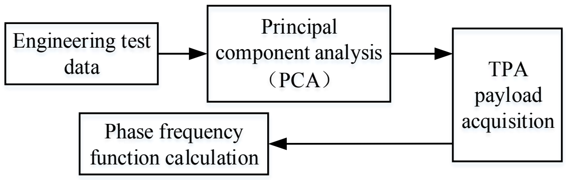

Figure 2. TPA load acquisition

Generally speaking, when the speed of a vehicle is increased, the excitation forces on the road become greater. If the suspension structure in the vehicle transfer path design does not meet the requirements, the road noise performance of the vehicle will also deteriorate, [19], [20]. The suspension system of a car not only stabilizes the performance characteristics but also enhances NVH comfort. So it is important to optimize the performance balance of the suspension structure of the car while meeting the structural durability of the car. After simulation topology analysis and calculation of several iterations of optimization solutions, the structural optimization of the rear suspension transverse thrust rod consists of three solutions. Firstly, the thickness of the 4 mm pockmarked sleeve at the right end of Fig. 3 is adjusted to 3 mm. Then the thickness of the 3.3 mm long tube in the middle of the thrust rod is adjusted to 3 mm. Finally, the intercepted transverse thrust rod is optimized. After optimizing the above three solutions, the modal frequency of the Z-bending in the rear suspension transverse thrust rod finally meets the vehicle NVH requirements.

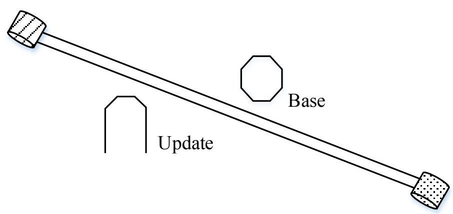

Figure 3. Display of optimization scheme for transverse thrust bar of automobile rear suspension

C. *Optimization of Acceleration*

The research on road noise in automobiles is based on the "excitation source-path transfer-response point" approach, which corresponds to the "tyre-suspension-body" process of a vehicle. The inverse matrix method of transfer functions is often used in the extraction of the wheel centre load method. The wheel centre load is obtained by measuring the transfer characteristics at the wheel centre and the acceleration signal at the steering node. The linear superposition of each transfer path contribution is the sound pressure at the response point, as shown in Equation (6).

$$G_f = H_s^{+} G_a H_s^{+H} \tag{6}$$

In Equation (6), the conjugate transpose is denoted by H and $+$ refers to the pseudo-inverse. The value G_a is derived from the test, and the value H_S is calculated from the CAE model.

The wheel centre force approach has two main advantages. First, by capturing the load on the wheel centre of the vehicle, the suspension system for vehicle road noise is optimized and applications are carried out, [21]. Secondly, the analysis frequency of vehicle road noise is usually up to 250 Hz, while in the finite element model, the analysis frequency can be extended to 500 Hz. The acceleration of the time domain signal generated by the front and rear suspension steering of the vehicle needs to be tested and converted. So combined with the inverse matrix principle, the frequency domain signal can be obtained. *TF* of the finite element transfer function is simulated and calculated. The calculation *Spindle Force* is shown in Equation (7).

$$\text{Spindle Force}=1/\text{TF}*\text{Acceleration} \tag{7}$$

Equation (7), *Acc.* stands for m/s^2 and *TF* stands for $m/s^2/N$. Finally, the wheel centre force of the car is extracted in the whole vehicle model. Then the noise inside the car can be found under the condition of driving at constant speed on a rough road.

Table 2. Conditions of wheel centre load extraction

Testing standards	Test environment	Test equipment	Test conditions	Test sensors
GB/T18697-2002	Rough pavement of cobbles with a diameter of approximately 20-30 mm	LMS digital front-end, accelerometer, microphone	Uniform speed 60 km/h	Positioned on seats, steering knuckles, human ears, etc.

The extraction of the vehicle wheel centre load requires the acquisition of the transfer function and acceleration of the response points. The measurement of the optimized transfer function is carried out by using the force hammer excitation method. Three directions and four-wheel centers at each point are regarded as input points. And unit load excitation forces are applied at corresponding positions to determine the transfer function of the response of 16 steering knuckle measurement points. As shown in Table 2, the test requirements for extracting wheel centre loads for new energy vehicles. Firstly, a cobbled road surface with a certain degree of roughness is selected. Because intake noise, exhaust noise, and motors would have an impact on the optimized test, a neutral skid is used. The initial speed of the skid is 60 km/h and the end speed of the skid is 40 km/h. Secondly, four accelerometers are installed at the steering knuckles of the four wheels. So it can obtain the vibration acceleration of the wheels at different locations in conjunction with specific road conditions.

IV. Analysis of the Optimization Results of the Vehicle Road Noise Problem

After modelling the new energy vehicle using the finite element method, the correctness of the vehicle model was checked. As can be seen from Table 3, the difference values between the top cover mode, the breathing mode, the torsion mode, and the bending mode test results and simulation results are 0.80%, 4.20%, 2.08%, and 4.65% respectively. And the four modes are all controlled within the modal error range of 5%, which better ensures the accuracy of the whole vehicle model. So the accuracy of the road noise optimization analysis can be guaranteed effectively.

Table 3. CAE and benchmarking test results of vehicle key modes

Modal (Hz)	Breathing mode	Bending Modes	Torsional Modes	Top cover modal
Tests	25.1	28.7	32.9	37.4
Simulation	26.2	30.1	33.6	37.7
Differences	4.20%	4.65%	2.08%	0.80%

The following will show the results of the key prototype of the new energy vehicle generating the road noise problem. The actual vehicle test after the modified solution has achieved significant results, as shown in Fig. 4(a). The results show that when the new energy vehicle is driven at a speed of 80 km/h on a smooth road surface, the peak of the road noise problem is reduced by approximately 11 dB(A). Compared with before optimization, the evaluation noise of transverse stinger optimization is reduced by 17.54%. The road noise problem is significantly improved and the problematic peaks are eliminated, reaching the expected acceptable range.

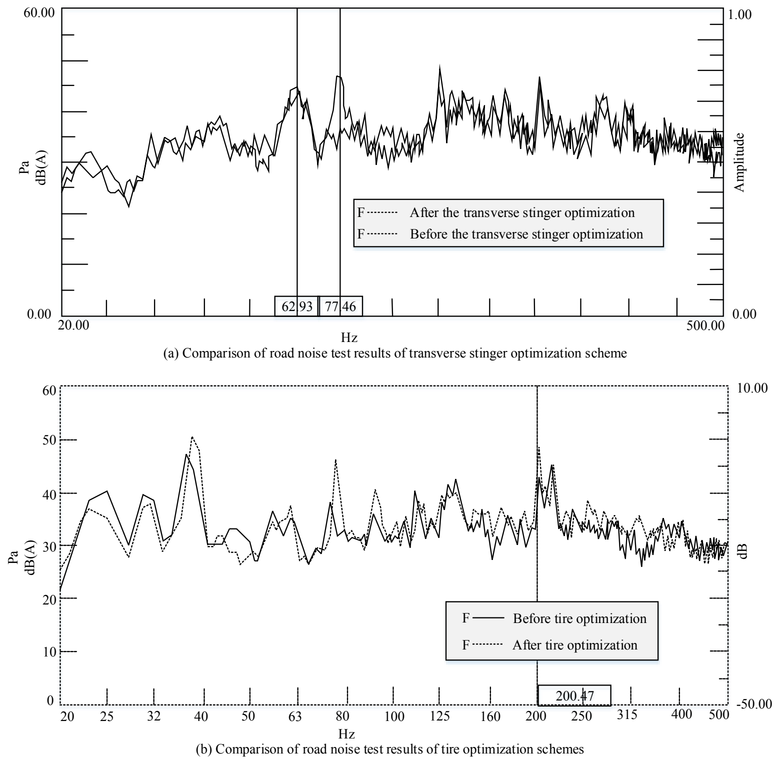

Figure 4. Test results of optimized road noise of lateral thrust bar and tire

The noise caused by the unevenness of the road surface during the movement of a vehicle is generally concentrated between 200 and 300 Hz. This sharp increase in noise tends to make the driver and passengers feel fatigued and irritable. This noise is caused by the ultra-low pressure resonance among the tyres of the wheels and the road surface, therefore the parameters and effects of the tyres are optimized. After comparing the NVH performance indicators, a variety of optimized tyre samples were selected for testing. As shown in Fig. 4(b), when the tyres were replaced with be were applied to spe

The results showed that when the cavity resonance of tyre was at a frequency of 200 Hz, the corresponding peak dropped by 4 dB(A). Compared with before tire optimization, the noise after optimization is reduced by 23.22%. From the above optimization of the NVH tyre performance and lateral thrust bar, combined with objective test data and test driver evaluations of the prototype vehicle, the noise problem was significantly improved before and after the optimization. It reduces the possibility of road noise problems and improves the comfort of new energy

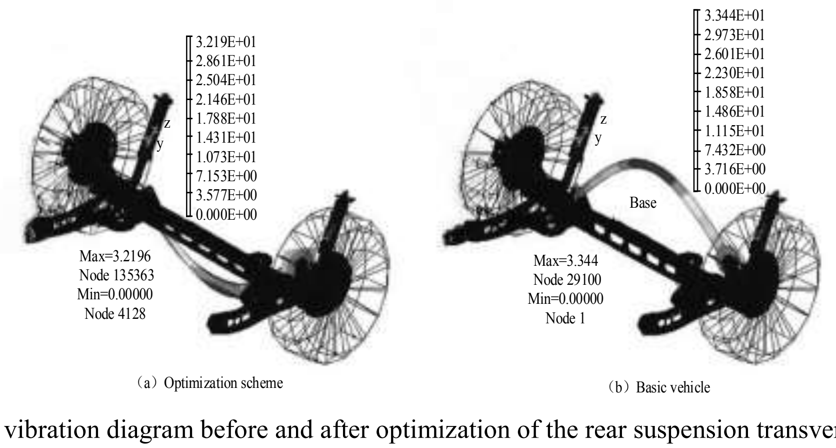

Figure 5. Modal vibration diagram before and after optimization of the rear suspension transverse stabilizer bar

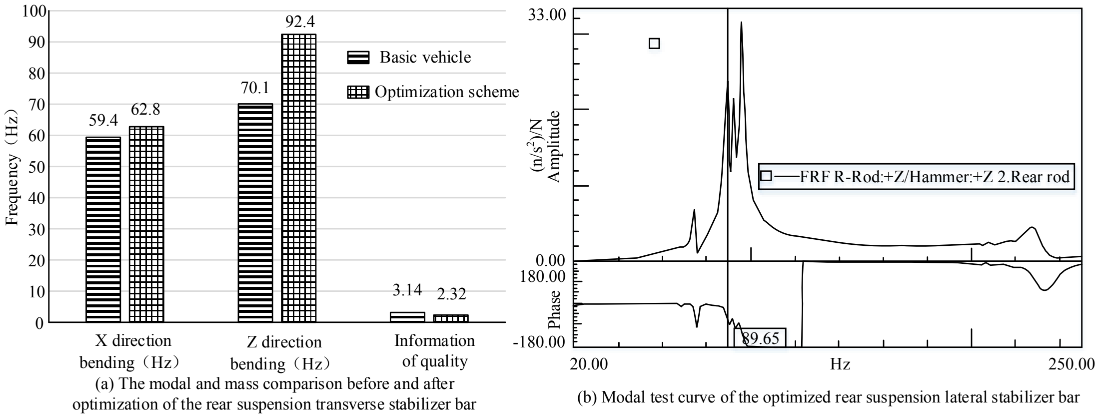

Figure 6. Analysis of optimization results of rear suspension transverse thrust rod

After optimization of the rear suspension transverse thrust bar, the modality and masses of the X- and Z-directional bending in this modal vibration pattern have changed significantly. The modal vibration pattern before and after optimization of the rear suspension transverse stabilizer bar are shown in Fig. 5. After the simulation experiment analysis in Fig. 6(a), the modal frequencies of the rear suspension transverse thrust rod modality in X-directional bending and Z-directional bending of the base car are 59.4 Hz and 70.1 Hz respectively. And the modalities of X-directional bending and Z-directional bending after optimization are 62.8 Hz and 92.4 Hz in turn. And the Z-directional bending modal is improved by 22.3 Hz compared with the previous base scheme, which has a significant optimization effect. At the same time, the mass of the car's transverse thrust rod is reduced from 3.14 kg to 2.32 kg, a reduction of 0.82 kg compared to the base car design. The results show that the rear suspension transverse thrust rod in the new solution not only improves the X- and Z-directional modes but also takes into account the car's lightweight performance. When the NVH properties meet the target requirements, the rear suspension transverse thrust bar optimization can also serve the purpose of cost and weight reduction for the research. Through the simulation analysis of the optimization scheme and the modification of the prototype, the specific modal test results of the rear suspension transverse thrust rod after optimization can be seen in Fig. 6(b). The results show that this rear suspension transverse thrust rod results in a Z-directional bending frequency that can reach 90 Hz, and the error between the test results and the optimization results is 2.59%. When the new energy vehicle is driving, the amount of bush open between the stabilizer bar will increase. At this time, if the uneven road surface is passed, it will lead to the stabilizer bar moving up and down in the bushing, resulting in noise. The study provides a solution to the NVH problem of new energy vehicles by improving the bending mode of stabilizer bars.

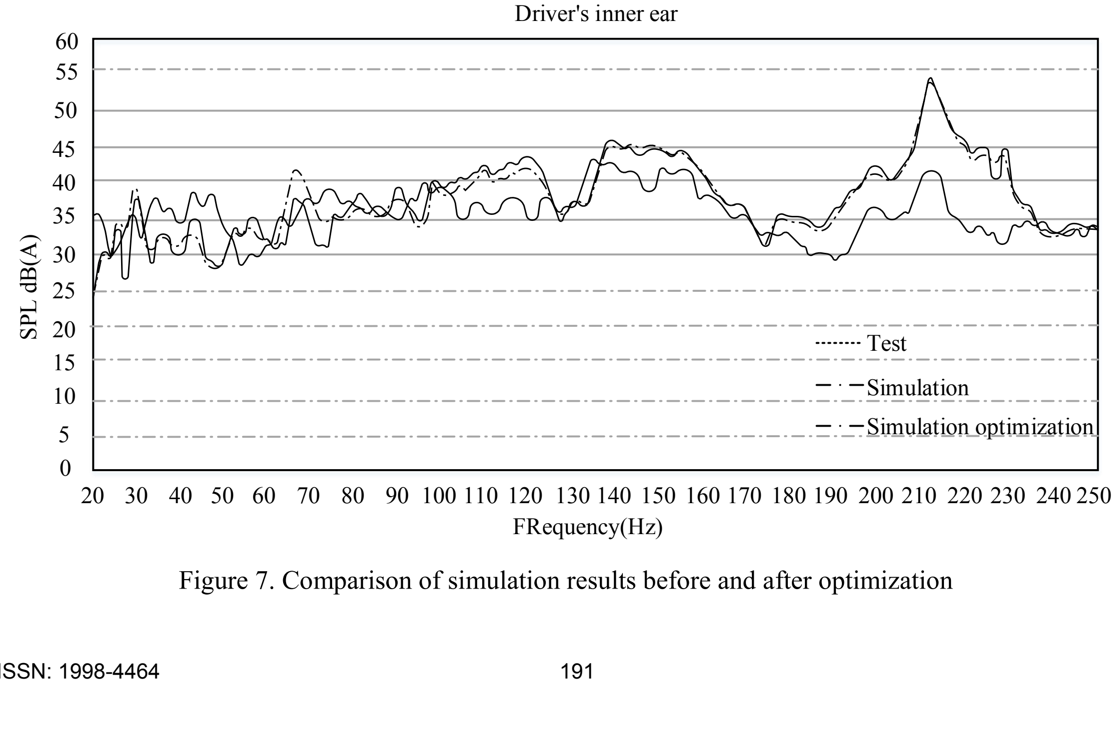

Figure 7. Comparison of simulation results before and after optimization

Combining the suggestions from the CAE feedback, the rear suspension of the completed U-section transverse thrust rod was applied to the finite element model. And three scenarios for the whole vehicle road noise problem were calculated for test, simulation, and simulation optimization. Combining the curves of the three scenarios, the specific working condition results are shown in Fig. 7. Among them, the average noise of the finite element analysis model in the test is 33.67 dB (A). The average noise in the simulation experiment is 43.24 dB (A). The average noise of the optimized finite element analysis model in the simulation experiment is 39.81 dB (A). It can be seen from the results that the noise problem has been improved, far lower than the standard 60 dB (A), which verifies the validity of this study. In addition, when the new energy vehicle travels at a speed of 60 km/h on the rough road surface with a frequency of 65Hz, the peak value is reduced by about 5 dB(A), and the road noise problem has been improved and optimized.

V. Conclusion

With the progress of new energy technology, new energy vehicles are increasingly popular in the market. However, in the driving of new energy vehicles, the noise problem has not been a concern. The problem of new energy noise not only reduces the comfort of driving and riding but also threatens people's life safety. To solve this problem, the finite element analysis method is used to test the road noise of new energy vehicles, and the tire and lateral stinger of new energy vehicles are optimized. The results show that the peak value of new energy vehicles based on finite element analysis decreases by about 11 dB(A) when they run at 80 km/h on a smooth road surface. After tire optimization, the peak value decreased by 4 dB(A). After the optimization of the transverse stinger, the bending mode of the rear suspension is improved by 22.3 Hz. When the optimized new energy vehicle runs at 60 km/h on the rough road surface, the peak value is reduced by about 5 dB(A). As can be seen from the above, the road noise problem has been significantly improved, and the optimized scheme has an obvious effect on the noise problem. In addition, the proposed improvement scheme also optimizes the performance of the vehicle. The research contributes to reducing road noise and improving the driving comfort of new energy vehicles, which have good practical application value. Although this study has made some achievements, there are still some shortcomings, especially the small sample size of this study, which may have a large error. Therefore, based on this study, it will become the main research direction in the future to further introduce the method of this research into a broader field of social practice.

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REFERENCES

[1] J. Chen, X. Yin and K. Chen, “Feature extraction based on instantaneous frequency of subband signal and its application in vehicle classification,” J. Appl. Acoust., vol. 39, no. 1, pp. 97-103, 2020.

[2] D. Frej, A. Zuska and E. M. Szumska, “Laboratory studies of the influence of the working position of the passenger vehicle air suspension on the vibration comfort of children transported in the child restraint system,” Open Eng., vol. 11, no. 1, pp. 470-482, 2021.

[3] Y. Xiong and S. Qin, “Differences in the effects of China's new energy vehicle industry policies on market growth from the perspective of policy mix,” Energ. Environ-UK., vol. 32, no. 3, pp. 542-561, 2021.

[4] H. Gao, Z. Wang, S. Yin, J. Lu and Q. Ma, “Adaptive real-time optimal energy management strategy based on equivalent factors optimization for hybrid fuel cell system,” Int. J. Hydrogen Energ., vol. 46, no. 5, pp. 4329-4338, 2020.

[5] D. Baker, P. O. Sturesson, C. Sale, K. Kulkarni and C. Boston, “Development and optimization of vehicle systems for improved road noise and prediction using vehicle system model in an autonomous vehicle application,” SAE Int. J. Adv. Curr. Pract. Mobil., vol. 4, no. 1, pp. 299-308, 2021.

[6] S. Mohammadi and A. Ohadi, “Introducing a procedure for predicting and reducing tire/road noise using a fast-computing hybrid model,” J. Acoust. Soc. Am., vol. 151, no. 3, pp. 1895-1912, 2022.

[7] H. Huang, X. Huang, W. Ding, M. Yang, D. Fan and J. Pang, “Uncertainty optimization of pure electric vehicle interior tire/road noise comfort based on data-driven,” Mech. Syst. Signal Pr., vol. 165, pp. 108300-108323, 2022.

[8] S. P. Yun, M. H. Cho, S. O. Chi and Y. J. Kang, “Coherence-based sensor set expansion for optimal

sensor placement in active road noise control," Mech. Syst. Signal Pr., vol. 169, pp. 108788-108802, 2022.

[9] D. Clar-Garcia, E. Elasco-Sanchez, M. Sanchez-Lozano and H. Campello-Vicente, "An alternative drum test method to UNECE regulation 117 for measuring tyre/road noise under laboratory controlled conditions," Appl. Acoust., vol. 151, no. 8, pp. 113-123, 2019.

[10] V. F. Vázquez, M. E. Hidalgo, A. M. García-Hoz, A. Camara, F. Terán, A. M. Ruiz-Teran and S. E. Paje, "Tire/road noise, texture, and vertical accelerations: Surface assessment of an urban road," Appl. Acoust., vol. 160, no. 3, pp. 107153, 2020.

[11] L. G. Del Pizzo, L. Teti, A. Moro, F. Bianco and L. Fredianelli, "Influence of texture on tyre road noise spectra in rubberized pavements," Appl. Acoust., vol. 159, no. 2, pp. 107080, 2020.

[12] Y. J. Kang, J. G. Kim, D. P. Song and D. Kang, "Derivation of road noise improvement factor within a suspension system using the inverse substructuring method," P. I. Mech. Eng. D-J Aut., vol. 233, no. 14, pp. 3775-3786, 2019.

[13] R. M. Knabben, G. Trichês, E. F. Vergara, S. Gerges and W. Keulen, "Characterization of tire-road noise from Brazilian roads using the CPX trailer method," Appl. Acoust., vol. 151, no. 8, pp. 206-214, 2019.

[14] N. Liu, Y. Sun, Y. Wang, P. Sun, W. Wen and H. Guo, "Mechanism of interior noise generation in high-speed vehicles based on anti-noise operational transfer path analysis," P. I. Mech. Eng. D-J Aut., vol. 235, no. 1, pp. 273-287, 2021.

[15] T. Liu, A. D. Fulvio, K. C. Long and K. J. Kearfott, "Radiation mapping for an unmanned aerial vehicle," Health Phys., vol. 120, no. 3, pp. 321-338, 2021.

[16] M. Satar, A. Mazlan, M. H. Hamdan, M. Isa and M. Ghapar, "A lab-scale HVAC hissing-type noise and vibration characterization with vehicle system validation," Arch. Acoust., vol. 46, no. 2, pp. 365-373, 2021.

[17] Y. Majd and E. Ebrahimi, "Analysis and design of a new low-phase noise and Gm-enhanced class-C quadrature VCO," IET Microw. Antenna. P., vol. 14, no. 13, pp. 1537-1546, 2020.

[18] Y. Jiang, P. Wu, J. Zeng, X. Wu, Q. He and X. Wang, "Influence of bridge parameters on monorail vehicle-bridge system," J Low Freq. Noise V. A., vol. 40, no. 3, pp. 1194-1214, 2021.

[19] K. Wu, C. Ren, J. Cao and Z. Sun, "Reach on damping control and stability analysis of vehicle with double time-delay and five degrees of freedom," J Low Freq. Noise V. A., vol. 40, no. 2, pp. 1024-1039, 2021.

[20] S. Li, J. Zhao and Z. Zhang "Investigation on linear quadratic Gaussian control of semi-active suspension for three-axle vehicle," J Low Freq. Noise V. A., vol. 40, no. 3, pp. 1633-1648, 2021.

[21] M. Asahina, K. Yamamoto and T. Goto, "Analytical method of noise contribution ratio in railway vehicle using small speaker and acoustic particle velocity sensor," Quarterly Report. RTRI, vol. 61, no. 3, pp. 171-177, 2020.

Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

The author contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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The author has no conflict of interest to declare that is relevant to the content of this article.