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Simulation and Experimental Study of Vibration and Noise of Pure Electric Bus Transmission based on Finite Element and Boundary Element Methods

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P A P E R   I N F O

A B S T R A C T

Since the electric motor of pure electric vehicle replaced the engine, the "masking effect" disappears, and the problem of vibration and noise of the transmission becomes prominent. This is generated during the gear meshing and is transmitted to the housing through the shaft and bearing. Thereby, radiation noise of the housing are generated. The prediction and analysis of the vibration and noise problems of transmission can be avoided during the design process, which will shorten the development cycle and reduce the development costs. In this paper, the finite element model and boundary element model of the three-axis four-speed automated mechanical transmission (AMT) for pure electric bus were established by Finite Element Method (FEM) and Boundary Element Method (BEM) for modal and acoustic analysis. The excitation of the gear system is used as the input, and the direct boundary element method is used to predict the noise of the AMT. The correctness of the simulation method is verified by the comparing simulation with bench test results.

1. INTRODUCTION

The power source of the pure electric bus is electric motor, the transmission is used to transfer power from electric motor to drive axle [1]. The transmission noise becomes dominated especially when the transmission given the absence of masking noise from the internal combustion engine [2,3]. As passengers demand more and more on comfort, there is an increasing demand for noise quality in electric buses[4].

Due to gear transmission error and meshing excitation, the vibration is caused, which passing through the shaft and bearing to the gearbox housing [5]. The vibration stimulation radiation noise, which causing discomfort to driver and passengers. If the natural frequency of the housing is coincided with the working frequency of the gear system, it will cause the resonance of the housing, and aggravate the vibration and noise of the gearbox.

Therefore, the inherent characteristics, vibration and noise of the gearbox housing can be predicted, the structure of the housing can be improved at the design process. So the development cycle can be shortened and the costs can be reduced.

In the early stage of research on transmission noise and vibration, the aim is mainly to find the noise source through repeated tests. But, with the development of Finite Element Method (FEM) and Boundary Element Method (BEM), the technology of vibration and noise prediction of transmission has been improved.

Fang Yuan and Zhang Qiang based on the design parameters, the CAE software was used to predict the vibration and noise of the transmission [6,7]. A. Kumar and H. Jaiswal have concluded that the mechanical properties are directly related with natural frequency and vibration mode shapes by Finite Element Analysis (FEA) [8]. Then, they carried out research work on optimization of connecting bolts number by response surface methodology (RSM) and finite element analysis (FEA). RSM was used for parametric optimization and FEA was used for calculation of modal frequency and

mode shapes [9]. Li Runfang made the mathematical model of the gear transmission system, and the noise level of transmission was predicted through gear drive system excitation size.

In this paper, the FEM and BEM simulation method is used to predict the vibration and noise of the transmission. Simulation and analysis the vibration and noise performance of the transmission is carried out to understand the inherent characteristics and radiated noise characteristics of the housing. The transmission vibration and noise bench test is carried out and the vibration source is identified and improved, so as to avoid the vibration and noise problem of the transmission and shorten the design process.

2. TRANSMISSION VIBRATION AND NOISE PERFORMANCE PREDICTION TECHNOLOGY BASED ON FEM AND BEM

The vibration excited by the gear transmission system is simulated by FEM, and radiation noise characteristics is simulated by BEM [10].

Firstly, modal analysis of transmission housing finite element model is carried out, and its inherent characteristics and modal parameters are obtained.

Secondly, the vibration response of the transmission housing is analyzed with the excitation of the gear system, and the acoustic boundary element model of the transmission is established by LMS Virtual Lab software. The vibration response of the transmission is used as the boundary condition, and the direct boundary element method is used to predict the noise in model.

Finally, the vibration and noise test of the transmission is carried out, and the simulation and experimental results are compared to verify the correctness of the simulation method. Basic steps for predicting radiated noise by FEM and BEM are shown in Figure 1.
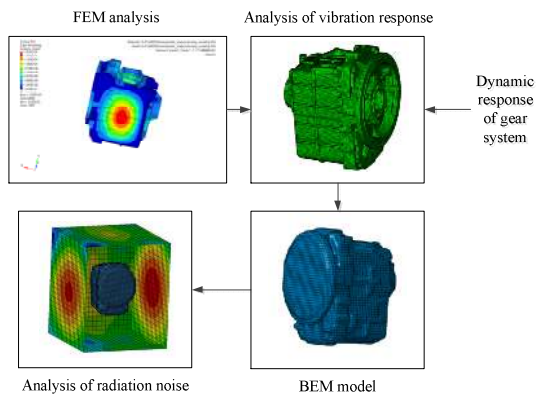

Figure 1. Basic steps for predicting radiated noise by FEM and BEM

3. MODAL ANALYSIS OF THE TRANSMISSION HOUSING

A three axis automated mechanical transmission (AMT) of pure electric bus is mainly to be researched. As shown in Figure 2, the FEM is used for modal analysis.

3. 1. Finite Element Modeling of Transmission Housing   The shape of the transmission housing is complex. It is necessary to simplify the structure of transmission housing and mesh it into tetrahedral element. The finite element model and the coordinate system are shown in Figure 3. The model consists of 93093 nodes and 338489 tetrahedron elements.

Usually, when the noise analysis is carried out, the noise energy of the housing radiation is distributed in the range of 0~3000Hz, and the influence of the high frequency part is not significant. Therefore, only the modal parameters within the 0~3000Hz of the housing are calculated. Using the Optistruct solver in Hyperworks software, the modal analysis of the transmission is carried out. Transmission housing is constraint on electric bus chassis frame by connecting bolts. To simulate the same environment for housing, the fixed- fixed constraint boundary condition is suitable for transmission housing analysis. Grey cast iron HT250 has been selected as transmission housing material. Its density is 7150kg/m^3, the young's modulus 120Gpa, and the Poisson's ratio 0.3.
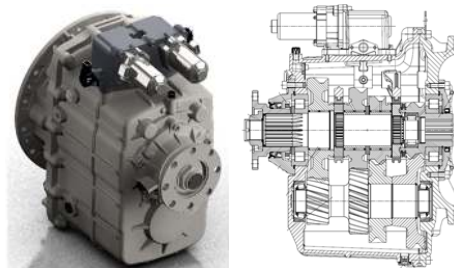

Figure 2. Basic structure of automated mechanical transmission
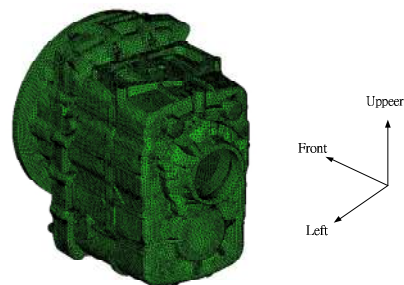

Figure 3. FEM model and direction definition of housing

3. 2. Finite Element Modal Analysis of Transmission   Modal analysis of transmission housing is carried out, and the first 10 modes of vibration are extracted [11,12]. Modal analysis is shown in Table 1.

It is shown that the 10 orders natural frequencies of the housing are between 700Hz and 1600Hz. In this range, it is easy to resonate. The left, right, upper and lower sides of the housing are weak parts, and vibration displacement is larger during the working process.

3. 3. Simulation Analysis of Vibration Response on the Surface of the Housing   It is necessary to analyze the vibration of the finite element model, to get the vibration response of the surface, and to take the vibration response as the boundary condition of the acoustic boundary element analysis to predict radiation noise of transmission housing [13].

The finite element model of the housing is saved as the LMS Virtual Lab readable BDF file format. In the LMS Virtual Lab software, the material properties and boundary conditions of the transmission are defined and the vibration response analysis is carried out. The Nastran solver is called to define the constraint mode of the transmission. The vibration response signal of the bearing block is used as the excitation for the vibration response analysis of the housing.

The Spider unit is set on the bearing seat hole, and the vibration response of the bearings in each direction of the gear is loaded at the central node of the Spider unit, as shown in Figure 4. The acceleration response of each node on the housing is calculated through modal vibration response module in LMS.Virtual Lab.

4. PREDICTION OF TRANSMISSION NOISE BASED ON BEM

4. 1. Boundary Element Modeling of Transmission   The FEM model of the housing structure is introduced into the LMS Virtual Lab software, the repair and coarsening operation of the housing are carried out, and the appropriate boundary element model of the transmission is established.

Considering the characteristics of the housing and the maximum frequency, set the size of the boundary element mesh unit is 12mm, and the maximum frequency is calculated to be 4722.2Hz and satisfies the requirement of the transmission noise. The boundary element model of the transmission is shown in Figure 6. The QUAD4 shell element is used in the boundary element meshes, and the number of elements is 7131. The surface vibration response of the finite element model needs to be matched with the acoustic boundary element model by interpolation, and it can be completed automatically in the software.

4. 2. Field Grid Division   The field point grid is set in the range of about 300mm of the housing, which is to see the radiation noise of the housing structure in the set site grid position. The field point grid model is shown in Figure 6.
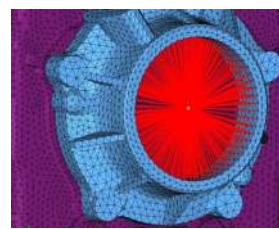
TABLE 1. Modal analysis of the first ten order modes

Orders	Natural frequency(Hz)	Mode shapes
1	754.7	The bending vibration of the box body has larger displacement in the middle position of the left and right sides of the box.
2	934.3	The bending vibration of the box body has larger displacement in the middle position of the left and right sides of the box, opposite to the vibration direction of the first mode.
3	1082.6	The vibration displacement of the upper side of the box is larger
4	1118.1	The vibration displacement of the lower side of the box is larger
5	1159.9	The vibration displacement of the left and right sides of the box is larger
6	1285.9	The vibration displacement of the upper and lower sides of the box is larger
7	1363.6	The vibration displacement of the left and right sides of the box is larger
8	1384.1	The bending vibration of the box is larger than that of the upper and lower sides of the box, and the direction of vibration is opposite.
9	1526.3	Local vibration on the upper side of a box
10	1597.7	Torsional vibration of a box

Figure 4. Spider element of bearing seat hole

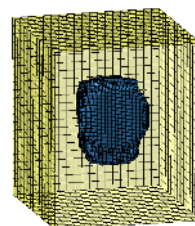**Figure 5.** The boundary element model of the gearbox

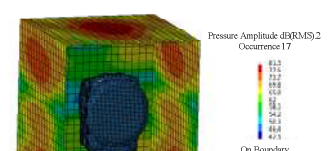**Figure 6.** Field point grid model

Figure 7. Prediction results of transmission noise

4. 3. Analysis of the Prediction Results of the Housing Radiation Noise   The boundary element mesh model, the field point grid model and the structure grid model are introduced into the LMS Virtual Lab software. The frequency range is set from 500 to 3000Hz, and the calculation frequency is 50Hz. The distribution of the acoustic pressure level of the external sound field on the field point grid is calculated within the set frequency range. The simulation results of the 3 gear are calculated, and the input speed is 1500r/min.

It is known from the calculation results that the radiation noise on the left and right sides of the housing is the largest. Under high frequency, the radiation noise of the upper and lower sides of the housing is larger. At 700Hz and 900Hz, the radiant noise in the middle position of the left and right sides of the housing is larger, which is close to the first two order radiation noise frequency and the vibration pattern, and the radiation noise distribution at the other frequencies is similar to the natural vibration type of the housing. The maximum value of the radiation noise is 81.5dB, when it appears at 1300Hz, as shown in Figure 8. This is close to the two frequency doubling of the meshing frequency of the constant meshing gear pair, and is close to the sixth order modal frequency of the housing. The radiation noise of the transmission is also affected by the vibration characteristics of the gear system and the inherent characteristics of the housing.

5. TEST FOR VIBRATION AND NOISE OF TRANSMISSION

5. 1. Test Scheme   The vibration and noise test is carried out in the semi anechoic chamber, and the vibration and noise bench of the transmission is shown in Figure 9.

(1) Test equipment. The noise test and vibration test are completed on the same bench. The vibration test software is LMS Test.Lab, and the acceleration sensor is the Chi Chi 3 direction acceleration sensor. The speed of the input shaft is measured by a Holzer speed sensor.

(2) Layout of test point. In order to obtain the vibration signals, a three direction acceleration sensor is arranged respectively near the input shaft and output shaft bearing seat of the transmission. In order to obtain vibration signals on the surface of the housing, a three direction acceleration sensor is arranged in the weak link of the housing, and the specific arrangement of the acceleration sensor is shown in Figure 8. The measurement direction of the acceleration sensor +X, +Y and +Z are corresponding the direction of the forward, left side and upper side of the vehicle.

In order to obtain the noise signals during the test, three microphones were monted on the left, right and upper sides of the tested parts, respectively. The three

points are labeled as No. 1, No. 2 and No. 3. No. 1 and No. 2 are in the same horizontal plane with the center line of the input axis. The sound level meters arranged at each measuring point are aligned to the measured surface at zero incidence. The maximum emission pressure level is recorded as the acoustic pressure level of the measured sound source, and its measured value is recorded.

(3) Vibration and noise test conditions. The speed test is adopted in the vibration and noise test. The input torque is 0Nm, 200Nm, 400Nm and 600Nm, respectively. The input speed is 800~2000r/min and the test time is 120s. The test results of the constant speed can be obtained from the slicing map of the results of the speed up test.

The effects of different gear positions, input torque, input rotating speeds and measuring points on the noise of transmission are studied. Multiple working conditions are set, the input torque is 0Nm and 400Nm, the input rotating speed is 800r/min, 1000r/min, 1500r/min and 2000r/min, respectively, and the test time is 20s.

5. 2. Analysis of Noise Test Results   The maximum value of the noise test result of each point is taken as the record value during the test. The noise level and the radiation noise characteristics of the transmission are analyzed, which provides the basis for reducing the vibration and noise of the transmission.

(1) Comparison of the different gear position noise test results. In the test, the transmission is in first, second, 3rd and 4th gear respectively, 800r/min, 1000r/min, 1500r/min and 2000r/min are selected as the input rotating speed of the transmission, the noise data of three measurement points are recorded, and the test results of each gear position at No. 1 point are shown in Figure 10. Due to the limitation of the speed condition of the test bench, in the 4th gear, the noise data which was below 1500r/min was recorded. From Figure 10, it can be seen that the results of the noise test of each gear position increase gradually with the rotating speed increase, and with the rise of the gear position, the noise is greater. The noise of 4th gear is the largest at the same speed.
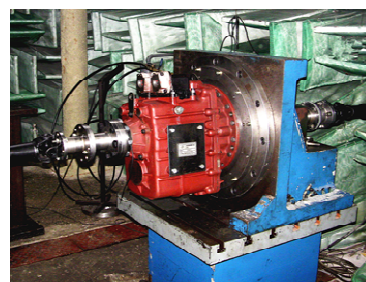

Figure 8. The physical map of the installation position of the transmission

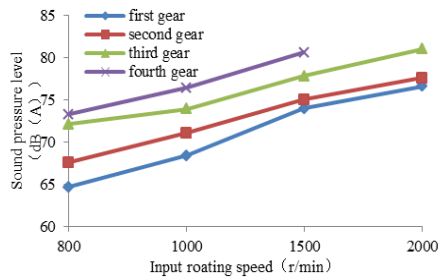**Figure 9.** Acceleration sensor layout position diagram

Figure 10. Each gear noise test result

(2) Influence of measuring point position and input torque on noise test results. The test results of the different point position and the different input torque are given only for the 3rd gear. At 0Nm and 400Nm, the test results of the noise of the three test points are shown in Figures 11 and 12, respectively. From these figures, as the speed increases, the results of noise test at each point increase gradually, and the results measured by No. 2 sound level meter are larger than the other two points, and the result of No. 3 point is the smallest. That is, the radiation noise on the upper side of the transmission is less than the right and left sides. The simulation results can reflect the radiation noise characteristics of transmission to a certain extent. It can be seen from the diagram that the input torque has little effect on the transmission noise test results.

5. 3. Transmission Vibration Test Results Analysis and Vibration Noise Source Identification (1) Vibration test results. Under zero load conditions, the acceleration signal of the Y axis of output shaft on different gear positions are shown in Figure 13. On first, second and 3rd gear, the acceleration amplitude of the 72 order and 96 order are more obvious. The meshing order of the gear pairs is 24 order, that is, the order of the acceleration amplitude is three times and four times than the constant meshing gear pairs. It can preliminarily determine the larger amplitude of the acceleration caused by the meshing of the gear pairs. There is no obvious order characteristic on the waterfall chart in the 4th gear. This is mainly because the 4th gear is the direct gear, and no gear pairs are involved in transmitting power. The waterfall map of acceleration signal collected with different gear

positions and different input torque under the no-load condition is shown in Figure 14.

In the elliptical area of the waterfall diagram, the obvious longitudinal bright band appears in the range of 600~1100Hz frequency. The amplitude of the acceleration in the frequency range is larger, and the vibration caused by the vibration source has nothing to do with the rotational speed of the input shaft. The vibration frequency range is close to the first three frequencies in the modal analysis results of transmission housing. Therefore, the vibration source is related to the inherent properties of the housing, that is, the resonance of the housing happens near the frequency. Especially at the 4th gear, the power is transferred directly from the
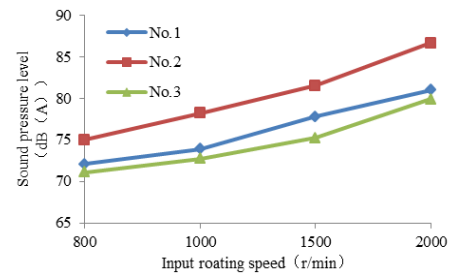

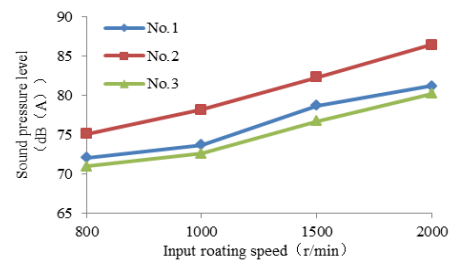**Figure 11.** Noise test result when input torque is 0Nm

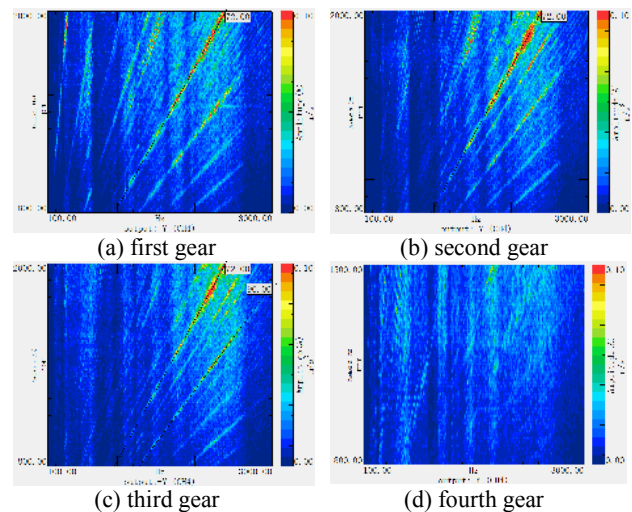**Figure 12.** Noise test result when input torque is 400Nm

(a) first gear   (b) second gear

(c) third gear   (d) fourth gear

Figure 13. Physical maps of the installation position of the transmission

(a) first gear   (b) second gear

(c) third gear   (d) fourth gear
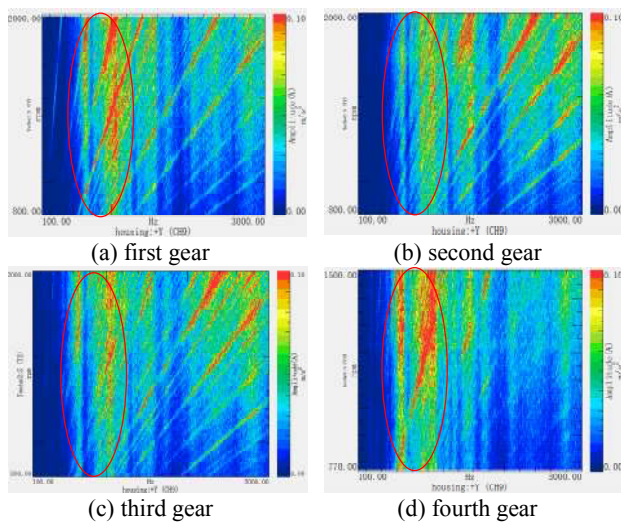
Figure 14. Acceleration of y direction of 1st ~4th shift of transmission case

Figure 15. The Y direction acceleration spectrum of the output axis at 400Nm

Figure 16. The Y direction acceleration spectrum of the output axis at 0Nm

Figure 17. Simulation result

input axis to the output axis, without gear meshing transmission. From the acceleration waterfall map, the position of the larger amplitude of acceleration has no obvious order characteristics. It has little relation with the pair of the gear meshing vibration, which is mainly caused by the resonance of the housing [14].

To study the influence of the input torque on the vibration characteristics, the data from the waterfall map of the speed up test are extracted. When the input rotating speed is 1500r/min, the input torque is no load or 400Nm, the acceleration amplitude of the Y direction of the output shaft as shown in Figures 15 and 16, respectively. The change of the input torque has almost no effect on the acceleration amplitude measured. At the meshing frequency of the constant meshing gear and its frequency multiplication, the acceleration spectrum has a peak, the maximum amplitude of the acceleration appears at the three times frequency. It can be further determined that the meshing vibration of the gear pairs is the ultimate cause of the transmission noise.

It can be known from the test that the possible cause of the excessive noise of the transmission is the meshing vibration of the constant meshing gear pairs and the resonance of the housing.

(2) A comparison of the simulation with test results of transmission vibration. Taking the 3rd gear as an example, the vibration simulation results of the surface node of the housing near the bearing seat of the output shaft (in Figure 17) are compared with the test results (in Figure 16) when the input torque is 400Nm and the input rotating speed is 1500r/min. The frequency of the acceleration peak coincides with the experimental results, which further verifies the correctness of the dynamic model and the vibration simulation analysis method. However, the amplitude of the two diagram shows that the acceleration signal is quite different in
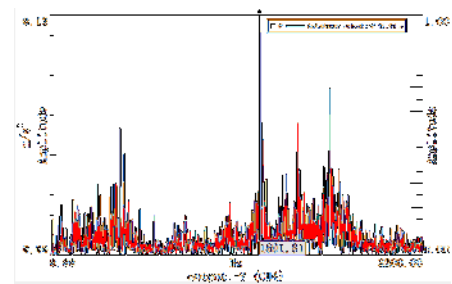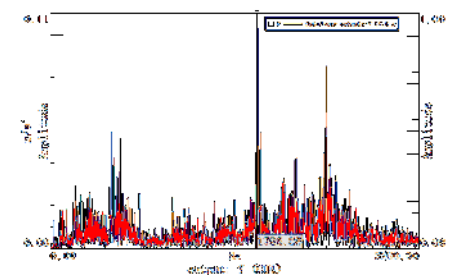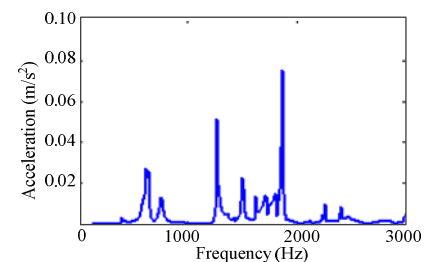
the numerical value, mainly because the precision of the gear system dynamics model is poor, the box is simplified, and the modal analysis results are in error.

6. CONCLUSION

The modal frequency and vibration mode are obtained from the modal analysis. The vibration displacement of the left and right sides of the housing is large, which is the weak link. The vibration response at the bearing seat is used to calculate the vibration response on the surface of the housing, and the results are compared with the test results to verify the rationality of the model, which can reflect the dynamic characteristics of the gear system. In the LMS Virtual.Lab software, the boundary element method is used to predict the radiation noise size and distribution of the field around the transmission. The simulation results show that the inherent characteristics of the housing have great

influence on the radiation noise characteristics of the transmission.

The vibration and noise bench test of the transmission is carried out, and the vibration and noise characteristics are analyzed. The influence of the different gear position, working condition and point position on the noise of the transmission is studied. The frequency spectrum and order analysis of the vibration test results are carried out, and considered the meshing frequency of the gear pairs of the transmission. The constant meshing gear is the main noise source of the transmission, and the inherent frequency of the housing falls to the range of the working frequency of the gear increase the noise to a certain extent, the noise is aggravated. The correctness of the simulation model is verified by bench test.

7. ACKNOWLEDGMENTS

8. REFERENCES

1. Palermo A, Britte L and Janssens K, "The measurement of Gear Transmission Error as an NVH indicator: Theoretical discussion and industrial application via low-cost digital encoders to an all-electric vehicle gearbox", *Mechanical Systems and Signal Processing*, Vol. 110, (2018), 368-389.

2. S. Binbin and G. Song, "Parameters Design and Economy Study of an Electric Vehicle with Powertrain Systems in Front and Rear Axle", *International Journal of Engineering*, Vol. 29, No.4, (2016): 454-463.

3. M. Delkhosh and M. Saadat Foumani, "Modification of Equivalent Consumption Minimization Strategy for a Hybrid Electric Vehicle", *International Journal of Engineering, Transactions C: Aspects*, Vol. 29, No. 12, (2016): 1757-1764.

4. Kale G , Kulkarni M A and Arun S, "NVH challenges and solutions to mitigate cabin noise in electric vehicles", in IEEE International Transportation Electrification Conference (ITEC). IEEE, (2015).

5. Xiao H , Zhou X and Liu J, "Vibration transmission and energy dissipation through the gear-shaft-bearing-housing system subjected to impulse force on gear", *Measurement*, Vol. 102, 64-79, (2017).

6. Fang Yuan, Zhang Tong and Yu Peng. "Joint simulation of radiated noise of electric powertrain based on finite element modeling and boundary element method", *Transaction of the Chinese Society of Agricultural Engineering*, Vol. 21, (2014), 40-46.

7. Zhang Qiang, "Dynamics characteristics analysis and experimental study of a gearbox", Chongqing University, (2014).

8. Kumar A , Jaiswal H and Jain R. "Free vibration and material mechanical properties influence based frequency and mode shape analysis of transmission gearbox casing", *Procedia Engineering*, Vol. 97, (2014), 1097-1106.

9. Kumar A and Patil P P. "FEA simulation and RSM based parametric optimisation of vibrating transmission gearbox housing", *Perspectives in Science*, (2016), S2213020916301070.

10. Enrico Galvagno and Antonio Tota, "Mauro Velardocchia, Alessandro Vigliani. Enhancing Transmission NVH Performance through Powertrain Control Integration with Active Braking System", in SAE International Conference, Detroit, USA, (2017).

11. Popov, Alexei P., and George Nerubenko. "Noise Reduction in Novel Transmission with 3D Point Contact Gear System." *SAE International Journal of Engines*, Vol. 8, No. 4 (2015): 1782-1789.

12. Zhou, Jianxing, Wenlei Sun and Li Cao, "Vibration and noise characteristics of a gear reducer under different operation conditions", *Journal of Low Frequency Noise, Vibration and Active Control*, (2019), 1461348419825603.

13. Chen X , Song C and Zhu C, "Effects of macro-parameters on vibration and radiation noise for high speed wheel gear transmission in electric vehicles", *Journal of Mechanical Science and Technology*, Vol. 32, No. 9, (2018), 4153-4164.

14. G. Zaza and A. D. Hammoub, "Fault Detection Method on a Compressor Rotor Using the Phase Variation of the Vibration Signal", *International Journal of Engineering, Transactions B: Applications*, Vol. 30, No. 8, (2017), 1176-1181.

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چکیده

از آنجا که موتور الکتریکی خودروهای الکتریکی خالص جایگزین موتورهای درون‌سوز شده است، "اثر ماسک" ناپدید می‌شود و مشکل لرزش و سروصدای سیستم انتقال نیرو برجسته می‌شود. این صداها هنگام درگیرشدن دنده‌ها تولید و از طریق محور و یاتاقان به قاب جعبه‌دنده منتقل می‌شود. به این ترتیب، نویز تابشی قاب جعبه‌دنده تولید می‌شود. پیش‌بینی و تحلیل مشکلات ارتعاش و سروصدای قاب جعبه‌دنده را می‌توان طی فرایند طراحی بررسی و از آن پرهیز کرده و چرخه‌ی طراحی و هزینه‌های توسعه‌ی محصول را کاهش داد. در این مقاله، مدل برای یک جعبه دنده‌ی مکانیکی خودکار یک موتور چهارسرعته‌ی سه‌محوره در اتوبوس الکتریکی خالص برای تحلیل‌های مودال و آکوستیک به روش اجزای محدود (BEM) و اجزای مرزی (FEM) طراحی و تولید شد. از تحریک سیستم دنده به عنوان ورودی برای پیش‌بینی نویز در جعبه دنده‌ی مکانیکی خودکار استفاده شد. صحت روش شبیه‌سازی با مقایسه‌ی نتایج شبیه‌سازی و نتایج عملی تایید شده است.

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