An Overview of NVH Problems Caused by Changes in the Excitation Source of HEV

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Abstract. HEV (Hybrid Electric Vehicle) is the most promising vehicle among new energy vehicles. In view of the structural changes of hybrid electric vehicles compared with traditional fuel vehicles and the subsequent changes in NVH (Noise, Vibration, Harshness) performance, the main reasons for the vibration and noise of hybrid electric vehicles and the research results of NVH at home and abroad are detailed introduction. Through the classification and summary of the factors affecting the vibration and noise inside and outside the HEV, the advantages and disadvantages of the NVH control technology currently being developed and developed are summarized, and the future development of the NVH of the HEV is prospect.

1. Introduction

HEV (Hybrid Electric Vehicle) is a new energy vehicle composed of two or more drive systems that can operate independently or at the same time. Because of its low fuel consumption and low emission characteristics, which can meet the current increasingly stringent vehicle emission regulations, HEV is a new energy vehicle type that has successfully achieved industrialization and has promotion significance. NVH (Noise, Vibration, Harshness) performance is one of the most important indicators to measure the quality of automobiles, and it has been paid more and more attention in design and manufacturing. Compared with fuel vehicles, the structures of HEV have undergone several significant changes: the powertrain system integrates the engine, driving machine, engine start-stop motor, power coupling mechanism, final drive and other components, and can realize pure electric operation, engine drive, and hybrid electric drive. By increasing the energy-to-electric conversion system and related components, the energy utilization rate of the HEV is improved. The NVH performance of HEV has changed greatly due to the electric motors and the power battery packs that are large in size and weight. Accompanied by the excitation of multiple complex power sources, the torsional vibration problem of the transmission system is more prominent, and the torque fluctuations during the switching of various driving modes can also bring sudden impacts, which have a great impact on the ride comfort of the entire vehicle. Advanced electronic wire control technology is widely used in HEV, and the radiated noise generated by the booster circuit system becomes the noise source of high frequency noise inside and outside the HEV. In addition, due to the reduced shielding effect of engine noise, NVH problems that are not considered in traditional fuel vehicles, such as wind noise and road noise, have gradually become prominent.

2. Classification of HEV

Compared with traditional fuel vehicles, the structural changes of HEV are mainly manifested as follows: 1. the powertrain of HEV that integrates engine, drive motor, engine start-stop motor, gearbox, and final drive can realize pure electric driving, engine driving, and hybrid driving;
2. the driving mode of the auxiliary system is changed from engine-powered to electric-driven, which can ensure the orderly operation of air-conditioning compressor system, cooling system, vacuum assist system and other auxiliary systems under various working conditions. For this purpose, various electric pump structures must be added to HEV; 3. the adjustment of the power system and auxiliary system has caused changes in the quality, overall layout, load distribution and driving dynamics of the HEV. According to different power transmission methods, HEV can be divided into three types: series, parallel and parallel-series\(^9\). The composition differences of the three types of HEV are shown in the following Figure 1-3\(^{10}\).

3. NVH Challenges Caused by Changes in Incentive Sources

3.1. Vibration and Noise of Motors

The noise frequency of the motor is often in the noise-sensitive frequency band of the human ears, so the NVH performance of the vehicle is largely affected by the motor noise. The NVH problems of motors can be divided into three types according to the different generation mechanisms\(^{11,12}\): electromagnetic vibration and noise, aerodynamic vibration and noise, and mechanical vibration and noise. Their causes and analysis are shown in Table 1.

| Types                | Causes                                                                 |
|----------------------|------------------------------------------------------------------------|
| Electromagnetic vibration&noise | Air gap magnetic waves can generate radial and tangential electromagnetic force that vibrate and deform the stator core and tooth roots. Electromagnetic alternating changes cause vibration and noise |
| Aerodynamic vibration&noise    | The local air pressure in the ventilation system changes rapidly and pulsates sharply with time, and the friction between the gas and the air duct generates vibration |
| Mechanical vibration&noise     | The vibration and noise caused by the interaction of moving parts of the motor during operation. The method of assembly and the processing materials of the components are all influencing factors |

Since most modern motors use high-damping and low-noise sliding bearings or high-precision rolling bearings, and the stator and rotor have received strict dynamic balance correction, mechanical vibration and noise problems are not serious. Aerodynamic vibration and noise are not prominent when the motor speed is not high, and the aerodynamic noise of the water-cooled drive motor can basically be ignored. Therefore, electromagnetic noise is the main concern. The vibration and noise of the motor are mainly obtained by combining simulation analysis and experimental verification, and the simulation model is verified and optimized through experiments. The NVH optimization process of the motor includes three parts: structural modal calculation and experimental verification, forced vibration response calculation and experimental verification, and acoustic radiation calculation and verification, as shown in Figure 4. The optimization of the motor NVH performance mainly revolves
around electromagnetic noise. The optimization scheme mainly includes electromagnetic excitation source optimization and motor structure optimization. By optimizing the modal of the motor housing, the optimization method to avoid the resonance of the motor structure caused by the excitation frequency of the electromagnetic force wave being the same as the modal frequency of the motor is relatively passive, poor in versatility, and does not have the significance of promotion.

![Figure 4. Simulation and prediction process of electromagnetic noise](image)

Therefore, the optimization of the electromagnetic noise of the motor is mainly from Start by optimizing the electromagnetic excitation source. The optimization of electromagnetic excitation sources can be divided into two directions: ① Optimize the electromagnetic parameters: reduce the ellipticity of the stator inner circle and the rotor outer circle in the motor manufacturing process, while ensuring that the stator and rotor are concentric, so that the air gap can be uniform. In addition, noise can be reduced by reducing the air gap flux density and increasing the air gap. But these may bring adverse effects on motor efficiency, power, and torque performance. Salon S[17], WANG[18], Hur J[19] and others adopt different optimization schemes for the rotor structure and winding arrangement, which effectively reduces the torque ripple, vibration and noise of the motor. ② Optimization of the control strategy: inject the compensation current to weaken the amplitude of the target electromagnetic force, appropriately increase the carrier frequency to improve the current waveform and reduce the relative noise. CHAI[20], LIU[21], Gwak[22], Taniguchi[23] and others improve the NVH characteristics of motors by designing harmonic synthesis, spectrum adjustment and voltage injection schemes.

Problems to be explored and studied: ① When the motor vibration and noise modeling is in the design stage, establish accurate stator structure models without the help of experiments; ② In addition to the model under steady-state operating conditions, establish a motor noise analysis model under non-steady-state operating conditions such as starting, acceleration and braking; ③ Solve the problem that some solutions reduce motor noise while sacrificing motor performance.

3.2. Vibration and Noise of Motors

3.2.1. The NVH Challenge of HEV Transmission. The vibration of the transmission is a very complicated random vibration process. The rotation vibration of the shaft, the vibration of the gear transmission system and the high frequency vibration of the bearing are transmitted to the transmission case, causing the case to generate extremely complex random vibration. Various excitation forces are the vibration source of the complex vibration of the gearbox, and the noise of the gearbox mainly comes from the gear system[24]. The series HEV is not equipped with a gearbox mechanism, so the NVH performance of the transmission system can be improved. The noise of parallel and series-parallel HEV transmission mainly includes gear whistling and gear knocking[25]. The main cause of
gear knocking noise is the obvious fluctuation of speed and torque in the transmission system, which causes the non-working parts of the transmission to emit irregular reciprocating knocking noise within the allowable working clearance. Gear knocking noise mainly appears in the low-speed area during the acceleration of the hybrid acceleration mode, and its frequency spectrum presents a broadband characteristic. Gear whistling noise is a kind of noise caused by the dynamic excitation force of the internal gear in the meshing transmission, and the transmission error of the loaded gear in the meshing process. This kind of medium and high frequency pure tone is very easy to be recognized by the human ears, so it is the main NVH problem of gear transmission system.

There are many parts involved in enhancing the coupling stiffness of the transmission system, and the cost is relatively high. Therefore, without changing the gear material and heat treatment, making small changes to the gear and using the original design tool as much as possible, the target gear can be modified and optimized for the purpose of reducing the transmission error of the meshing gear, thereby reducing the noise of the meshing gear. Scholars at home and abroad have done a lot of research on gear modification technology. It is generally believed that gear modification is mainly divided into two categories: tooth profile modification and axial modification. Liu and YUAN et al. use genetic algorithms to determine the tooth profile and tooth direction parameters that effectively reduce gear noise. Ghosh et al. and Barlam et al. study gear deformation and optimization of NVH performance through contour graphics and finite element slip line contact simulation models, respectively.

3.2.2. The NVH challenge of engine start-stop. The engine is mainly excited around the crankshaft at the moment of starting and stopping. For the purpose of torque and battery power and fuel saving, the engine on the HEV needs to be started and stopped frequently. The continuous switching of the start and stop modes of the engine can cause various transient shocks, as shown in Figure 5, and will be accompanied by high-frequency noise that causes obvious discomfort to passengers.

![Figure 5. Vibration conditions when the engine starts](image)

In order to reduce the start-stop vibration impact, the current methods of electronic control technology are mainly implemented: adopting measures such as delaying the ignition advance angle, delaying the closing time of the intake valve, and controlling the fuel injection volume to improve the combustion of the engine; when the initial position of the control piston is after the intake valve closes and is close to the top dead center, the starting vibration amplitude is small; the starting torque of the generator acting as the starter is increased to reduce the torsional resonance of the power unit. Toyota’s team take their first and second generation hybrid systems as the research objects, and analyze the effects of various control methods on improving the NVH performance of the start-stop process. Aiming at the problem of unstable idling operation when the engine restarts, MENG proposes the H-inf control algorithm to control the speed change. In addition, the suspension problem of the engine can be improved by shortening the distance between the power center of gravity and the rotating elastic shaft, and adding torsional vibration damping dampers. Sugimura et al. and YUE et al. improve the restraint on vibration and shock by adjusting the damping and stiffness layout of the transmission system.
3.2.3. The NVH challenge of HEV engine start-stop. Since the power source and corresponding transmission system composition of each working mode of HEV have to change, the characteristics of the torsional vibration problem of the transmission system will also change with the change of working mode. The quality of the dynamic coupling device is directly related to the efficiency of the dynamic coupling and the stability of the coupling process. When the coupling device has problems in the process of synthesizing power, it will produce shock and vibration of the coupling device, and associated noise. Unsteady coupling power output can also cause vibrations in the power transmission system connected to it. In addition, the power coupling device is also responsible for the power decomposition and energy feedback functions, storing part or all of the engine power in the battery through the generator, which will cause the stability of the power switching process. The rapid change of working mode will cause the continuous switching and coupling of various torsional vibration problems with different characteristics to produce complex effects. This aspect is summarized as the increase of HEV power sources and the switching of working modes profoundly change the inherent characteristics of torsional vibration of the transmission system, making it more complex and changeable. In order to achieve better fuel economy, the three types of HEV are equipped with supercharged engines with smaller displacement. The trend of engine miniaturization and supercharging has caused the problem of engine output vibration to be aggravated, and the torsional vibration problem of the drive train may be further exacerbated by the addition of fast-response motors. Due to the switching of HEV between various working modes, the coupling of different torsional vibration characteristics and the profound change of excitation response characteristics of power source lead to the complexity of natural vibration characteristics and excitation characteristics of transmission system. It is a new solution to suppress or reduce the torsional vibration of the transmission system based on the active control of the motor, rather than limited to the passive measures such as optimizing the structural parameters of the transmission system and installing matching damping devices. DAVIS, KIM and ZHANG track the torque fluctuations of the engine and clutch and optimize the control to reduce the influence of the switching process.

3.3. Vibration and Noise of Electrical Accessories System

Compared with traditional vehicles, HEV are equipped with electrical accessories such as electric air conditioners, electric vacuum pumps, and battery pack cooling systems. Since the noise of various electrical accessories is a factor that affects the NVH performance of hybrid electric vehicles, it is necessary to optimize the corresponding NVH performance of different electrical accessories.

3.3.1. NVH problems of battery pack cooling system. There are generally several ways to cool the battery pack: natural cooling, fan cooling and water cooling. The natural cooling method is difficult to cool the battery pack at low speed or idling speed, which is not only inefficient but also unreliable. Therefore, the latter two measures are mostly used for HEV. The sound energy of the water pump and cooling fan is not too great when they work alone, but because the noise frequency is relatively high, and there is no shielding of engine noise, it is easy to be perceived by passengers. In power battery systems, fan cooling is more common. The fan cooling solution is superior to liquid cooling in terms of reliability and cost, but it needs to solve its complicated noise problem. Modifications around the fan's noise characteristics may lead to changes in aerodynamic performance such as static pressure and flow, and these performances must be guaranteed in actual engineering applications, and aerodynamic performance cannot be sacrificed for noise performance. Therefore, it is not recommended to modify the fan structure to reduce the noise of the fan. Fully consider the cooling requirements of the system and match the appropriate cooling fan before considering the noise characteristics of the fan.

The noise of the battery fan system mainly appears in the following aspects: 1. The fan noise transmitted through the air; 2. The structure noise transmitted through the structure connecting the battery and the body; 3. The fan duct is caused by the vortex of the fan airflow noise. Therefore, for the noise of the battery cooling system, it is necessary to reduce the sound source noise. In addition to reducing the noise of the fan itself, it is also necessary to control the derivative noise generated by the fan, such as the noise generated by the battery components and the duct wall under the excitation of
the fan. To reduce the noise of the fan itself, it is necessary to adopt multi-level speed control for the fan. By reading the information on the CAN bus and verifying with the battery temperature, the speed control strategy is implemented to ensure the speed of the battery fan under different working conditions. In the proper range, the battery temperature is also taken into consideration without exceeding the noise level. For HEV, the noise in the passenger compartment is minimal when the vehicle is stationary and the engine is not started. At this time, the high-speed start of the fan has the greatest impact on the noise of the occupants. Therefore, the key to the control of HEV fan noise is to keep the noise as low as possible under stationary and engine non-starting conditions. The structure of the battery cooling system can be optimized in terms of the cover plate of the air inlet and the thickness of the wall of the air outlet pipe. Singh et al.\cite{45} and Scheit et al.\cite{46} use the method of changing the shape and angle of the fan blade to reduce the fan noise of the cars. REN et al.\cite{47}\cite{48} analyze the axial and radial vibration of the battery cooling fans in electric vehicles, and reduce the vibration energy in the axial and radial directions through improved schemes. WANG\cite{44} suppresses the fan noise of HEV by adjusting the speed, changing the structure of the system, and improving thermal management.

3.3.2. Noise and vibration of air-conditioning system. The electric vehicle air conditioning system is mainly composed of electric compressor, condenser, evaporator, condensing fan, blower, connecting pipeline and other components. The noise sources during the operation of the air-conditioning system mainly include two categories:\cite{49}: 1. Fan and air duct noise: wind noise generated during the operation of the condenser fan and the air-conditioning box blower, and the mechanical vibration noise caused by the vibration and transmission of the fan; 2. Compressor vibration noise: including the radiated noise emitted by the compressor itself and the noise generated by the vibration of the structural parts caused by the compressor vibration.

The compressor is the power source of the refrigeration system and the main noise source. There are unbalanced inertial forces of the motor rotor and other rotating parts in the compressor, flapping of the valve plate, and friction between relatively moving parts. These factors cause the compressor itself to generate relatively large vibration and noise. At the same time, the vibration and noise of the compressor are transmitted to the body and the interior of the car through the structural connectors, which affects the subjective feelings of the drivers and passengers. The noise sources of compressors are complex and affect each other. So far there is no systematic method to conduct a comprehensive and systematic analysis of the noise sources of air-conditioning compressors and their control methods. Published papers and research reports generally only involve part of the excitation source or vibration isolation scheme. There are many separate studies on the mechanical noise, aerodynamic noise and electromagnetic noise of the compressor\cite{50}\cite{51}.

3.3.3. NVH characteristics of electric vacuum pumps. To ensure that there is enough vacuum source when the engine is not working, an electric vacuum pump is added to the brake booster system. According to the "incentive source-transmission path-receiver" model, NVH problems caused by the operation of electronic vacuum pumps mainly rely on two types of transmission paths, as shown in Figure 6: 1. Air transmission: The noise emitted by the electric vacuum pump when it is working is spread from the engine compartment to the atmosphere, and then passed into the cab through the air. This part of the noise is transmitted through the atmosphere and is lost more, especially when the windows and doors of the cars are completely closed, this part of the noise is basically not perceived and can be ignored. 2. Body transmission: The noise emitted by the electric vacuum pump is transmitted by the mounting bracket and the front panel of the body, and is sensed by the occupants after being amplified by the approximately closed cockpit. This part of the noise is the main noise perceived by the occupants.
Since the noise transmitted in the air has been weakened during the transmission process, and it cannot be improved from the transmission path, this part of the noise can be ignored in practical applications. The noise transmitted through the vehicle body can be reduced by changing the noise source, damping, isolating vibration, and changing the transmission path. NVH control for electric vacuum pumps mainly involves adjusting the installation position of the electric vacuum, designing a sound insulation structure in the cockpit, and diagnosing noise problems through experiments, and then combining engineering experience to optimize NVH performance. YU, GU, SONG and LIAN and others achieve NVH performance control by adjusting the installation position and working performance of the electric vacuum pump or arranging solutions such as vibration isolation, sound insulation and environmental sealing.

3.4. Wind Noise and Road Noise

The shielding effect of engine noise on HEV is weaker than that of traditional fuel vehicles. Therefore, the contribution of wind noise and road noise to the noise source of HEV has increased. In order to pursue high fuel economy, low-friction tires are usually used on HEV, and weight reduction is also being pursued in the design of body structure. These changing factors have brought challenges to the control of road noise and wind noise of HEV.

3.4.1. Types and solutions of road noise. The road noise of HEV can be divided into structural road noise and aerodynamic road noise. The excitation forces that cause structural road noise include: the vertical force generated by the continuous local compression and release of the contact surface of the tire and the road surface, and the longitudinal force generated by the continuous rolling and release of the tire and the road contact surface. The excitation force is transmitted to the axle through the tire and rim coupling system, and the axle is transmitted to the chassis and body. The frequency range of structural road noise is generally between 20 and 400 Hz, which belongs to medium and low frequency noise. Aerodynamic road noise includes the noise generated by the compression and release of air in the interaction between tires and the road, and the noise generated by the friction between the tire and the road and transmitted to the car through the air. The frequency range of air road noise is 400-5000Hz. It belongs to medium and high frequency noise.

Based on the mechanism of road excitation noise, it can be controlled from excitation source, transmission path and response: 1. In terms of tire design, performance can be improved by optimizing the tire structure and material and tread pattern design; 2. Optimize the vibration isolation performance, structure and bushing parameters of the suspension to reduce the vibration transmission from the suspension to the body mounting point; 3. Vehicle body response control, including the stiffness of the suspension mounting point and the control of the vibration transfer function and noise transfer function into the vehicle, as well as the decoupling of the overall and local modes of the vehicle body. In the above-mentioned control method, the optimization of tire and suspension parameters sometimes conflicts with ride comfort and stability. Therefore, it is necessary to comprehensively consider all aspects of vehicle performance in the optimization process.

3.4.2. Types and solutions of wind noise. The As shown in Table 2, the wind noise generated during driving can be divided into four types. The energy of this kind of pulse brought by wind vibration noise to the human ears is very large, and the noise level can exceed 100dB, which makes the
occupants feel uncomfortable. Buffeting noise occupies the largest proportion of vehicle interior wind noise, so the research work on it is currently the most. Combining the control of the wind noise source and the optimized design of the transmission path, the wind noise can be suppressed from the following perspectives:\(^{[62]}\): ①The whole vehicle design: including the design between the overall flow line of the body and the engine compartment cover, the engine compartment and the front wind design between window glass; ②Partial design: design of reflector, design of sunroof; ③Dynamic sealing design: sealing between door and body, and sealing between glass and sealing strip.

**Table 2. Types of wind noise and control methods**

| Types          | Causes and characteristics                                                                 | Control Methods                                                                 |
|----------------|------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Leakage noise  | Due to the existence of gaps, leakage noise appears in the car body and is transmitted    | Under the condition of ensuring that the static sealing of the body is not problematic, the dynamic sealing of the body is further improved to effectively reduce the leakage noise. |
|                | to the car; mainly concentrated in the high frequency band, making a "whoop" sound.       |                                                                                 |
|                | The noise generated when the air blows to the gaps outside the HEV and the small cavity  | Shorten the gap between the outer panels of the car body; fill the cavity structure; and avoid the resonance sound generated after the airflow is blown into the gap and cavity. |
|                | formed between the car body and the lap joint; the frequency is mainly determined by the |                                                                                 |
|                | air velocity and the size of the cavity passing through.                                 |                                                                                 |
| Cavity noise   | The noise generated by pressure fluctuations on the surface of the car body is a broadband | Start with the overall body design and local design to reduce pressure pulsation and turbulence. |
|                | noise that is not easy to make occupants feel annoying.                                   |                                                                                 |
| Pulsating noise| When the sunroof or window is opened during the driving of the car, a strong roar is     | Control the interaction between the airflow outside the car and the cavity inside the car; and design a reasonable sunroof spoiler. |
|                | generated in the car; the frequency is very low, and the occupants feel uncomfortable due to the feeling of pressing their ears. |                                                                                 |

3.4.3. **Active noise control.** At present, most of the control of wind noise and road noise still adopts passive control schemes, such as sound absorption and insulation, and adding acoustic packages, which contradict the trend of lightweight vehicles. In addition, using the above methods also bring great damage to the speech signal, and even eventually reduce the readability of the speech signal. ANC (Active Noise Control) is an effective noise reduction method proposed in the early 20th century, which can reduce target low-frequency noise (usually below 500 Hz). The principle of ANC is to generate secondary destructive anti-noise signal with the same size and opposite phase as the engine and transmission system to suppress noise\(^{[63]}\). By reasonably arranging microphones and secondary sound sources in the vehicle cab to adaptively eliminate broadband random noise, it can effectively control mid-frequency and low-frequency noise, without changing the body structure through topology optimization, and without having to install heavy and high-cost sound-absorbing materials. By reasonably arranging microphones and secondary sound sources in the car, adaptively eliminating broadband random noise, and real-time feedback and optimization of the online control system, it can effectively adapt to various working conditions and reduce mid-frequency and low-frequency noise. There is no need to change the body structure through topology optimization, nor to install heavy and expensive sound-absorbing materials, so it is of great promotion significance\(^{[64]}[65]\).

4. **Summary**
A variety of power sources are used to drive the HEV, and its working conditions are diverse and complex. HEV often switches between stable operating conditions and transitional operating conditions, so its vibration and noise characteristics are much more complicated than traditional fuel vehicles and pure electric vehicles. The rapid development of HEV presents new challenges for NVH problems and brings new opportunities. For NVH problems that have similar vibration and noise characteristics to traditional fuel vehicles, existing vibration and noise reduction measures can be adopted. For some unique NVH problems of HEV, new prevention and control technologies should be actively researched to improve the NVH performance of HEV.

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