VIBRATION, NOISE AND RIDE QUALITY

1 Introduction

The 26th United Nations Framework Convention on Climate Change on (COP 26) was held in Glasgow, UK in November 2021. The heads of the 120 countries gathered at this summit of world leaders reached an agreement on carbon neutrality stipulating the reduction of CO_2 emissions to effectively zero by the middle of the century. In the automotive industry, which is deeply involved in the realization of a carbon-neutral society, electrification is expanding rapidly as powertrains used in internal combustion engine (ICE) vehicles are replaced with powertrains for zero-emission vehicles that do not emit carbon dioxide while driving, or plug-in hybrid vehicles that can reduce carbon dioxide emissions throughout their lifecycle. At the same time, ongoing efforts to build lighter vehicles bodies, which contribute significantly to reducing CO_2 emissions constitute a headwind for the field of noise and vibration. Focus is not limited to reducing the burden on the environment, as the pursuit of fully automated driving is intensifying in the context of reducing the driving burden and enhancing safety. Furthermore, the continuing demand for solutions to environmental noise issues is prompting assessments for stronger regulation values for standalone vehicle noise.

These social trends are spurring the development of technologies related to reducing the high-frequency noise caused by EVs made conspicuous by the decrease in ICE-produced noise resulting from the spread of electrification or to the building of a brand image based on an improved auditory psychological feel and sound design. Technology to achieve a ride comfort performance that offers the greater comfort expected from fully automated driving, and to establish the prediction techniques necessary to strengthen standalone vehicle noise regulatory values are also being developed. The use of model-based development (MBD) is not only essential to the efficient development of complex vehicle systems that balance multiple areas of performance, and further advances in that methodology will be require.

2 Road Traffic Noise

In Japan, noise regulations for standalone automobiles began with the enactment of safety standards for road vehicles in 1951. Initially, regulations were imposed on steady-state driving noise and exhaust noise, and regulations on acceleration driving noise were added in 1971. The current regulation is UN R51-03, which was introduced as an international harmonized standard in 2016. According to the report on the continuous monitoring of vehicle noise conducted by the Ministry of Environment since 2000, the attainment of environmental standards has been improving moderately over time, as shown in Fig. 1. However, there are still regions where the standards are not met, and continuous improvement in environmental noise remains necessary.

UN R51-03, the current standalone vehicle noise regulation in Japan, is a test method with a stronger focus on urban driving than previous regulations. It evaluates light-duty four-wheeled vehicles for noise level during moderate acceleration based on urban driving. These conditions magnify the contribution of tire noise as a source of noise, which means that achieving further noise reduction requires reducing not only the noise coming from the engine, but also that coming from the tires. The introduction of the stricter regulatory values represented by Phase 3 is under discussion, and complying with those values involves many difficulties in terms of cost as well as of balancing multiple areas of performance. However, the use of simulations relying on MBD models has been reported to boost development efficiency.

The United Nations is currently reviewing the UN R51-03 test method and considering the eventual introduction of road surface correction and temperature correction for tire noise to reduce measurement uncertainty, as well as the revision of the Additional Sound Emission

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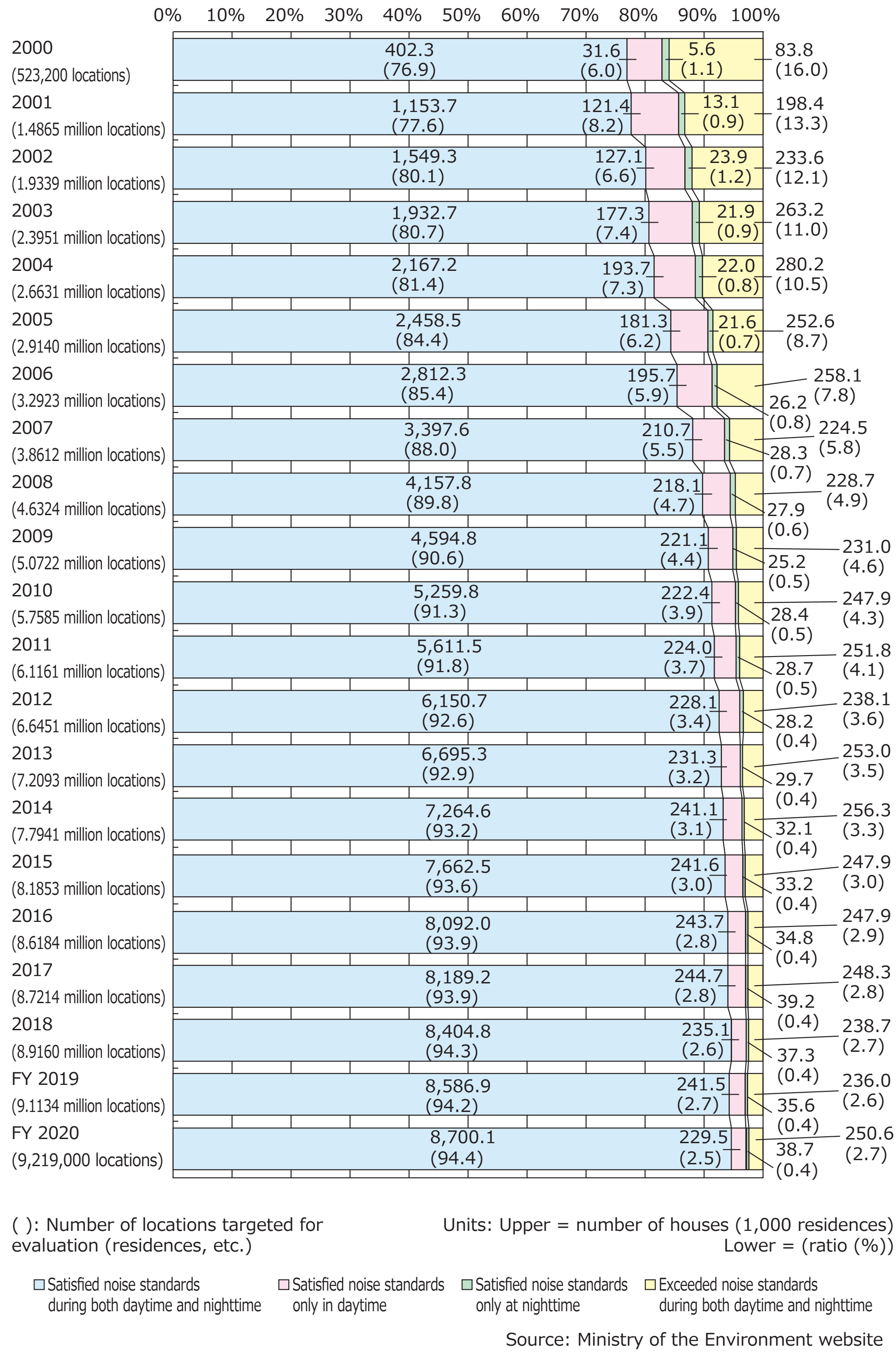

Fig. 1 Status of Compliance with Environmental Noise Standard in Japan (nationwide change over time)

Provisions (ASEP) to expand evaluation conditions and reduce the range of driving that cannot be evaluated during certification testing. In March 2021, a task force was set up under the Groupe Rapporteur Bruit et Pneumatiques (GRBP) to discuss not only standalone vehicle noise regulations but also comprehensive efforts to further reduce road traffic noise.

At the same time, approaching EVs, HEVs, PHEVs and other electric vehicles, which are increasingly common, are difficult for pedestrians to perceive due to their quietness. This led to the proposing acoustic vehicle alerting systems (AVAS) for safety purposes, and the UN

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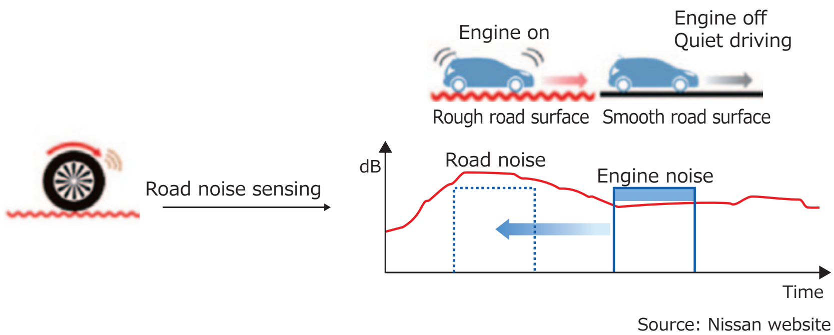

Fig. 2 Engine control based on road noise estimation

R138 regulation for acoustic vehicle alerting systems was introduced in 2018. The use of multipoint microphones for better test accuracy is under consideration.

3 Noise and Vibration of Vehicle Components

3. 1. Powertrains

The tightening of requirements for improved fuel efficiency and environmental friendliness year after year shows no sign of abating, a situation that is bringing major changes, such as government policies to ban internal combustion engines in the future, in the environment surrounding powertrains. With developed countries setting the goal of carbon neutrality by 2050 at COP 26, reducing CO_2 emissions can no longer be put off, prompting a succession of announcements for vehicle equipped with a powertrain containing more electric components than ever from the various OEMs.

The image of electric vehicles as quieter than ICE vehicles creates high expectations for improved quietness, which has been the subject of many technical reports. There have also been many reports on the use of MBD in devising ways to make noise inconspicuous by skillfully controlling the operating conditions of increasingly complex systems, as well as in efficient system development.

In hybrid vehicles with both an electric component and an ICE, various efforts have been made in the ICE driving range to avoid impairing quietness during EV driving. In general, many cases involve controlling driving to mask noise from the ICE by modifying noise according to vehicle speed. One reported driving control masks the noise of the internal combustion engine by monitoring the fluctuation in wheel speed at the same vehicle speed to estimate road surface conditions, and raising or lowering the ICE drive frequency depending on whether road noise is determined to be high or low (Fig. 2).

Environmental concerns continue to impose a strong demand to improve ICE fuel efficiency and exhaust gas quality, and high-speed combustion is one technique demonstrating such improvements. Rapid combustion is generally considered to worsen combustion noise and the possibility of balancing it with noise reduction is being studied. The reduction of excitation force in combustion waveform control through bimodal two-stage combustion in pre-mixed charge compression ignition (PCCI), and the analysis of vibration transmission from the piston and connecting rod to the crankshaft or cylinder block present examples of reducing the combustion noise region by changing the cross-sectional shape of the connecting rod and optimizing the vibration characteristics.

Various measures have been taken in the support and transmission system of the power plant to address the increase in noise and vibration during combustion. Attempts to use active mounts not only to reduce vibration, but also in the role of vibrators that create pleasant sounds for occupants are being made. Similarly, there have been reports of decreasing noise by improving the vibration characteristics of the engine structure itself, as described above, and transforming noise into sounds that make occupants feel comfortable.

One reported approach to improving sound involves adding active sound control (ASC) not only in ICEs, but also in BEV powertrains, which tend to generate a monotone, to convey information such as vehicle state or acceleration to the driver.

The second generation of FCVs has been drawing attention for its next-generation powertrain, which apply the experience and feedback acquired in the first generation to address the high-frequency noise differing from that of ICEs that is generated by the various auxiliary

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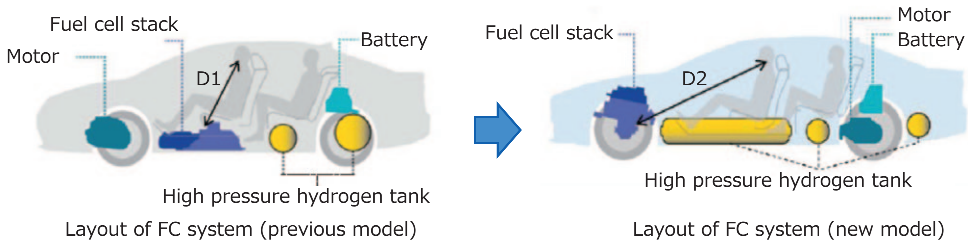

Fig. 3 Modified FC Component Layout

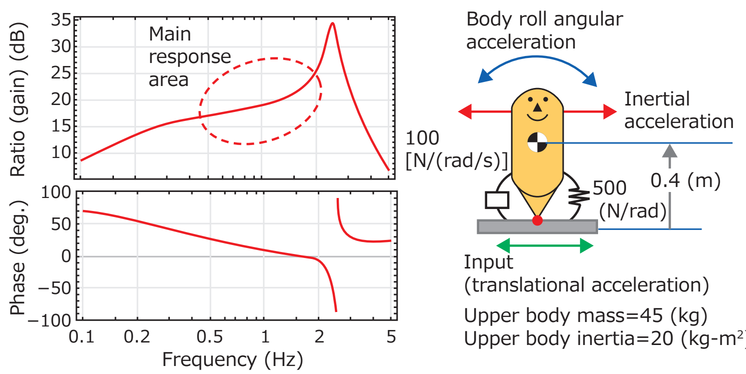

Fig. 4 Single Rigid Body Occupant Model

components. Reported initiatives to reduce various types of noise and vibration include the optimization of auxiliary drive conditions, the downsizing of auxiliary components, noise reduction through system integration, and an improved mounting layout obtained by downsizing the fuel cell stack. (Fig. 3).

All cases involve not only reducing noise and vibration, but also complex analyses of phenomena from other domains such as fuel economy and efficiency. As electrification continues to spread, the diversity of powertrain systems and their control is anticipated to require even more complex analyses using MBD or other techniques.

3. 2. Tires and Suspension Systems

The electrification of automobiles has reduced the noise and vibration caused by the powertrain, making it more important to decrease the noise produced by road surface inputs such as road noise. Consequently, many research reports on ride comfort are being released. One underlying reason is the ever growing need to build technology to create a comfortable interior space in preparation for the anticipated near-future realization of fully automated driving. In addition, the values of the R51-03 regulation vehicle exterior noise regulation will be tightened starting with Phase 3 in 2024, increasing the need to further reduce tire noise, which contributes significantly to exterior noise.

One study on improving ride comfort has reported the impact of tire structure on ride comfort performance in the time domain. The study illuminates the concept of reducing axial force by estimating vertical and longitudinal inputs from protrusions through a deconvolution of the tire alone driving over protrusions in bench tests, and by observing the impact of the structure of the tread and sidewall on the axial force of the tire alone. Ride comfort performance has conventionally been assessed by combining the tires and vehicle. However, focusing on the tires as a component and considering ride comfort performance in the time domain is expected to result in tire model advances that will lead to the further development of analysis technology.

The ideal vehicle behavior that improves comfort in the age of automated driving is being explored by performing optimization calculations using an evaluation function that is based on the quantity of state of the occupants relative the two combined inputs of steering and acceleration/deceleration and also factors the physical motion of the occupants (Fig. 4). Progress in such research is expected not only in the field of suspension control but also in various fields such as conventional suspension and seat characteristics.

A semi-active suspension system using a functional fluid whose viscosity can be reversed by a magnetic or

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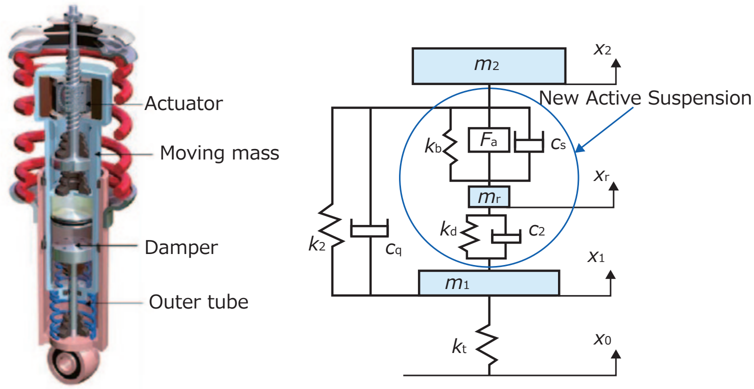

Fig. 5 Active Suspension Structure and Analysis Model

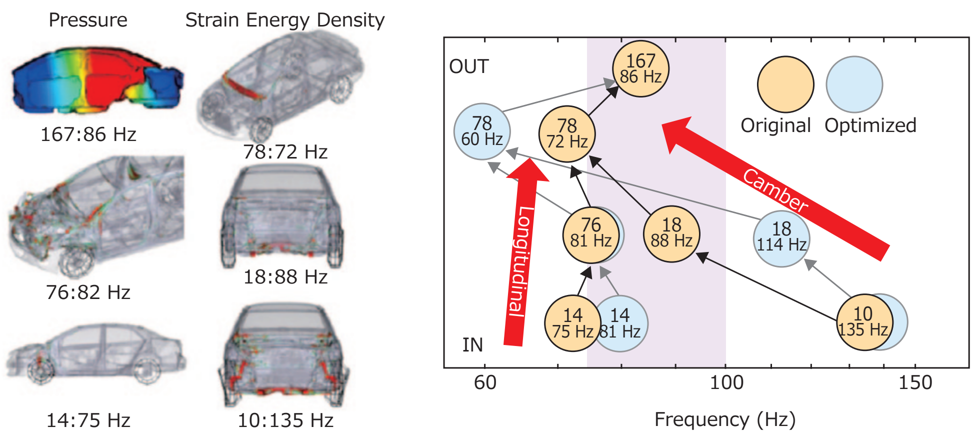

Fig. 6 Unit Mode and Transfer Path Diagram

electric field is being developed for the damping characteristics of the suspension, which affect ride comfort. The development of systems for electro-rheological fluids, which place fewer restrictions on shock absorber structure and have quicker response than the magneto-rheological fluids frequently used as functional fluids, and assessments of their performance, have demonstrated their effectiveness. Despite durability and cost issues, they promise higher performance in terms of improving ride comfort.

Technology that applies energy optimization control theory to an active suspension in which an actuator and a shock absorber are arranged in series to reduce sprung mass vibration in the frequency band of ride comfort performance, including the unsprung resonance frequency has also been reported (Fig. 5). Further advances in technological innovations that improve ride comfort are expected.

One study to reduce exterior noise investigated the effects of differences in tire tread patterns and road surface conditions on noise during acceleration, and compiled guidelines on reducing exterior tire noise classified by the mechanism that generates it. Innovations in material technology and other improvements are likely to be pursued to achieve both noise reduction and lower rolling resistance that decreases fuel and electricity consumption.

In the future, component performance design methods based on mechanical analysis of the road surface, tires, chassis, and vehicle body, and system design methods that take occupants into account are expected to evolve while coexisting with other functional performance.

3. 3. Vehicle Body and Trim

Reducing the weight of the vehicle body is essential to improving the fuel and electricity consumption efficiency of vehicles. At the same time, vehicle electrification and quietness requirements are intensifying year after year and balancing them with weight reduction is becoming increasingly difficult. Initiating assessments using CAE analysis in the early stages of development is essential to satisfying such conflicting requirements. However, the number of elements in vehicle models keeps growing to

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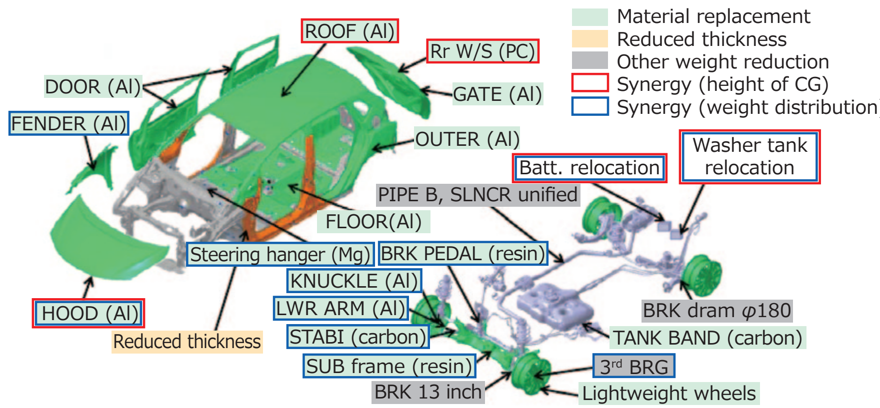

Fig. 7 Lightweight Portion of Vehicle

improve the accuracy of analyses, increasing the number of eigenmodes commensurately, which makes factor analysis difficult. Various solutions are being explored. One example is a technique proposed to extract the unit mode, which is mode of the component, and change the eigenvalue array of the unit mode by focusing on the vibration transfer between modes to reduce vibration noise (Fig. 6).

Moreover, performing CAE analysis in the initial design stage often means that there is no detailed design information. Attempts to address that issue through the use of statistical energy analysis (SEA) to examine the optimization of damping addition positions and verify their effectiveness in actual vehicle tests have been reported.

Furthermore, the electrification of vehicles is making CAE analysis technology for the medium frequency range, which includes motor and tire noise, necessary. An acoustic sensitivity prediction technique that accounts for the effects of both panel and soundproof material vibration modes using an index called equivalent radiated power with phase-cancelation (ERPWP) has been proposed, examples of verifying its accuracy through experimental result have been introduced.

Examples of replacing steel with aluminum or plastic, and optimizing the structure to achieve both weight reduction and noise and vibration performance have been reported (Fig. 7).

Electrification has made tire noise, aerodynamic noise, and inverter noise from electric components, which were previously masked by engine noise, more apparent, making it increasingly necessary to improve the sound insulation performance of glass. Assessments and experimental verification results have been presented for an

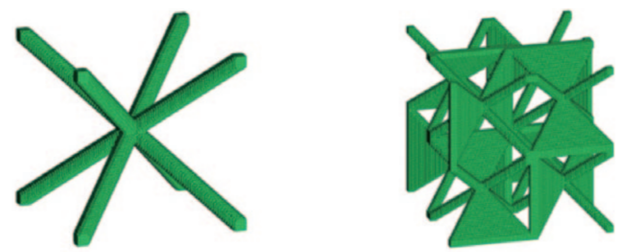

Fig. 8 Lattice Structure Unit Cell Model

example of creating a mathematical model and evaluating the optimization of the physical properties of the intermediate film, and for a technique that reduces sound transmitted from the door glass by matching the impedance of the glass run serving as sealing material between the glass and the frame, and dissipating vibration through the damping of the glass run without relying on sound insulating glass.

In sound absorbing material, a honeycomb structure made of polypropylene (PP) is bonded with a PP or polyester (PE) film to obtain both high sound absorption performance and weight reduction. One example involved assessing an acoustic metamaterial augmented with sound absorbing capability via Helmholtz resonance by controlling the out-of-plane vibration. Another introduced example used numerical analysis to study the lattice structure of porous material, as shown in Fig. 8, and measured the sound absorption coefficient of a test piece created with a metal 3D printer to verify the accuracy of the calculations.

4 Sound Quality

Electric-powered vehicles such as PHEVs and BEVs are becoming popular due to environmental considerations. Although these vehicles are quieter because noise

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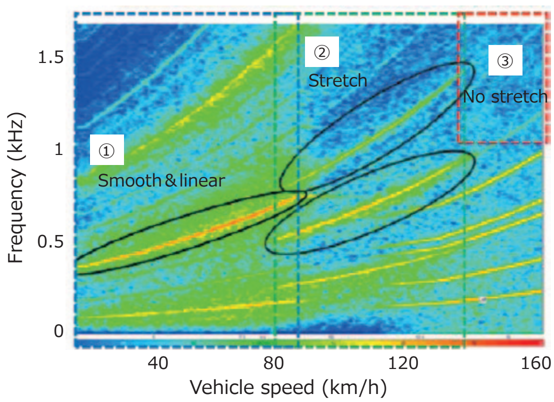

Fig. 9 Acceleration Sound during EV Driving

caused by the ICE is eliminated during EV driving, they also lose some of the auditory psychological acceleration feel when the vehicle accelerates, suggesting the need for some form of acceleration sound to replace that of the ICE sound. Also, as in ICE vehicles, designing the quality of the acceleration sound is expected to build automaker brand image and create an identity for the vehicle. Electro-acoustic devices are used as a means of producing the acceleration sound of EVs, and are being adopted and sold in some vehicles.

In ICE vehicles, the quality of the acceleration sound is controlled by the main order component of the engine revolution, enabling the vehicle to produce a natural acceleration sound. However, in EV driving, the main order component of the motor sound has a higher frequency range than the order of the engine revolution, leading to concerns that occupants may find the sound as unpleasant as gear noise. Creating acceleration sounds using electro-acoustic devices also offers a high degree of freedom, presenting the challenge of determining what frequency band and order component can be used to create an acceleration sound appropriate to EV driving.

One reported approach to this challenge involved a technique to convey a seamless acceleration feeling unique to EVs by creating acceleration sounds by applying an infinite scale using auditory illusions in a frequency band capable of expressing the vehicle's identity.

A different example involving an acceleration sound that makes it easy to grasp the vehicle speed during EV driving and reflects the brand image has been reported. This sound is achieved using a tone that makes perceiving frequency changes as easy as with the engine order component, a tone that evokes the power source of the EV, and a tone and pitch that is pleasant to listen to combined with the production of multiple types of sound sources for the various vehicle speed ranges (Fig. 9).

Beyond their application in producing acceleration sounds, electro-acoustic devices have also been considered for the localization of sound images in the vehicle cabin using 3D sound technology, and research such sound design is expected to gain even more momentum.

References

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