VIBRATION, NOISE AND RIDE QUALITY

1 Introduction

Addressing the demand for lower CO_2 emissions remains a top priority for automobile manufacturers. The introducti2on of fuel cell vehicles (FCVs) to the marketplace has also become a big story. In terms of vibration and noise, they are very similar to electric vehicles (EVs), but there are also some FCV-specific phenomena, such as the noise generated by the compressor and fluid system needed for the chemical reaction between oxygen and hydrogen, and the noise associated with the air flow from air intake and discharge. In Japan, the comparatively early market launch and growth in popularity of EVs and HEVs, means the electrification of automobiles has lost its freshness. In Europe, however, where efforts to reduce automobile CO_2 emissions have relied on diesel fuel, the field of vibration and noise appears to have provided the major turning point leading to more genuine efforts to promote the electrification of automobiles.

European automobiles have exhibited remarkable improvement in vibration and noise performance over the past 15 years or so. This stems partly from a greater awareness of vibration and noise issues in the European market than in Japan. Another major reason is that complying with the strict European emissions regulations significantly worsens the vibration and noise characteristics diesel engine vehicles, leading to widespread efforts not only by automobile manufacturers, but also by parts suppliers and research institutes to develop new technologies to address these vibration and noise issues. Therefore close attention is being paid to what this very wide base of experienced European researchers and engineers in the field of vibration and noise will aim to do next as they move on from diesel engine vehicles to the new age of electric vehicles.

The efforts of automobile manufacturers in the U.S. and China to comply with the new Corporate Average Fuel Efficiency (CAFE) standard is also expected to have considerable impact on vehicle vibration and noise. The downsizing of internal combustion engines and increasing use of electric-powered powertrains is being accompanied by dramatic reductions in vehicle weights. These lighter vehicle bodies and other components have a large influence on vibration and noise, creating a need for new technologies to address this issue.

At the same time, the strengthening of vehicle external noise regulations is another environmental issue that has reached a major turning point. Noise regulations based on UN R51-03 have already been issued in Europe and Japan, and Phase 3 will introduce new noise limits so strict that even current EVs cannot satisfy them. Continued discussions on the noise limits that will actually be legally applied are expected, but innovative technologies will nevertheless prove essential. Technologies that minimize the engine noise from internal combustion vehicles or prevent it from leaking outside the vehicle will become necessary, as will technologies to dramatically reduce tire noise, an issue common to all vehicles. Obviously, there are still a large number of issues that the researchers and engineers involved in vehicle vibration and noise need to address.

2 Road Traffic Noise

In Japan, vehicle noise regulations for cruising noise and stationary noise were implemented in 1951, and a new regulation covering full throttle acceleration noise followed in 1971. These regulations have been updated and strengthened numerous times up to the present day. According to a Ministry of the Environment (MOE) report on road traffic noise monitoring, Japan has made gradual progress in reducing road traffic noise level, but there are still some regions, such as in spaces adjacent to roads carring arterial traffic of national highways, where environmental quality standards for noise have not been met (Fig. 1).

EU countries have also strengthened regulations concerning the noise from vehicles, but these were criticized for not being sufficiently effective at reducing road traffic noise. Consequently, revisions to the acceleration noise testing method (Fig. 2) and introduction of the tire noise regulations were discussed within UN WP 29/GRB (Working Party on Noise), leading to the issuance of the acceleration noise regulation as UN R51-03 and of the tire noise regulation as R117-02. The UN R51-03 acceleration noise regulation began in 2016 and is scheduled to become stricter over time in three steps from Phase 1 to Phase 3. By Phase 3, a 4 dB reduction in noise (equivalent to 60% reduction in energy) will be required. The noise limits in Phase 3 are very severe and even current EVs are not in compliance with them, mainly due to tire noise, and further reductions that tire noise is likely to become essential.

In 2015, the third report on vehicle noise reduction issued by the Japanese Central Environment Council presented the following measures.

(1) Change the acceleration noise testing methods to base them on actual driving in urban areas, as well as determine the new noise limits and their application date .
(2) Abolish the cruising noise regulation.
(3) Review the stationary noise regulation.
(4) Determine the application date for the tire noise regulation.

Bringing the acceleration noise testing methods in alignment with actual driving conditions in urban areas made it possible to abolish the cruising noise and stationary noise regulations, which had only been enacted in Japan. Furthermore, to effectively detect any worsening in exhaust noise due to actions such as the illegally modified muffler in use vehicle, the regulation was amended to require stationary noise level equivalent to that when the vehicle was original condition (relative value regulation). These reductions in vehicle noise are expected to contribute to reducing road traffic noise as well.

The revisions to the noise regulations described above were officially announced as part of safety regulations for road vehicles on April 20, 2016. Not only was the scale of these revisions unprecedented in the history of Japanese noise regulations, they also harmonized the standards with UN regulations to adopt R51 and R117.

A new challenge involving hybrid electric vehicles (HEVs), EVs, and FCVs is their quietness at low speeds which, as these vehicles become more widespread, is raising the issue of the difficulty for pedestrians to notice the approach of such vehicles (Fig. 3). Japan was the first country in the world to issue official guidelines for vehicle approach alerting devices in January of 2010 and now all new HEVs, EVs, and FCVs from Japanese automobile manufacturers come equipped with devices based on those guidelines. The UN has also followed suit and discussions about these devices began within WP 29/GRB in 2010. By 2011 the same guidelines as those used in Japan had been added to Annex 2 of R.E.3 (Consolidated Resolution on the Construction of Vehicles). After that, debate and discussions about making these into an official legal regulation continued, and they entered into force as UN R138 in October of 2016.

The purpose of vehicle approach alerting devices is to alert pedestrians that the vehicle is approaching by emitting a sound from speakers installed on the vehicle. However the optimized sound must be determined in terms of characteristics that strike a balance between being recognizable to pedestrians, avoiding negative noise impacts on the surroundings, and being acceptable to the driver. In particular, a sound that changes frequency according to the vehicle speed was selected to associate with the movement of the vehicle for better

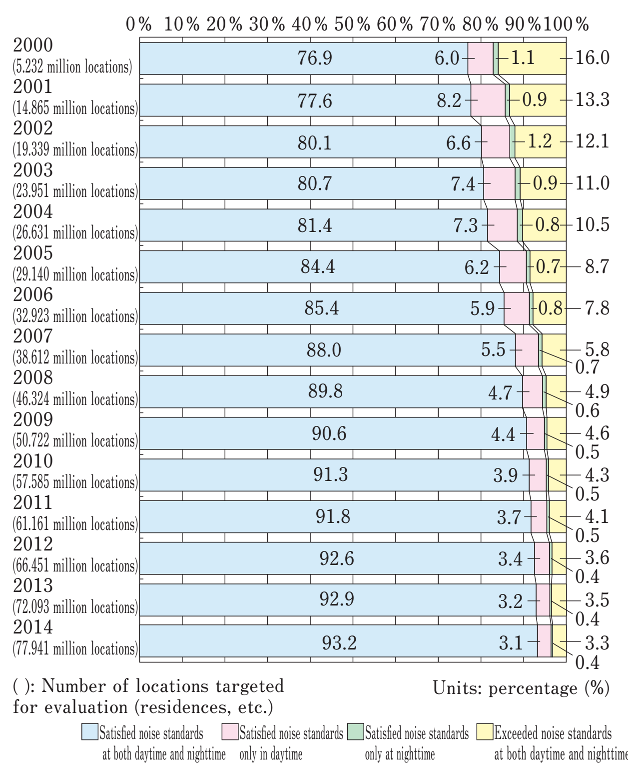

Fig. 1 Status of Compliance with Environmental Noise Standard in Japan (nationwide change over time)

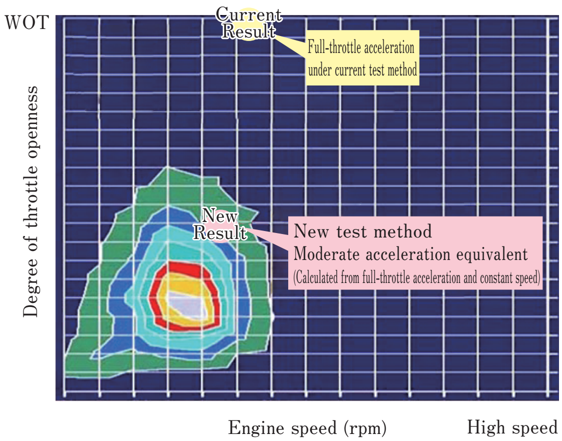

Fig. 2 Driving Conditions under both New and Old Test methods

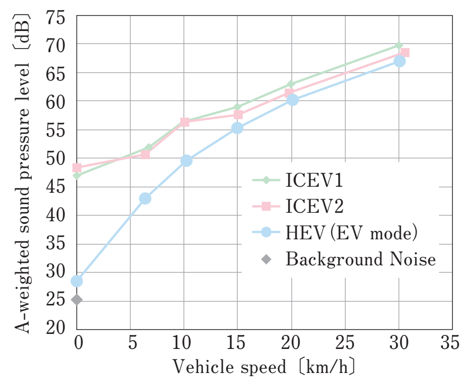

Fig. 3 Difference in Noise Levels between Gasoline-engine Vehicles and HEV Electric Running

recognition by pedestrians. When the R138 technical requirements were discussed, the Japanese automobile manufacturers who first commercialized vehicle approach alerting devices and the ministry that first established the guidelines collaborated in leading the UN rule-making process as well as the creation of the ISO standard for the testing method. In the U.S. as well, the Pedestrian Safety Enhancement Act of 2010 was passed by Congress and signed into law in January 2011.

Other future issues concerning vehicle noise regulations currently being discussed within the GRB include: improving the Additional Sound Emission Provisions (ASEP) testing methods added to R51-03, noise regulations for in use vehicles, and developing different road surface classifications to address the eventual widespread use of low-noise road surfaces. As a result, there are strong expectations for even further reductions in road traffic noise.

3 Noise and Vibration of Vehicle Components

3. 1. Powertrains

New vehicle vibration and noise technologies to address fuel efficiency and environmental friendliness remain essential. At the same time, the search for new possibilities in automobiles is driving the examination of new ideas for powertrains.

As HEVs and EVs grow in popularity, automobile manufacturers have launched FCVs, which use fuel cells as their source of energy. FCVs share many vibration and noise issues with HEVs and EVs, but there are also FCV- specific vibration and noise phenomena. Generating electricity requires drawing air into the fuel cell stack, and possible countermeasures to the unique noise issue associated with this intake and discharge of air have been published (Fig. 4)[1]. In HEVs, the unpleasant vibrations when the engine was started have already been improved to the point of going unnoticed, and efforts have moved on to examining whether the number of cylinders in the engine can be reduced to achieve even greater fuel efficiency. In older HEVs the combustion force of the engine generates vibrations when it was started. However, in newer engines with a smaller number of cylinders, it is the vibration prior to combustion that has become a problem, and reports on the mechanism causing these vibrations and possible countermeasures have been published (Fig. 5)[2]. The demand for further improved fuel efficiency also remains strong for internal combustion engine (ICE) vehicles, and progress on measures such as further lowering the lock-up speed of the CVT and reducing friction continues to be made. However, such measures have resulted in other unpleasant phenomena, including a worsening of booming noise and self-excited vibrations from the clutch, and factor analysis and simulation technologies to find countermeasures are being developed[3][4]. Since the technologies that improve the fuel efficiency of ICE vehicles and HEVs also strongly affect vibration and noise characteristics, the development of new vibration and noise technologies that address fuel efficiency is expected to continue in the future.

Reports on vehicles equipped with in-wheel motors (IWM) as the possible new form of next-generation powertrain packaging have also been issued. IWM systems place an electric motor within the wheel itself, resulting in constraints on design and vehicle packaging that differ

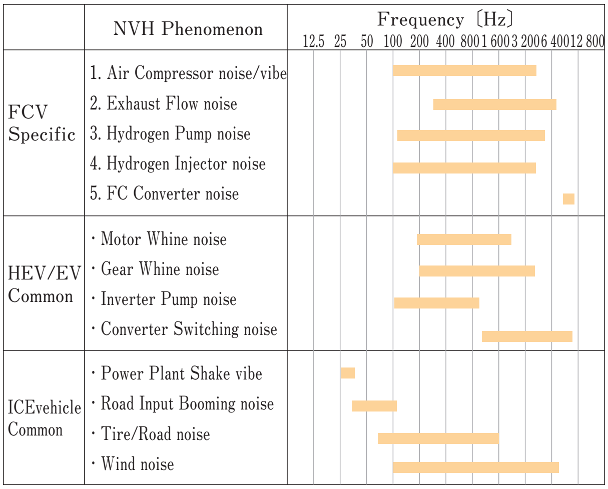

Fig. 4 Noise and Vibration Phenomena of FCVs(1)

considerably from those of current powertrain system. This has the potential to produce completely new and unprecedented forms of vehicles. Since they can leave out the driveshaft, these systems also have the advantage of dramatically improving vehicle responsiveness. This not only means that acceleration and deceleration responsiveness can be raised dramatically higher than in conventional vehicles, but also that it is possible to increase driving stability through independent driving control of the left- and right-side wheels. The absence of a driveshaft also means that the resonance frequency of the torsional system has become significantly higher, and new technology using driving force controls has been reported to improve vibration in the ride comfort zone, a heretofore impossible feat(5).

At the same time, the lack of a driveshaft results in characteristics that are more sensitive to torque fluctuations. Attempting to place components such as the motor, gears, and brakes within the limited space of the wheel creates unprecedented constraint conditions, and in some motor specifications, torque fluctuations resulted in the generation of vibrations at low speeds, a problem specific to IWM systems. However, examples of countermeasures using controls and the suspension system have been reported as possible solutions to this vibration problem(6).

3. 2. Tires and the Suspension System

Reducing tire noise has become crucial as the previously mentioned vehicle external noise regulations have become stricter over time. In electrically-powered vehicles such as HEVs, EVs, and FCVs, the main source of vehicle noise is often the inputs from the road surface

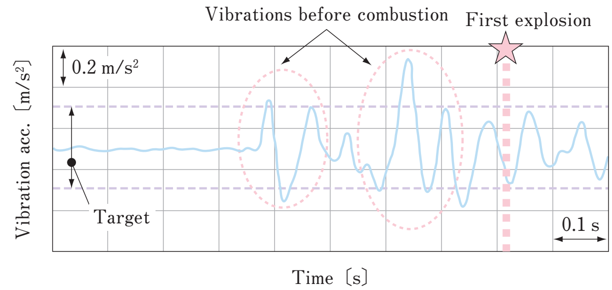

Fig. 5 Floor Vibrations at Time of Engine Start(2)

rather than the powertrain. This has led to more active reporting on the research conducted on the topics of tire and road noise(7)-(13). It is critically important to accurately grasp tire characteristics to improve road noise performance. A simple linear model is absolutely unable to reproduce the actual phenomena, and a variety of different efforts to overcome this issue have been reported so far.

The latest tire model for road noise evaluations performs a non-linear analysis of the shape of the tire when it is in contact with the ground and incorporates the decrease in rigidity, the gyroscopic effect, and the Doppler Effect as changes in the dynamic characteristics of the tire when it is rolling (Fig. 6). Road noise can be reproduced satisfactorily by entering the unevenness of the road surface into this model. This method was effective in improving the road noise performance of the tires and suspension up to about 250 Hz and advances such as enhanced accuracy are expected to follow. In addition, research into increasing the damping of the tire tread portion to reduce vibration transmission as a potential technique for improving the road noise performance of the tire itself has been reported. It is hoped that this will eventually be applied to actual tire products.

Tire treads have also been designed to form a resonator in an attempt to reduce the sound radiated from the tire, and this silencing technology has already been commercialized. At the same time, research into the analyses of the tire tread vibration behavior is also continuing since this is the main portion of the tire responsible for radiated noise. The tire tread is a complex construction of multiple materials and represented by a multi-layered FEM model with anisotropic properties. The uneven displacement inputs of the road surface were converted to a pressure distribution from the rubber to the steel belts, which were then applied to the model to clarify how the vibrations are transmitted from the road surface inputs to each tread surface, which is where the noise is gener-

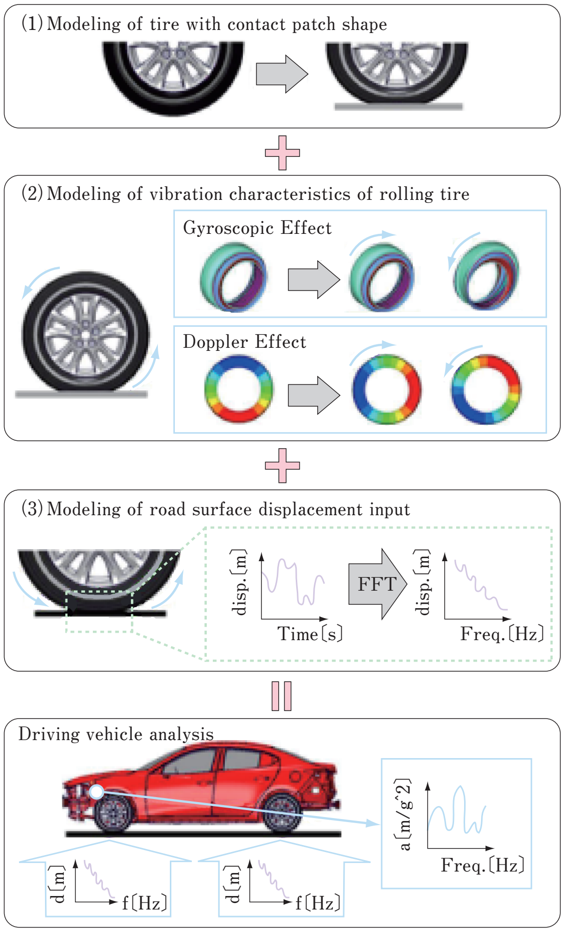

Fig. 6 Model that Considers Tire Characteristics during Driving[7]

ated. A deeper understanding of this type of phenomenon is expected to advance the development of low noise tires.

3. 3. Vehicle Body and Outfitting

Reducing the weight of the vehicle body has been widely promoted for several years as a means of improving the vehicle's fuel efficiency. In addition, the need to reduce the vehicle weight has only become more and more important as the manufacturers attempt to keep their vehicles compliant with regulations such as CAFE. However, simply reducing the weight of the vehicle body aggravates various vibration and noise issues, making it necessary to build a vehicle body structural framework that is both lightweight and has low sensitivity from the initial stages of development. Consequently, the use of CAE technologies for efficient optimization of the vehicle body during development is also becoming more and more important.

In the past, adjunct items were represented in a model using simple mass and rigid elements as substitutes, but

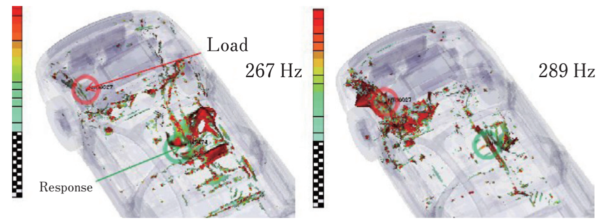

Fig. 7 Extracted Principal Component Mode[14]

now, thanks to improvements in computer capabilities, it has become easier to reproduce and model these items in more detail. This has contributed to improvements in the precision of analyses. In contrast, the degrees of freedom in these analysis models keep increasing, leading to an enormous number of eigenvalues. The true essence of the phenomenon can no longer be found by simply observing the strain energy and kinetic energy of the natural modes, preventing efficient problem solving in many cases. Up until now, automobile manufacturers have each employed their own unique schemes and proposals to address this issue. However, a new method that uses principal component mode analysis to reduce the degrees of freedom, eliminate those modes that have only a small influence on the phenomenon, and extract the modes that have a large influence has been proposed (Fig. 7)[14].

Furthermore, another proposal considers the vehicle body sensitivity by first dividing it up into the framework (structural) system and the acoustic system. In this case the framework system is one that still allows design and engineering changes. In this proposal, a new attempt is made to interpret the vehicle body sensitivity by breaking it up into indicators of the ease of excitation of both structural-specific modes and acoustic-specific modes[15]. Efforts such as these are expected to lead to new technologies that will allow regular engineers to carry out efficient factor analyses and examinations of potential countermeasures that only highly-skilled engineers could perform in the past. In addition, the research into noise problems being cause by air flow is also being pursued more actively[16-20]. As more automobiles rely on electric power, the noise generated by the air flow in and around the vehicle is also becoming relatively more noticeable. Furthermore, recent improvements in the computational capabilities of computers have made it more practical to apply computational fluid dynamics (CFD) in analyses of vehicle wind noise and air conditioning noise. In particular, CFD is starting to be used to examine the

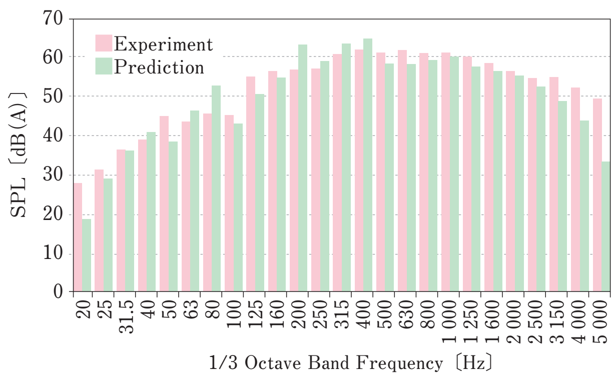

Fig. 8 Comparison of Wind Noise Prediction Analysis Results with Experimental Results[21]

optimal structure of air conditioning devices since they generate noise in the vehicle interior.

Nevertheless, it is still not easy to accurately calculate the wind noise for the entire vehicle system over the entire frequency range from low to high when the vehicle is traveling at high speed. At the research level, projects such as this using the K supercomputer have been making progress and it was reported that good accuracy has been obtained (Fig. 8) (Fig. 9)[21][22]. At the locations where actual wind noise research is being carried out, the reality is that a variety of different techniques are being deployed depending on the different standpoints and purposes of the research.

Another issue confronting researchers as they pursue a better understanding and more precise analysis of the mechanism of wind noise is the fact that the technologies in this field straddle the line between fluid dynamics and vibration noise. At the current time, the theoretical system attempting to integrate these two areas is insufficient and very few researchers and engineers are equally well-versed in both of these fields. From the standpoint of vibration noise engineers, the size and distribution of vibration sources caused by air flow are important, but in the world of fluid dynamics the vibration sources are often separated into sound and sound-like effects (pressure fluctuations that do not become sound) for reasons of computational efficiency and the analysis techniques being used. This poses no problem when all vibration sources and the whole transmission response system are in a uniform piece of air. However, in the case of vehicle wind noise, the transmission system includes vibrations passing through the glass and steel sheet of the vehicle body, so identifying the proper theory and methods needed to separate the vibration sources has become an

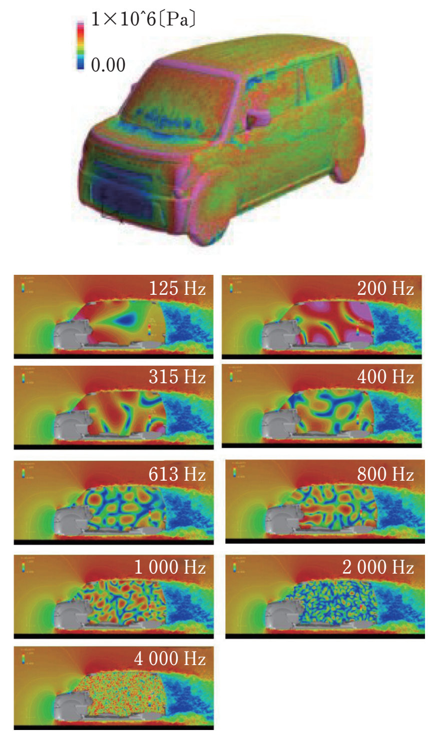

Fig. 9 Wind Noise Prediction Model[22]

issue. The use of a wave-number filter and of methods that do not separate the sound and sound-like effects have both been reported, but it is expected that some new theoretical basis will have to be established in the future.

Obviously, this field of vehicle wind noise requires expertise in both fluid dynamics and vibration noise, but as mentioned previously, there are almost no engineers who currently possess the necessary expertise in both these areas. Consequently, it is thought that another challenge to solving this issue in the future will be the need to reform the educational system at universities and the training methods for engineers at companies.

In recent years, there have also been reports on research into the unconventional characteristics of new materials used in automobiles. These include the move away from the conventional sound insulation materials made from fibers and urethane to the construction of acoustic circuits composed of a large number of fine structures, or even the periodic placement of materials with different acoustic impedances[23][24]. It is expected that in the near future materials such as these will be applied to actual products thanks to innovations in manufacturing technologies such as 3D printing.

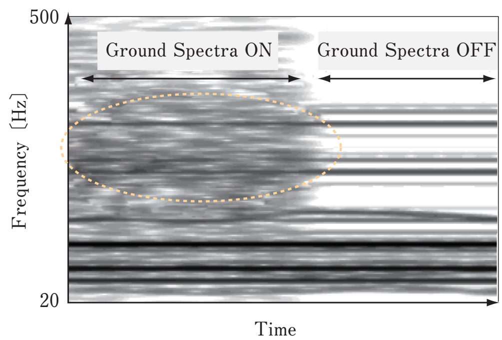

Fig. 10 Example of Sound Design with Added Broadband Sound[25]

4 Sound Quality

Products that add sound through electric means in an effort to improve the sound quality during driving have been increasing in number. The exhaust emissions control devices such as the diesel particulate filters installed on diesel engine vehicles suppress low-frequency noise, which tends to make it difficult to obtain the powerful exhaust sound expected of sportier vehicles. To compensate for this problem, various technologies that add the low-order sound of the engine via speakers placed within the vehicle interior or near the exhaust port have been commercialized in Europe for the last several years. Other products that electrically add sound to substitute for the internal combustion engine sound that is absent when a plug-in hybrid vehicle is running in EV mode have also appeared.

Products such as these add sound electrically to compensate for all the sound of an internal combustion engine lost for some reason, or to partially enhance it. However, there are also products that exist to improve the sound of a typical internal combustion engine. In the past, these sound enhancements had a simple low-order harmonic structure. However, in recent years there have been reports about other examples of sound design that not only take into consideration the auditory information, but also the relationship of the sound to driving operations and senses other than hearing by adding a broadband sound with a more complex order composition (Fig. 10)[25]. One such report stated designing the sound so it matched the accelerator and gear shifting operations required taking “the relationship between people and things” into consideration. In other words, what hardware is present and what role does it play? It is important to consider the overall relationship between the environment around drivers, their intentions, and their perceptions, including senses other than just hearing.

However, there are still many who misunderstand this and believe that “sound only equals auditory information”, and therefore mistakenly believe that a good sound and a good vehicle can be achieved by treating this issue completely independently of all others and pursuing an ideal sound design. It is now quite common to design the sound of a vehicle, and electrical means of generating sound have improved the freedom with which this sound design can be pursued. Therefore, it is hoped that as research into the field of perceptual psychology continues to advance, the results of this research will become more widely known and accepted.

In addition, research into adding sound in the vehicle for a completely different purpose, that of helping keep drivers awake and alert during long-distance drives, is also beginning to be carried out[26]. In comparison to the technologies available to reduce noise, the theories about creating sound for a specific purpose are still very immature, and there are strong expectations for this kind of research in the future.

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