VIBRATION, NOISE AND RIDE QUALITY

1 Introduction

Against the backdrop of the international sense of crisis concerning climate change, countries have been setting target years for achieving net zero greenhouse gas (GHG) emissions. All nations in the EU zone have agreed to set 2050 as the target for net zero GHG emissions, and the Japanese government also set a policy of achieving net zero in that year.

The rapid spread of battery EVs, as well as fuel cell and other vehicles running on fuels with no carbon content, such has hydrogen or ammonia will be critical to eliminating carbon dioxide emitted by standalone vehicles during driving. During the transition period, it will be necessary to minimize fuel consumption through approaches that include mounting the highly efficient powertrain of hybrid and other vehicles that combine a motor with a high energy conversion efficiency engine, further reducing vehicle weight, decreasing drag, and using tires with lower rolling resistance.

Vehicle development policies under these circumstances consist of expanding the use of electrified powertrains, reducing the weight of the overall vehicle, and reducing the running resistance cause by tire rolling resistance and aerodynamic drag. Consequently, the technical field of noise and vibration is shifting away from its original approach of reducing the noise of the internal combustion engine toward a focus on CAE technology aimed at balancing the wind and road noises made more prominent by electrification with vehicle body weight reduction and low-rolling resistance tires and optimal design that includes other areas of performance. Similarly, powertrains now have a greater degree of operating state flexibility than in the past, and there are more and more reports concerning model-based development (MBD) that uses 1D CAE to balance multifunctionality and noise in the more complex hybrid vehicles. However, these trends are limited to activities by individual corporations or organizations, and there are calls for a framework enabling cooperation on CAE and MBD technologies in non-competitive areas.

2 Road Traffic Noise

Rules on standalone vehicle noise were first introduced in Japan in 1952, and they have been gradually strengthened since then. 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.

The vehicle standalone noise regulations currently in effect in Japan follow the trend of harmonization with international standards and are based on the UN R51.03 regulation. For light-duty four-wheeled vehicles, the test method is based on simulating driving at moderate speed in an urban environment. Under those test conditions, the contribution of tire and road surface noise is relatively high compared to past test methods based on wide open throttle acceleration, frequently accounting for half or more of the contribution to the overall noise level. At the same time, the Phase 3 regulations currently under discussion will tighten the regulatory values by 4 dB (A) compared to Phase 1. This represents a 60% reduction in terms of energy conversion, and will require a significant decrease in tire and road surface noise. However, the majority of tire and road surface noise is emitted in the vicinity of the contact patch, making it difficult for vehicles to reduce that noise through sound insulation or absorption. In addition, reducing noise is further complicated by the frequent need for tradeoffs with other concurrent tire requirements such as low rolling resistance, handling on wet surfaces, or braking performance.

While the regulations described above apply to new vehicles, actual road traffic noise considerations also in-

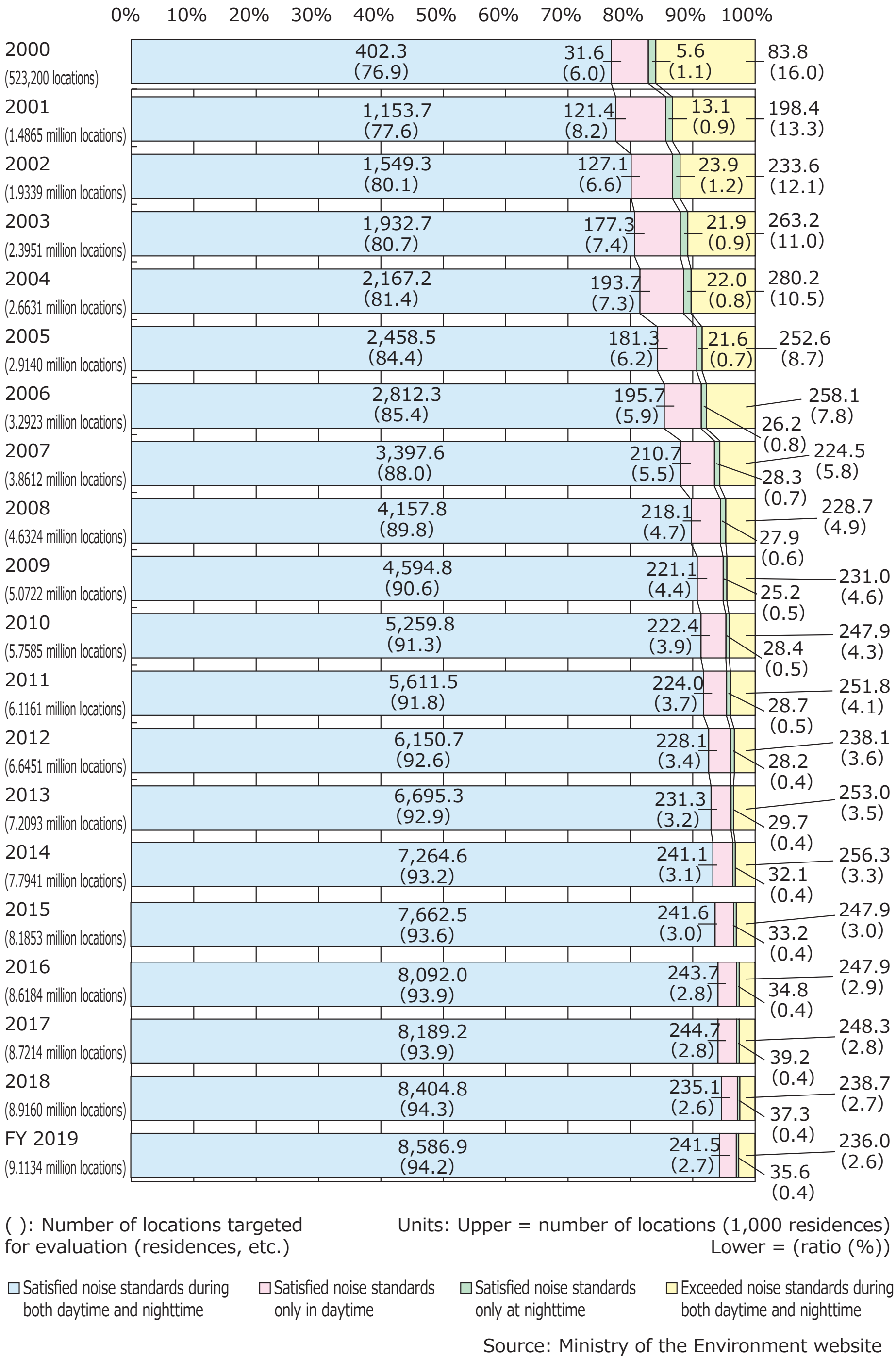

Fig. 1 Status of Compliance with Environmental Noise Standard in Japan (nationwide change over time)

volve complaints about the noise from older vehicles or customized vehicles, and that issue must also be addressed. At the United Nations, a proposal for updating the Additional Sound Emissions Provisions (ASEP) to expand evaluation conditions (vehicle speed, engine speed, engine load) and tighten regulations on replacement mufflers and other aspects of customized vehicles, will be submitted the Working Party on Noise and Tyres (GRBP) in 2022. In addition, the need for comprehensive efforts to reduce road traffic noise that go beyond standalone vehicle regulations, has led to forming a task force under the GRBP to discuss future noise regulations.

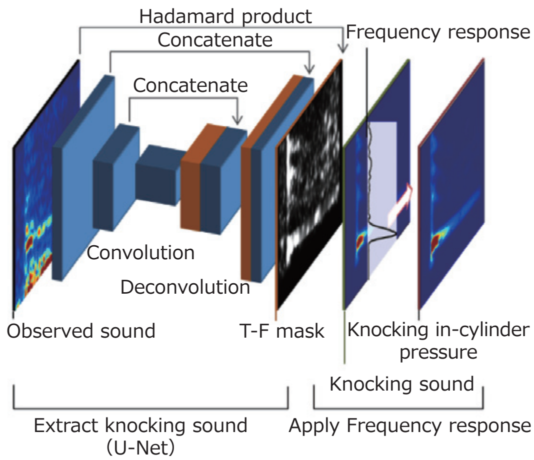

Fig. 2 Conceptual Diagram of Deep Learning-Based Knock Detection Technique

3 Noise and Vibration of Vehicle Components

3. 1. Powertrains

Various research projects on technologies to reduce noise and vibration from the powertrain are being carried out to address the ever more stringent requirements on fuel economy performance, environmental measures, and greater interior comfort. In particular, the perceived quietness of electric vehicles compared to ICE vehicles is creating high expectations concerning NV performance, and many technologies that enhance the quietness of hybrid and electric vehicles have been presented. There have also been many reports on increasing prediction accuracy and reducing calculation time in the initial stages through 1D and 3D CAE to make development more efficient.

Many analysis methods aimed at reducing the pressure and raising the quality of sound originating from solid-borne noise have been proposed. One example demonstrates vehicle noise reduction design guidelines based on a characteristic optimization analysis method that combines a transfer path analysis (TPA) of all vehicle systems with an exhaust pipe model of the main path with the power plant (FEM) and consists of a modal differential structure for each part. A technique to calculate the optimal mass and rigidity of each portion in a short time by expanding the above characteristics optimization analysis method and combining it with several model differential structure and acoustic transmission functions to quickly predict sound radiation from the engine in the early stages of design was introduced. One example application of the technique was reported to be effective at reducing the excitation force on the crankshaft main journal and decreasing sound radiation from the rigidity balance of the crankshaft based on the relationship between the excitation force caused by combustion and the equivalent rated power of the powertrain structure surface.

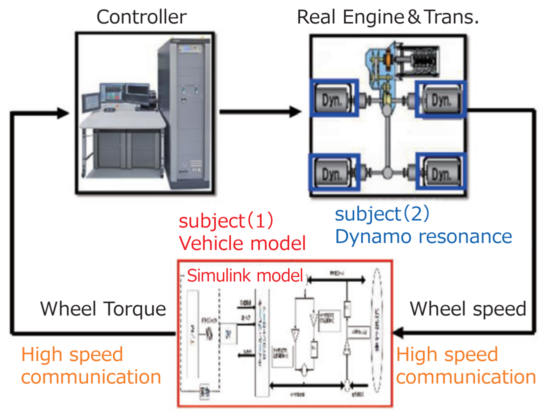

Fig. 3 Simulator Combining a Vehicle Model and Actual Powertrain Test Bench

One technique proposed for reducing knocking noise in gasoline engines draws on the recent rapid advances in deep learning to estimate knocking in the cylinders from the noise radiated by the engine and determine the knocking strength (Fig. 2) to achieve automatic determination based on quantitative values during engine calibration.

Homogeneous charge compression ignition, which is drawing attention as a means of reducing exhaust emissions from diesel engines, presents the issue of louder combustion noise than in conventional engines. Relying on understanding of the combustion noise mechanism to elucidate the damping characteristics that accompany the propagation of combustion power in the structure is important, and a method that calculates the damping factor from the vibration speed at the source of the noise with a smaller margin of error than in the traditional noise-based approach.

A technique that combines electromagnetic and structural analyses is being applied to the high frequency noise produced by hybrid and electric vehicle motors. Examples that reproduce the motor noise in high-speed, high-load conditions and optimizes the shape of the air gap by modifying the slot opening and rotor notch to decrease noise significantly have been introduced.

With respect to decreasing transmission gear noise in

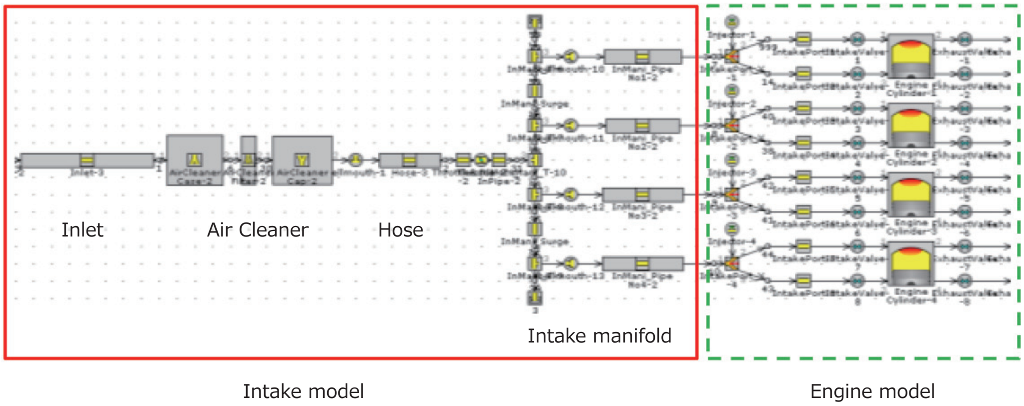

Fig. 4 1D CAE Model of Intake Noise Analysis

plug-in hybrid drivetrains, one study carried out a vibration analysis of a new gear train model that accounts for peripheral structures in addition to the planetary gears to propose improved optimizations for elements such as gear specifications, tooth shape, and manufacturing methods.

Similarly, a method (Fig. 3) that uses a model base system engineering (MBSE) approach to assemble a vibration model consisting an actual powertrain test bench while applying a technique that mathematically removes the effect of dynamo inertia on the vibration system in a highly accurate real time vehicle calculation model has been proposed to achieve efficient development in the early stages of design and find an early resolution to the tradeoff between transient low-frequency phenomena and other areas of performance in the design of AT and CVT transmissions.

The need for enhanced precision in the initial stages of design, and for means of elucidating factors that combine model-based development using 1D CAE with machine learning, continues to grow in conjunction with further efforts to simultaneously improve both fuel efficiency and quietness in internal combustion engines, as well as the introduction of more complex control and systems that incorporate electrification.

3. 2. Engine Mounts, Intake and Exhaust Systems

The engine mounts, as well as the intake and exhaust systems, are also the subject of numerous studies that incorporate 1D CAE/MBD and other techniques aimed at increasing early stage precision with respect to reducing noise and vibration from the powertrain. For engine mounts, a study of an AI model capable of predicting the nonlinear load on mount displacement and speed inputs via machine learning to balance the conflicting requirements of NVH and steering performance has been incorporated and applied to performance prediction in vehicle 1D CAE as a model-based development (MBD) initiative for the study of self-switching liquid-sealed mount requirement characteristics.

In the prediction of engine intake noise, a report on the use 1D CAE to estimate the performance of the non-reflective ducts that reduce the pressure variation in the intake pipes (Fig. 4), predicts intake inlet noise, transmitted sound, and flow variations and coordinate it with response surface methodology-based optimization to study the performance feasibility of specifications at the planning stage was presented.

Conversely, exhaust noise prediction has conventionally relied on solutions such as the transfer-matrix method. However, a study demonstrated the usefulness in initial design of using statistical energy analysis (SEA), which is effective at analyzing noise and vibration in the high mode density high frequency range, to set the pipe diameter as a design variable and minimized the discharge pressure as a way of reducing pressure pulsation in the exhaust pipe system. Proposals for solutions that combine even more advanced CAE technologies will be sought.

3. 3. Tires and the Suspension System

The recent electrification of vehicles has been decreasing the ratio of noise coming from the powertrain. However, this is making it more important to reduce the now relatively larger proportion of noise generated by road surface inputs or abnormal noise from the chassis system. Electrification is also prompting studies on improv-

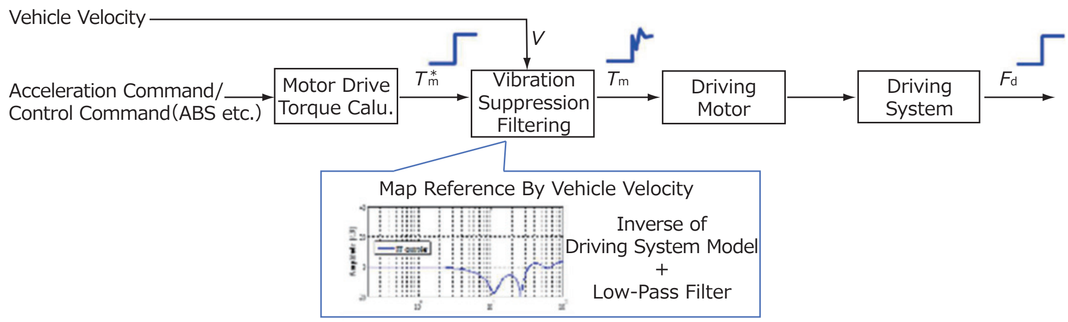

Fig. 5 Block Diagram of Vibration-Reduction Control Accounting for Tire Forces

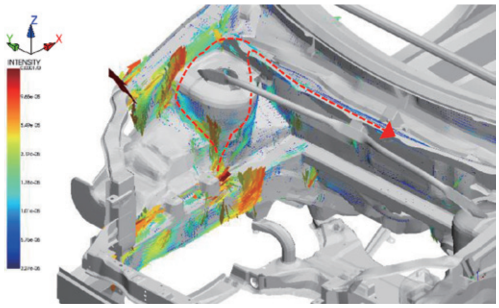

Fig. 6 Analysis of Vibration Energy Propagation in a Vehicle Body Model

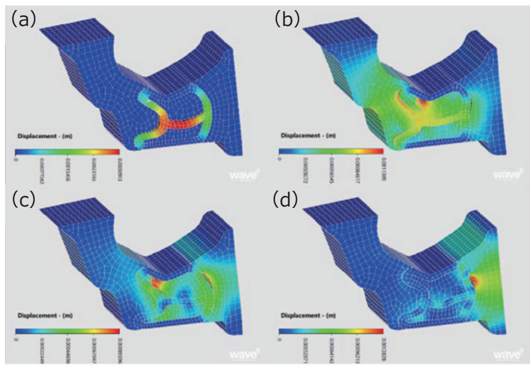

Fig. 7 Example of Weatherstrip Transmitted Sound Analysis

ing ride comfort using vibration-reduction control based on the highly responsive motor drive power.

Various techniques are being studied in research on road noise. A component TPA technique that calculates the translation and rotation direction force components on the vehicle axles from the localized rigidity and vibration data measured at several locations at the joint between the axle and the wheel, without disassembling, has been proposed to shorten the development time and reduce cost.

Examples of research aimed at creating the conceptual and functional designs in the early stages of the design process include applying the SEA traditionally used primarily to analyze high frequencies to wide band noise and vibration such as road noise and observing the relationship between the overall system (vehicle body) and subsystem (suspension) of a model defined in terms of energy propagation. Another SEA-based technique that estimates radiated tire noise in terms of the vibration emitted noise produced by the tires while driving (noise radiated due to tire vibration) and the direct noise produced by the contact between the tire and the road surface (noises other than those emitted by vibration) has been studied, and cases that examine the extent of the contribution of each type of noise have been presented.

With the reduction of road noise and other background noises resulting from greater quietness inside the vehicle cabin, several studies seek to quantify abnormal noises from the shock absorbers. One proposal using indicators with a strong correlation to subjective evaluations focuses on the fact that rattling consists of a noise variation caused by the expansion and contraction of the shock absorbers has demonstrated the possibility of identifying the causal frequency using fluctuation noise analysis.

Studies on ride comfort that use vibration-reduction control of the motor drive power are also being conducted. One technique for vehicles with in-wheel motors that uses a drivetrain system model (Fig. 5) accounting for the dependency of tire forces on vehicle speed to achieve vibration-reduction control at the front and rear of the vehicle springs, even when high-frequency torque commands are entered, has been proposed.

High expectations are placed on proposals that will introduce efficient development methods built on mechanisms that strongly take the relationship between the road surface, chassis, and vehicle body into account in the initial stages of tire and suspension design.

3.4. Body and Interior Materials

In conjunction with a growing need for quietness as electrification becomes more widespread, a significant

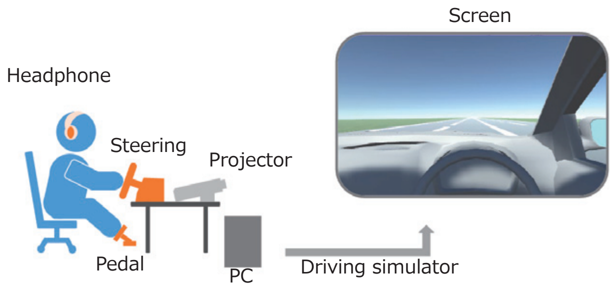

Fig. 8 Sound & Driving Simulator

amount of research is directed at efficiently achieving low sensitivity body structures in the initial stages of development since just reducing the weight of the vehicle body and interior materials leads to worsening noise and vibration.

The number of Eigenmodes keeps rising due to the tendency to make more detailed finite element method models to increase the precision of body frame models. One example of research to analyze them efficiently showed that static reduction can be used to separate the vibration and interior noise in a small number of modes into high-contribution frame vibration modes and other factors caused by local deformation in other panels, as well as to calculate their ratio. In another report the propagation of vibration energy visualized from vibration intensity (Fig. 6) and an understanding the propagation path were used to evaluate vibration transmission without relying on measures targeting input point structures or panels where mass tends to concentrate.

There have been many reports of efforts to elucidate the mechanism underlying performance against wind noise at high speeds by focusing on the resonance and permeability of sealing components around the doors, which form a path of entry into the cabin. Notable reports include a study that identified the major impact of upstream pressure fluctuations on the increase in sound pressure as part of the mechanism of resonance sound in the door parting cavity of the B pillar where airflow turbulence is strong. In another study, incorporating SEA and modeling based on periodic structure theory into the transmitted sound analysis of the weatherstrip (Fig. 7) made it clear that the impedance matching of the sound source or transmission acts to raise the excitation efficiency and radiation efficiency of the weatherstrip.

The using of a homogenization method to design microstructural material through a laminated structure consisting of porous sound absorbing material and perforated plates has been proposed as part of initiatives to reduce weight and improve performance in the context of the interior material sound insulation performance for the purpose of improving the sound absorption ratio in the low- to mid-frequency range.

Elsewhere, one project integrated felt containing ultrafine fibers in the dash insulator. Other research focused on the treatment of the end of the sound insulating material openings and used the finite element method to study how the number of openings at a fixed surface area ratio, as well as the treatment processes applied to the ends of those openings, affected sound insulation performance (acoustic transmission loss).

Efforts to improving quietness in the upcoming age of electrification hold the promise of further elucidating the mechanisms involved in the sound insulation performance of weatherstrips or interior materials in the vicinity of doors and pillar with respect to road and aerodynamic noise.

4 Sound Quality Evaluation

As usage, functionality, and expectations for both vehicle providers and users undergo the changes typified by the connected, autonomous, shared, and electric (CASE) concepts, there is concern that the current sound evaluation approaches of quantification by professionals and heuristics-based evaluation patterns will no longer be able to bring out new value or evaluation axes. It is also difficult to define and carry out tests every time various conditions changes. Consequently, the production of more natural wind noise and road noise is being studied in addition to the engine sound that has been the core of simulations until now. In an effort to assess situations with multiple stimuli, one initiative on evaluation methods linked a driving simulator to a sound simulator to assess how auditory and visual information relates to operational tasks (Fig. 8), and quantitatively evaluated whether sound acted as functional information.

Various major vendors have proposed system concepts that would enable direct sound evaluations of the powertrain system by combining a simulator reproduction that relies on powertrain calculation results modeled with 1D CAE with factors such as sound quality and acceleration or deceleration. If such systems are realized, it will become possible to conduct a range of assessments including subjective evaluations digitally, without having to build the vehicle. However, that will requires the designers of each individual component part to use model-based development to design their models.

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