VIBRATION, NOISE AND RIDE QUALITY

1 Introduction

In the wake of recent growing concerns over environmental issues, COP25 featured discussions on the possibility of raising the greenhouse gas emission reduction targets for various countries. Reducing CO_2 emissions is an important issue for the automotive industry. Accordingly, the industry is rapidly expanding electrification to reduce he environmental burden. Autonomous driving and new cross-industrial efforts represented by MaaS have come to the fore, and the entire automotive industry is on the cusp of a dramatic transformation.

The field of vibration, noise and ride quality often requires making a tradeoff between improving performance and increasing fuel efficiency. This has led to continuous research on methods to efficiently raise performance using less mass. As electrification expands, model-based development (MBD) is being applied to effectively develop complex systems. In addition, with advanced vehicle technologies such as electrification and autonomous driving raising expectations for comfortable vehicle interiors, studies on changes in customer demands concerning sound and its quality, as well as research on ride comfort to reduce occupant fatigue, are being conducted.

There are also calls to reduce environmental noise. In the area of road traffic noise, technologies that predict and reduce the radiated sound of tires and other vehicle exterior noise are studied to comply with stricter noise regulations. In response to the expansion of electrification, studies on the design of noise that alerts pedestrians to an approaching vehicle are underway.

Moreover, as exemplified by reports of technology that uses deep learning to estimate the noise caused by inputs from the road surface using road images from a camera for autonomous driving, technologies to analyze vibration, noise and ride quality are being developed, and further advances are expected.

2 Road Traffic Noise

Since their introduction in 1951 vehicle noise regulations in Japan have been gradually strengthened, and environmental noise has steadily improved. New international noise standards (UN R51-03) were introduced in 2016 and test methods were partially revised in 2019, resulting in regulatory noise reduction requirements adapted to actual urban driving. 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[(1)]. However, there are still regions where the standards are not met, and continuous improvement in environmental noise remains necessary.

With stricter automobile noise regulations resulting in decreased noise from the major contributor that is the powertrain and test methods have been, tire road surface noise now makes a higher relative contribution to overall traffic noise. Work on noise reduction involving tires and paved road surfaces will be critical to further improvement in road traffic noise. To that end, analysis technologies leading to the efficient reduction of various noises, and technologies providing highly accurate predictions of the effectiveness of road traffic noise reduction, are necessary. Initiatives undertaken include research relying on FEM to predict airborne noise, such as noise from powertrain and noise radiated from the tire[(2)], the announcement of a new model (ASJ RTN-Model 2018) to predict road traffic noise[(3)], and an investigation of the quantitative relationship between the road surface properties of general roads and the level of driving noise[(4)]. Furthermore, a revision of the test methods to add various conditions that would make the Additional Sound Emission Provisions in UN R51-03 reflect actual driving conditions more closely, as well as an automatic sensing system to identify high-noise vehicles modified to

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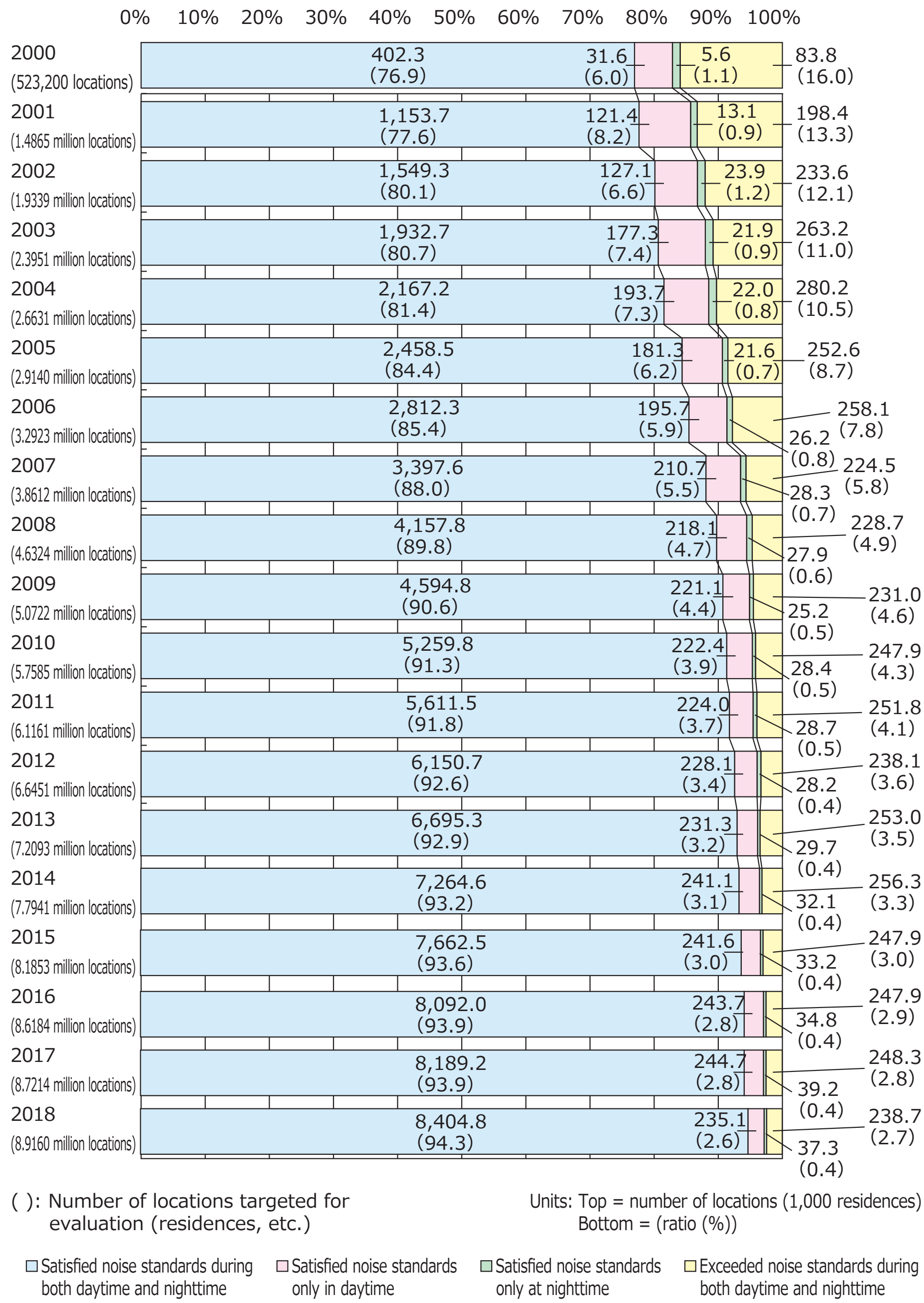

Source: Ministry of the Environment homepage (http://www.env.go.jp/press/files/jp/113527.pdf [in Japanese])

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

use a non-compliant muffler, were discussed. Comprehensive measures to further reduce road traffic noise are being prepared.

With EVs and HEVs becoming more widespread, an acoustic vehicle alerting system (AVAS) was devised because the low noise level of these vehicles made it difficult for pedestrians to notice an approaching vehicle. This led to the establishment of a UN regulation (UN R138-01) in 2016. Despite the introduction of regulations in various countries, the need for research on designing vehicle alert sounds resulting in higher safety remains significant. Test methods have also been reviewed to enhance their accuracy through, for example, the use of multiple microphones. Further research advances are anticipated.

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3 Powertrains

3. 1. Internal Combustion Engines

There is ongoing research and development aimed at raising the thermal efficiency and reducing the weight of internal combustion engines to increase their output and fuel efficiency. Technologies that solve the attendant issue of greater vibration and noise have been the subject of several studies.

For gasoline engines, research on rapid combustion technologies using compression ignition and prechamber ignition is being carried out to improve thermal efficiency. These forms of ignition involve a rapid cylinder pressure increase compared to conventional spark ignition combustion, presenting the problem of large combustion noise. Various solutions to that problem, including a dynamic vibration absorber that damps the resonance of the connecting rod system, encapsulation technology that enhances noise absorption and insulation performance, and control relying on a cylinder pressure sensor to suppress combustion excitation force, have been applied[5][6]. Examples of other studies on technologies offering effective solutions to contradictory issues include the application of machine learning in cylinder deactivation operations to determine cylinder deactivation conditions that balance vibration performance and greater fuel efficiency[7], and the adjustment of rigidity balance intended to move the bending vibration mode joint position closer to the engine mount to achieve both vibration performance and weight reduction in mini-vehicle vehicle power plants.

For diesel engines, combustion using premixed charge compression ignition (PCCI) is being studied to reduce fuel consumption and emissions. As with the rapid combustion technology for gasoline engines, the significant combustion noise accompanied by a rapid cylinder pressure increase is also a problem in PCCI. One reported solution effectively reduced combustion noise by making the resonance frequency of the connecting rod system coincide with the frequency band resulting in noise cancelling spikes during two-stage injection combustion[9]. Another reported solution involves a model-based control that automatically compensates the combustion noise and soot that increase when switching between PCCI and diffusive combustion[10].

As described above, solving the vibration and noise problems that conflict with improving engine efficiency is essential to realizing more advanced internal combustion engines. High hopes are placed on the development of new technologies that achieve both at a high level.

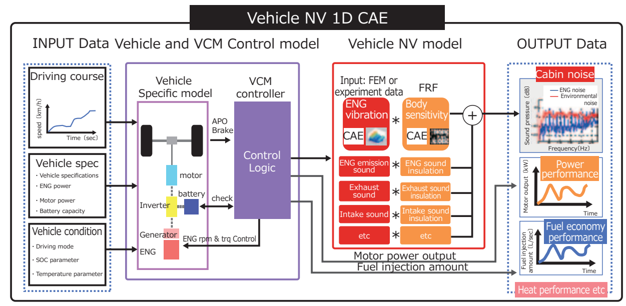

Fig. 2 1D CAE Model Integrating a Vibration Noise Model with an Engine Control Model[11]

3. 2. Electric Motor Systems

As vehicle electrification has become more common, power units with HEV, PHEV, range extenders, and other complex systems have been developed. When developing such systems, there is a strong need to predict and design vibration and noise performance in the early stages of development, and the use of MBD has been reported.

One study involved building a 1D CAE model(Fig. 2) that integrates a vibration noise model and an engine control model. The vibration control model combines experimental and CAE models, while the engine control model uses vehicle condition inputs such as a battery capacity and initial SOC to output engine speed, vehicle acceleration G, and other data. Applying the 1D CAE model to the electric powertrain to predict tradeoffs between factors such as engine noise and fuel economy contributed to effective development[11]. In another example, a functional mock-up interface (FMI) was used to integrate model groups (e.g. a driver model for passing information such as accelerator angle, and a powertrain controller) coded with different applications to create an integrated simulation environment that predicts single vehicle performance. In this example, an accurate prediction of vibrations when an HEV engine is restarted was accompanied by the prediction of the sensitivity of factors affecting vehicle body vibrations[12].

With respect to power units with complex systems, expectations for technologies that draw out the maximum performance in multiple areas, and balance them at a high level, have been raised.

3. 3. Drive Power Transmission Systems

One study on drive power transmission systems cov-

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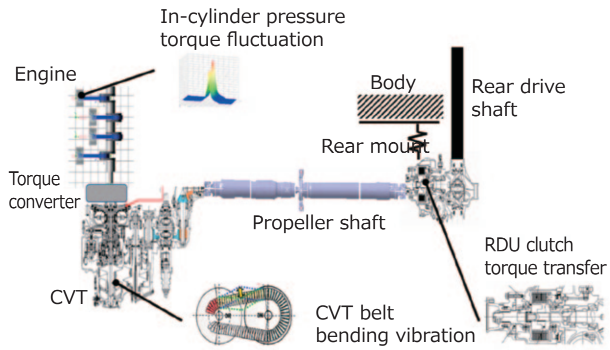

Fig. 3 Conceptual Diagram of Prediction Model for Drive System Vibration Transmission[13]

ered making actual vehicle predictions based on stand-alone actual drive unit validation prior to producing the vehicle to enable the efficient development of a complex drive unit with appropriate environmental performance. Another study sought to address noise and vibration phenomena caused by a torque fluctuation increase incompatible with the environmental performance required of the powertrain.

In one example of actual vehicle prediction technology, the CVT belt resonance produced when a 4WD vehicle starts and accelerates, as well as the rotation difference and fluctuation components of the rear differential clutch were modeled (Fig. 3). Standalone validations of results for the CVT and 4WD system were used to identify the parameters entered in the model, and vibration and noise were predicted before building a prototype[13]. For rear differential whine noise, a prediction of the vibratory force of the components and assemblies of the driveline torsional vibration system that also accounted for driving conditions was used to quantitatively assess changes in torsional vibration characteristics.

Various measures against noise and vibration caused by the powertrain have been reported. One proposed approach to reducing torsional vibration consisted of improving the performance of centrifugal pendulum dynamic vibration absorbers, which effectively reduce vibrations in almost all rotational speed ranges by varying the natural angular frequency of the pendulum in proportion to the rotational speed[15]. Another approach relied on a vibration analysis known as a return map to analyze torsional dampers. This allowed the non-linear vibration behavior, which generally increases the calculation load, to be checked visually with no increase in load[16].

A broad range of topics, from theoretical concepts to actual vehicle validation methodologies, were raised in drive power transmission systems studies. This is anticipated to lead to proposed measures early in the development stage, as well as to improved analysis accuracy.

4 Tires, Suspension Systems, and Vehicle Bodies

4. 1. Tires and Suspension Systems

The recent rapid electrification of vehicles has heightened the relative importance of reducing noise caused by inputs from road surfaces. The mechanism underlying the generation of that noise occurrence is complex and involves various associated components. Accordingly, effective noise reduction, a transfer path analysis (TPA) is required to identify the vibration source, transmission path, and response (sound) components.

Approaches proposed to solve the issues of analysis accuracy and measurement period that arose in applying road noise TPA to vehicle development include a TPA procedure that uses a six-component wheel force transducer[17], and an in-situ blocked force TPA procedure[18]. The common point between these TPA procedures is that the isolation of input from response differs from conventional body input criteria, and reliance on six-component wheel force. There are still issues concerning how to set index values for input and response and how to define and operate evaluation criteria. Therefore, noise analysis and reduction methods incorporating the above points, as well as further technical development, will be require to use them effectively in vehicle development.

One initiative looking at factors other than road surface inputs identified inputs from drive systems as a vibration source. The phenomena were reproduced using a stand-alone test device, and non-linear suspension resonance was found to contribute to idling vibration noise[19].

Conventional brake noise research involving structures, material or CAE has been complemented with research on complex phenomena, such as actuator operation noise[20] and regenerative brake squealing noise[21]. Taking motor vibration components and pump pulsation components into account through 1D/3D CAE (Fig. 4) in the study of actuator operation noise was studied, made it possible to quantitatively predict transmission vibration involving pipes or the body, as well as brake performance.

Efforts to solve noise produced from multiple vibration sources, such as road surfaces, power plants and brakes

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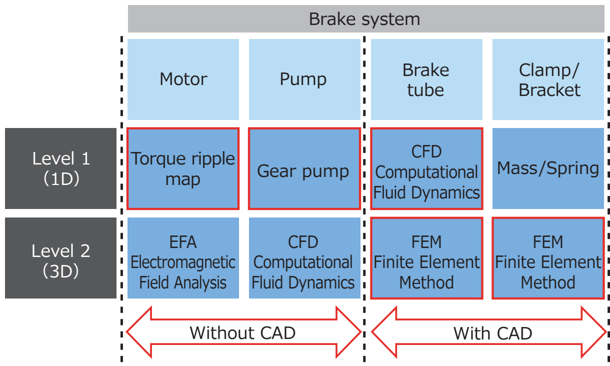

Fig. 4 Component Elements Required for Operating Noise Prediction and Modeling Method[20]

are anticipated for tires and suspensions, as are advances that balance the basic functions of suspensions and brakes with vibration noise suppression.

4. 2. Vehicle Body and Interior Materials

Improvements in fuel economy and expanding electrification are intensifying demand for weight reduction and improved vibration noise performance. Those two demands often involve making a tradeoff. Therefore, methods to efficiently improve performance with reduced mass are continuously being studied. In one study, topology optimization results from multiple load conditions applied to part of the body were applied in shape optimization[22]. In another study, damping nodes and a structural adhesive with an excellent vibration damping characteristic were used to reduce the vibration level while enhancing the rigidity of vehicle body frame[23]. Research on weight reduction using multi-materials was also reported. Using an aluminum material for roof panels to reduce their weight can result in increased in-vehicle noise when it rains (rain noise), and simulations were used to study effective positions for damping material.

The Biot model, which takes the airborne noise and solid-borne noise of porous materials into account, has been the object of a growing number of studies with respect to improving the sound insulation performance of interior materials. Technologies to identify Biot parameters for complex shapes of molded items in addition to simple shapes of conventional plate-like test pieces are being developed[25].

Furthermore, improved computer performance is enabling detailed modeling of clearances or sound insulation characteristics in body and interior materials. In one study, vehicle interior and exterior noises resulting from radiated tire or powertrain noise, was predicted by combining detailed models of the vehicle exterior sound field, vehicle structure, and vehicle interior sound field[2]. More complex coupled analysis incorporating structures, sound fields and fluids are likely to be applied to various vibration noise phenomena.

5 Sound Quality

The function and usage of vehicles have been changing with the emergence of connected, autonomous, shared and electrified vehicles. These changes will also alter customer expectations concerning in-vehicle sound quality[26]. Vehicle electrification, in particular, brings a significant change because it eliminates engine noise. Until now, the acceleration sound from the engine created added value for vehicles with high dynamic performance categorized as sports or sporty vehicles. Systems making complementary use of in-vehicle speakers to provide better added value are still being proposed[27]. Engine sound has also been reported to help facilitate vehicle speed control[28].

The idea that some form of sound is necessary to replace the absence of engine sound is necessary, and a system to design such sound is under development[29]. At the same time, in vehicles that emphasize comfort, the absence of engine sound is expected to lead to improvements in quietness. Since only aerodynamic noise and noise dependent on the road surface and vehicle speed will stand out, it is conceivable that adding sound in some form will be sought even for non-sports vehicles.

Moreover, changes in vehicle usage stemming from autonomous driving vehicles and shared cars may change customers expectations for in-vehicle sound quality. More and more research approaching sound and its quality from the above perspective is anticipated.

6 Ride Comfort

As expectations for a more comfortable moving space rise, ride comfort development faces issues such as reducing the rolling resistance and providing high inner pressure increase for tires that enhance fuel efficiency[30], and, as a result of advances in vehicle body weight reduction, balancing the handling and vibration noise performances.

In that context initiatives adopting fresh perspectives led to technologies such as control technology that enhances occupant comfort in the entire vehicle using a vehicle model encompassing the occupants[31], means of support to reduce occupant fatigue during prolonged

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sitting[32], and technology that equips seat cushions with a variable mechanism that enhances the fatigue reduction effect[33].

Parts related to ride comfort performance often have strong non-linear characteristics, and it is not easy to predict their performance at the initial development stage. This has led to ongoing efforts to incorporate the non-linear elements of primary components into CAE and to find physical indices indicating the comfort felt by occupants.

Examples include using AI to evaluate shock absorber performance[34], reproducing the dynamic characteristic of the urethane foam used in cushion material[35], and applying deep learning to sensory evaluation prediction methods to improve prediction accuracy[36].

Ride comfort will continue to provide important value to mobility as long as people want to move around, and is expected to be continuously improved.

7 Technological Trends

New technological trends include the application of currently high-profile AI technologies to vibration noise phenomena, and the use of cameras and other devices that have become commonplace with the spread of advanced safety technologies in measures against vibration noise.

One example of the application of AI technologies uses the random forest algorithm, a well-known machine learning technique, to quantify the contribution made by factors in the relation between the level of vibration and multivariate data such as the signals from engine or motor ECUs for the purpose of analyzing the factors in the variation in vibration when a hybrid vehicle engine starts[37].

Research on technology that combines an autoencoder and other image recognition techniques to extract road surface feature quantities from images taken by cameras in autonomous vehicles, and then uses deep learning to estimate road surface input noise in the low- to medium-frequency range with a high degree of accuracy, represents an example of integrating AI with advanced safety technologies[38].

The application of AI to the ever advancing vibration noise analysis technologies will expand, and it is hoped that the further merging of AI with advanced safety technologies or other new devices resulting from advances in vehicles will also spur dramatic progress in vibration noise technologies.

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