VIBRATION, NOISE AND RIDE QUALITY

1 Introduction

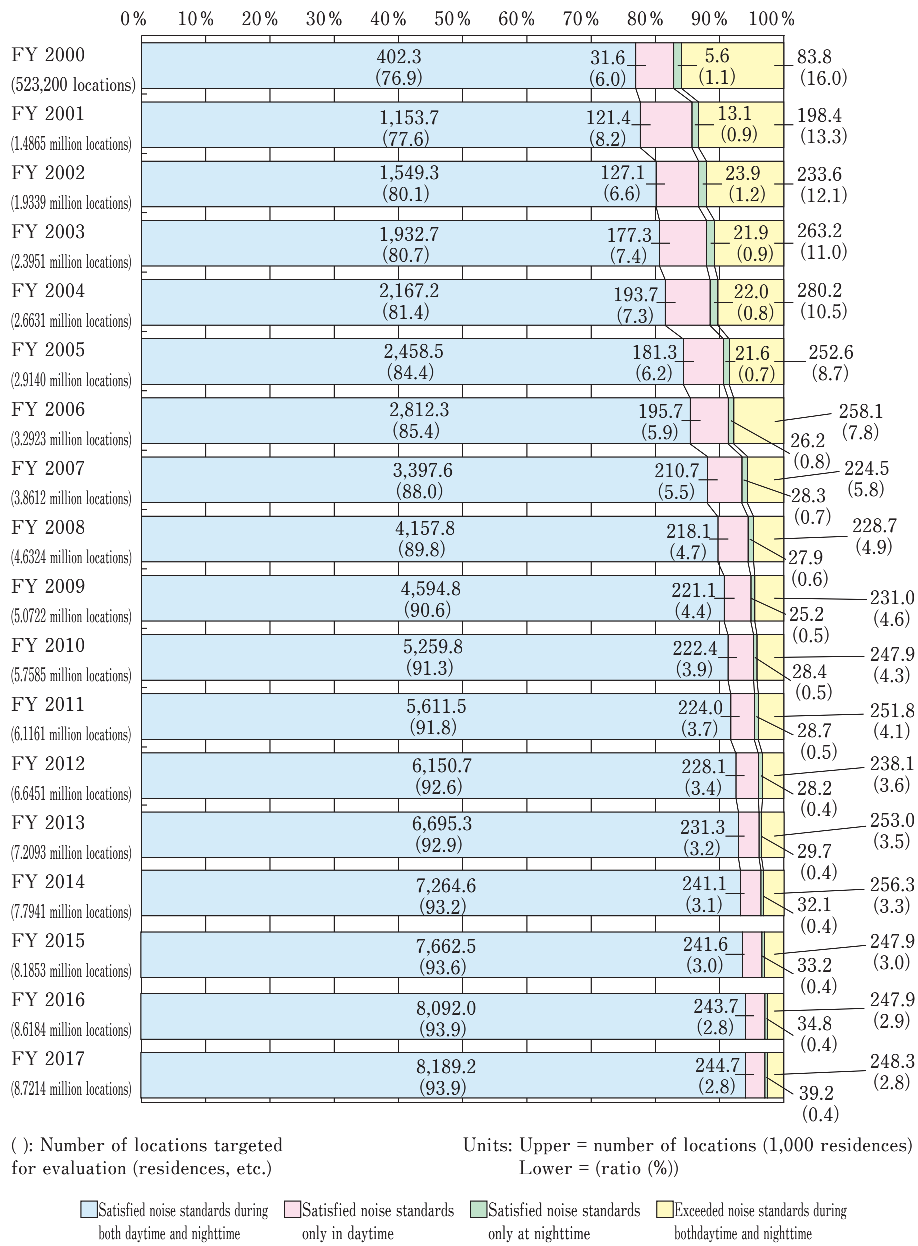
About 100 years have passed since the full-scale adoption and popularization of the automobile, which is now on the verge of a radical transformation to adapt to stricter environmental regulations, such as limits on CO_2 emissions. The greatest contributor to noise and vibration is the power source, starting with the internal combustion engine, continuing with hybrid systems that complement the engine with a drive motors, and moving on the development fuel cells. The number of electric vehicles using batteries and drive motors has been growing rapidly. Drive motors not only change how the vehicle handles, but also improve overall quietness both inside and outside the vehicle by eliminating the sound of the engine. However, other in-vehicle noises such as the electromagnetic noise from drive motors and their power supply system, gear whine noise, and road noise have become much more conspicuous. Regulations concerning vehicle exterior noise will be changed to impose even stricter limits in the future, and the conventional reduction in engine noise will have to be accompanied by a significant decrease in tire noise as well. New regulation on acoustic vehicle alerting system (AVAS) have also been put into effect to enhance pedestrian safety. Consequently, low-noise technologies addressing these changes are being developed in conjunction with efforts to reduce vehicle weight. Model-based development is also being applied to achieve both development efficiency and balanced performance. In addition, development has also started to take advantage of artificial intelligence. Thus, noise and vibration technologies are evolving and expanding their scope of application in the midst of an unprecedented transformation.

2 Road Traffic Noise

In Japan, regulations to address the noise produced by automobiles were first introduced in 1951. Since then, the addition of testing methods and gradual strengthening of the regulations have improved the state of environmental noise in the areas around roads. However, there are still some roads that do not meet either daytime or nighttime environmental noise standards, and continuous improvement is required (Fig. 1)[1].

The situation is similar in Europe, where the strengthening of regulations concerning the noise produced by automobiles did not lead to a sufficient decrease in environmental noise, prompting renewed debate on revising the regulations to match actual circumstances. In light of this situation the United Nations (UN) reexamined its R51.03 regulation, whose vehicle noise testing method had been updated to more accurately reflect actual urban driving in an effort to reduce noise in urban areas, and made additional amendments. Starting on October 16, 2018, limits will be imposed on the backfire noise from the exhaust pipe when the accelerator is released. A new approval test was also added for any electrical sound amplification device designed to generate sound outside the vehicle. (However, there is a grace period of 18 months for these devices). A tightening of the range of the off-cycle noise test (Additional Sound Emission Provisions: ASEP) has also been proposed. In conjunction with the strengthening of automobile noise regulations (UN R51.03: Phases 1, 2, and 3), efforts to make vehicle development more efficient through the use of an external noise optimization simulation method[2] or component bench evaluations to predict the degree of contribution to external noise[3] have been reported.

Reducing road traffic noise will require comprehensive efforts encompassing all of its sources, including automobiles, tires, and road surfaces. Therefore, in addition to the noise standards for automobiles themselves (UN R51.03), Japan also introduced the UN R117.02 regulation, which defines test methods and limits for tire noise, wet grip, and rolling resistance, on April 1, 2018. In Europe as well factors other than the tires themselves, such road



Source: Ministry of the Environment homepage (http://www.env.go.jp/press/files/jp/111259.pdf [in Japanese])

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

surface classifications based on the noise characteristics of paved surfaces are being examined, and road surface initiatives carried out in Japan are being taken into consideration[4]. More extensive initiatives that address road surfaces in addition to noise regulations for the automobiles themselves are anticipated to develop measures against LAmax values due, for example, to extremely loud mufflers that often lead to direct complaints, as well as more effective measures, for LAeq values that tie in directly to environmental standards[5]. Furthermore, it will be necessary to establish more comprehensive road traffic noise countermeasures that include the installation of sound insulation systems along roads, traffic flow measures, and educating automobile users about quiet driving.

In contrast to vehicle noise standards that regulate the reduction of exterior sound, other standards requiring vehicles to emit a sound are being established. Electric vehicles (EVs) and hybrid vehicles (HEVs) running only in electric mode so quiet that, in Japan, Europe, North America, and elsewhere, the issue of pedestrians failing to notice an approaching EV has been identified as a problem. Consequently, the UN and other bodies have discussed audible warnings to safely inform pedestrians of an approaching vehicle, and a UN regulation (UN R-138) concerning these acoustic vehicle alerting systems (AVAS) has been enacted. It was introduced in Japan on March 3, 2018 and is expected to be introduced in Europe on September 1, 2019. In North America, AVAS are regulated by FMVSS 141, which differs from R-138 and is scheduled to be phased in at 50% compliance starting on September 1, 2019 and full compliance on September 1, 2020. In addition, regulating back-up alarms that cover blind spots that the driver cannot fully confirm are safe while moving in reverse in a manner similar to AVAS has been proposed, and is being examined in UN GRBP meetings.

3 Powertrains

3. 1. Internal Combustion Engines

More efficient development is being sought through the study of many analysis methods and development processes aimed at reducing noise and vibration without sacrificing performance in other area from the initial stages of development. First, empirical rules and both 1D and 3D simulations were used to obtain the characteristics of the relevant components of medium- and high-frequency noise phenomena. Assessing the relative merits of these characteristics against the distribution range of past accumulated data then led to identifying methods that contribute to preventing noise and vibration problems during engine development(6), as well as to introducing examples of their applications(7). At the same time, a method for high-speed analysis of the vibration noise performance, fuel consumption performance, and drive power performance by using a one-dimensional model in the case of phenomena of relatively low frequency below the explosion order has also been reported(8). In addition, statistical methods such as statistical energy analysis (SEA) have reportedly been used as methods of examining measures for the high frequency range where numerous Eigenmodes exist, raising expectations for more efficient development(9).

3. 2. Electric Motor Systems

There are ongoing efforts to further reduce vibration at engine startup in HVs and PHVs. Conventional control of the crank angle at engine start-up has proven insufficient. One clarified that the air-fuel ratio of each engine combustion at engine startup is very important by ma-

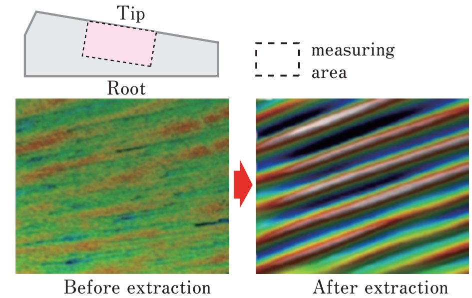


Fig. 2 Result of Extracting Tooth Surface Waviness(11)

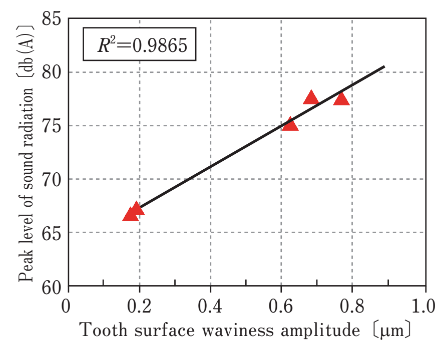


Fig. 3 Correlation between Extracted Amount of Tooth Surface Waviness and Level of Sound Radiation(11)

chine learning that uses a large amount of data(10). The need for factor analysis that incorporates artificial intelligence and machine learning is increasing as these systems and controls become more complicated.

3. 3. Drive Power Transmission Systems

A method to quantitatively evaluate gear tooth surface waviness, which is the cause of high-order gear sound radiation generated from hypoid gears, has been reported(11). Tooth profile cross-section curve data includes many order component cycles other than those corresponding to the gear noise generated in the vehicle, which has long made it difficult to quantitatively evaluate the amplitude and periodic order values of the peaks expressing waviness properties. A new analysis method that measures tooth surface waviness with a non-contact 3D measuring instrument and applies image filtering via 2D and inverse Fourier transforms to extract the periodic waviness components that affect the frequency of the gear sound (Fig. 2). Furthermore, the results of multiple specimen gear evaluations show that the amount of waviness can explain the level of high-order gear sound radiation (Fig. 3).

Slip control on lock-up clutches is increasingly used to improve the efficiency of automatic transmissions as well as to reduce booming noise and gear rattle noise. The

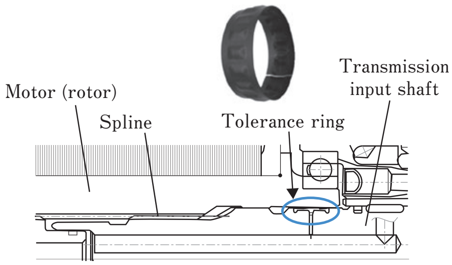


Fig. 4 Application of Tolerance Ring[14]

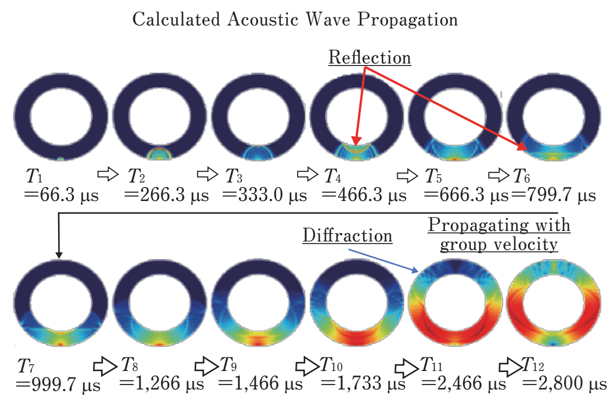


Fig. 5 Calculated Results of Sound Wave Propagation within Tire Cavity[18]

Automatic Transmission Oil Subcommittee of the Society of Automotive Engineers of Japan studied ways to reduce variation in the shudder prevention performance test that evaluates the stability of the friction characteristics of automatic transmission oil and reported that changing the surface pressure, one of the test conditions, stabilizes the formation of a lubricating film in the mixed lubrication region[12]. In light of the increasing importance of measures for deterioration of NV performance and torque fluctuation due to the smaller number of cylinders, defining formulas for the pendulum trajectory in centrifugal pendulum dynamic vibration absorbersis also being studied from the viewpoint of improving performance[13]. Although friction within the HVtransaxle is being reduced to achieve lower fuel consumption, it is also bringing the issue of gear rattle noise. In one case, this issue was addressed by adding an element (tolerance ring) that transmits only a small amount of torque to the gear tooth portion to decrease the rattle noise when the input shaft torque is 0 Nm (Fig. 4)[14]. In another case, the actual operating transfer path analysis (TPA) technique was used to identify the gear tooth rattle portion[15]. Ongoing efforts to reduce both friction and weight are raising expectations that noise and vibration reduction technologies.

4 Tires, Suspension Systems, and Vehicle Bodies

4. 1. Tires and Suspension Systems

Even as the growing use of motors and other electric-powered devices in automobiles has reduced the amount of noise and vibration generated from powertrains, it has also made it more crucial to reduce noise and vibration from uneven road surfaces. While assessing the vibration transmission characteristics of tires in contact with the road surface is extremely important, predicting the dynamic characteristics of tires with a composite structure is difficult. One proposed solution to easily measure vibration characteristics under actual operating conditions involves approximating the tire vibration transmission characteristics and projection input waveform from the shaft response waveform when driving over protrusions arranged on a drum road surface[16]. Further initiatives include applying an experimental SEA model to evaluate the input power to the tire from actual road surface operating conditions or calculate how sound waves generated in the air within the tire propagate due to reflection and diffraction (Fig. 5). Efforts to analyze the mechanism of cavity resonance have also been reported, and other research on this topic is being vigorously pursued[17][18].

In suspension systems, the design of springs, absorbers, and geometry are critical not only to address noise and vibration, but also to achieve other performance parameters such as steering stability and ride comfort. Research into various means of suspension control is now underway with the aim of further improving vibration damping performance. Skyhook damper control, which is effective for damping near the sprung mass resonance frequency, is a well-known typical method of controlling ride comfort. Similarly, a method of applying feedback control of forces proportional to the acceleration, velocity, and displacement of the sprung mass has been proposed to obtain a damping effect over a wider frequency, and examples of its effectiveness have been reported[19].

A great deal of research and analysis continues to be carried out on brake noise, which is a phenomenon caused by various factors such as the rigidity of brake components, eigenvalue coupling, the coefficient of friction, friction force fluctuations, and surface pressure, as well as influenced by the temperature and environment. This makes a design that anticipates and counters vari-

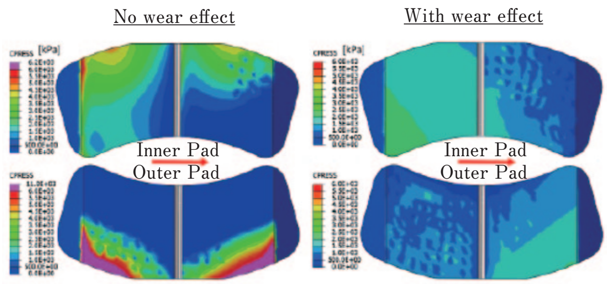


Fig. 6 Calculated Results of Surface Pressure Changes due to Lining Wear[20]

ous conditions necessary to provide a robust answer to brake noise. Therefore, a simulation that takes into consideration changes in surface pressure and tire shape due to lining wear was created (Fig. 6), and its results have been reported to correlate more closely with actual equipment test results than in cases where this wear is not considered[20].

4. 2. Vehicle Body and Interior Materials

One approach to verifying the validity of a vehicle body model is to carry out experimental modal analysis on the body structure and then confirm how well this corresponds to the calculation model based on an index called the modal assurance criterion (MAC). Applying optimization calculations (maximum likelihood estimation) to minimize errors between the measured data and the modal analysis results, even for transfer functions for acoustic characteristics with significant attenuation, such as in trimmed bodies or vehicle interiors, has been reported to identify the acoustic mode in the passenger compartment and improve the accuracy of the trimmed body model[21]. Vibration damping materials, sound insulation materials, and sound absorption materials have been used to improve the quietness with respect to the large amount of noise in the high frequency range generated by noise, vibration, and harshness (NVH) phenomena in electric vehicles.

Models based on empirical rules and, more recently, Biot models that take the characteristics of solid and fluid phases into account are widely used to predict the characteristics (sound absorption rate) of sound-absorbing materials. These Biot models are expressed by eight parameters, such as elastic constant and flow resistance, but their macroscopic definition makes it difficult to establish their relationship to the fiber structure of sound-absorbing materials. This has led to a reported attempt to correlate the Biot parameters with a microscopic definition, such as fiber diameter, by applying homogenization to the fiber material of the sound absorbing material[22]. In the future, demand for material development and high-performance materials will undoubtedly rise in the context of improving the quietness of vehicle interiors.

5 Development Methods (CAD/CAE/MBD)

Rapid and efficient vehicle development processes that not only achieve both excellent NVH performance and weight reduction, but also attain other performance parameters are desirable. The effective use of prototype vehicles or of simulations based on 1D and 3D models (model-based development) have been identified potential methods of realizing this desire. The creation of the appropriate development environment and mechanisms is very important to realize this kind of model-based development process. For example, CAD information must be maintained and performance prediction models must be created in a short time. In many cases, models for individual performance parameters have already been created, leading to duplication of data registration and management, as well as variation in model quality depending on who created it. This led to the automatic creation of a high-quality CAE model in a short time by sharing models and standardizing and automating the model creation process[23].

The goal of model-based development is to move away from prototype vehicle-based development, which incurs development costs, and assess vehicle configurations that balance multiple performance parameters during the initial stages of development. Many of the reports to date focused on conceptual research, but reports with concrete examples involving multiple performance parameters, such as fuel efficiency, drive power, and low-frequency noise and vibration are being released (Fig. 7)[8]. Due to the extremely large number of parameter studies that are performed, examining the feasibility of performance parameters during the initial stages of development requires a 1D model with a short calculation times that also ensures prediction accuracy. The level of detail of the model required for each performance parameter is also important and the appropriate level of model detail affects the success or failure of the entire project. In addition, the specifications and parameters of the models must be shared, and this knowledge must be accumulated quickly to put model-based development into practical

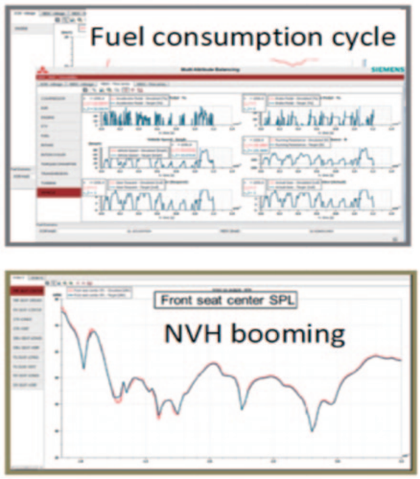


Fig. 7 Fuel Consumption Cycle and NVH Performance[8]

use.

6 Sound Quality

Traditional methods for improving sound quality from psychoacoustic evaluation indices based on subjective evaluations have often led to proposing powertrain and body design requirements for specific sound sources and phenomena. In contrast, recent research has increasingly examined the ideal state of the entire vehicle, including multiple sound sources and phenomena.

This shift in focus has, in part, been prompted by the rapid adoption and popularization of hybrid vehicles and electric vehicles. For example, the operating state of the vehicle becomes more difficult to ascertain when it is running on electric motor power, leading to the realization that engine sound of played an important role in driving functions. Changing the background noise parameters caused by wind or road noise in engine-driven vehicles is known to improve recognition of the engine sound and affect driving functions[24]. As mentioned previously, the different balance of the vehicle interior sound in electric vehicles calls for greater quietness in terms of wind and road noise, and makes it necessary to go beyond the conventional indicators of sound pressure level and loudness to improve sound quality. Once case in point is road noise forming a combined stimulus with floor vibration that affects driving sensation. It has been suggested that vehicle design should not only emphasize the individual levels of noise and vibration, but also the balance between the two phenomena[25]. Other research has built a model matching the physiological mechanism of hearing that explains noisiness in terms of changes in frequency and spatial characteristics with the "quality of being particularly noticeable (saliency), and proposed a new quietness evaluation method[26].

Various reports have noted ongoing studies concerning driving sounds to replace the engine sound that is absent during electric-motor driving carried out in Europe, South Korea, and elsewhere outside Japan. Research on these new sounds is also expected to be actively pursued in Japan as well.

In addition to the standardization of legal requirements for electric vehicles to emit proximity warning sounds, the importance of warning, caution, and advisory sounds emitted both inside and outside the vehicle is expected to grow with the spread of autonomous driving. This is another area in which various initiatives are gradually addressing the growing need for sound quality indicators that go beyond the conventional sound pressure levels. Reversing warning sounds that can be easily recognized by pedestrians, for example, have been the subject of studies on sound conditions that can both serve as an alert and be environmentally friendly against a variety of different background noises[27].

As show above, research on sound and sound quality is shifting toward the total design of the entire sound environment surrounding vehicle occupants with a focus on ensuring effective recognition of the necessary sounds.

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