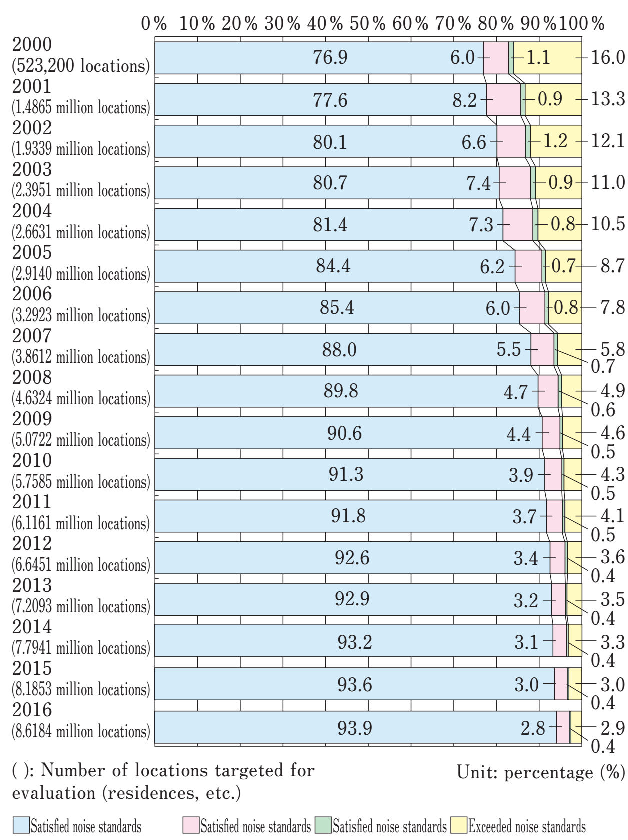
VIBRATION, NOISE AND RIDE QUALITY

1 Introduction

As environmental problems such as global warming continue to be actively debated, the social situation surrounding automobiles is becoming increasingly tense, and technologies to reduce CO_2 emissions, enhance fuel economy, or otherwise make automobiles more environmentally friendly have now become critical to the survival of manufacturers. The need to cope with stricter environmental regulations such as the zero emission vehicle (ZEV) regulation, and the electric vehicle (EV) trends forming on a global scale around German automobile OEMs leave no doubt that adapting to the electrification of vehicles will take over a large portion of development in the coming years. In plug-in hybrid vehicles (PHEVs) and EVs, vibration and noise problems that cannot be attributed to an engine are expected to become more apparent. Consequently, innovative technologies that solve these problems at a high level and also address other issues, such as significantly reducing the weight of vehicles and increasing the efficiency of power transmission systems, are being sought. At the same time, the same expectations are being placed on technology for gasoline engines, which remain the main power unit for the majority of vehicles. Efforts to overcome the development challenges presented by these various power units in a short time have led to improved, CAE technology and remarkable advancements in the application of model-based development.

2 Road Traffic Noise

Obtaining a proper understanding of the state of road traffic noise is necessary when examining the various countermeasures that could reduce it. In Japan, continuous monitoring of automobile noise has been carried out since 2000 on the premise that monitoring local noise levels over time is necessary to allow prefectures and other local authorities to systematically plan automobile noise countermeasures. According to the Japanese Ministry of the Environment report on the status of implementation of the continuous monitoring of automobile noise, 841 regional public entities across the country carried out an evaluation of the state of achievement of environmental standards in FY 2016. This evaluation was sent to 86,108,400 households, with 2.9% of that total (compared to 3.0% in 2015) reporting automobile noise exceeding the environmental standards during both daytime and nighttime, suggesting that the overall achievement of automobile noise-related environmental standards is slowly improving (Fig. 1). Breaking down the aggregated results by road type indicated that national highways had the



Source: The Status of Motor Vehicle Traffic Noise during FY 2016, Ministry of the Environment homepage

Fig. 1 Status of Compliance with Environmental Noise Standard in Japan (nationwide change over time)[1] highest percentage of responses indicating that environmental standards for noise during daytime, nighttime, or both were exceeded, with 247,100 (10.5%) of the 2,355,300 households reporting this result.

The recent development of residential land on roadsides where no one lived previously has resulted in traffic noise problems for those new residents. Therefore, the Guidelines Concerning Roadside and Railway Countermeasures to Prevent Traffic Noise Problems were formulated in 2014 as a reference for the selection of appropriate noise countermeasures along roads and railway tracks. In June 2017, a revised edition featuring the addition of examples of advanced initiatives implemented by regional public entities was released. The Ministry of the Environment (MOE) plans to promote initiatives for preventing traffic noise problems through the use of these survey results and the dissemination of these guidelines[1].

The need for comprehensive efforts to reduce road traffic noise by addressing all of its sources, including automobiles, tires, road surfaces, and traffic environments, has led to adopting UN regulation (UN R51-03) concerning the noise emitted by the vehicles themselves. This regulation replaces the conventional test method based on wide open throttle acceleration driving with a test method (ISO 362) that conforms to actual urban driving conditions, and the regulation values were determined precisely in accordance with factors such as the vehicle type classification, intended vehicle usage, and engine output. The method is expected to prove more effective on actual roads[2].

As stricter automobile noise regulations have resulted in greatly reduced noise from automobile power unit systems while driving and the use of electric power has become more prevalent, the relative contribution of tire road surface noise the overall traffic noise has increased. Europe introduced a regulation on the tires themselves in 1996 after the large contribution of tire road surface noise to overall road traffic noise was recognized, and has since strengthened this regulation. It is also looking into factors other than the tires themselves, such as road surface classifications based on the noise characteristics of different paved surfaces. These circumstances have led Japan to also introduce UN/ECE Regulation No. 117 02, the international standard that stipulates regulation values and test methods for tire noise, grip on wet surfaces, and rolling resistance and other factors, in April 2018. Further, plans for stricter regulations concerning the noise from the automobile itself in R51-03 clearly reflect the intensifying demand to reduce noise emissions related to tires and road surfaces. This context has prompted research in areas such as tire external noise analysis using the statistical energy analysis (SEA) method in an attempt to predict the noise emitted by tires at the design stage. Since the tires are the only parts of the vehicle that come in contact with the road surface, their performance must be further improved while fulfilling the many performance requirements. Even as addressing environmental issues makes it essential to reduce the rolling resistance of tires, reducing traffic noise has also become an urgent issue[2-4].

In the future, road traffic noise countermeasures will have to be comprehensively instituted by increasing the effectiveness of noise regulations for the vehicle itself, implementing road structure and traffic flow countermeasures, and educating automobile users about quiet driving. To reduce road traffic noise more effectively, expectations are directed at the construction of a framework that provides a commanding view of vehicle, tire, and paved road surface noise reduction technologies and consolidates the research and development of those topics.

3 Powertrains

3. 1. Internal Combustion Engines

Efforts to improve development efficiency have spurred research into a number of different analysis and examination methods to obtain performance estimates in the initial stages of development.

Indicators that can be presented during the design of the shape of a new engine have been developed. There are also reports concerning the development of tools that divide the engine assembly into multiple parts, clarify the influence of the mass and rigidity of these parts on engine vibrations, and then present indicators when designing a new engine shape to optimize this design (Fig. 2)[5]. A method that predicts and evaluates sound quality in an actual vehicle based on bench test evaluation results, and derives the probability of achieving the target in-vehicle sound quality before the prototype is completed, has also been reported[6]. Furthermore, a report concerning research into a shape optimization method that combines a one-dimensional model and a three-dimensional model to achieve engine weight reduction[7] has

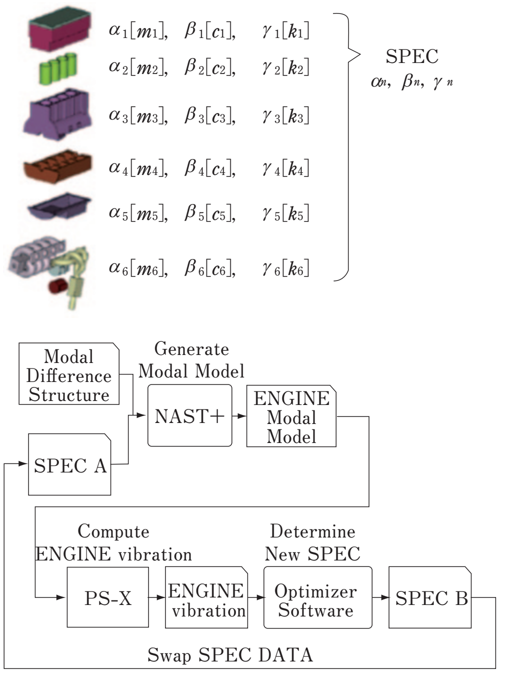


Fig. 2 Parametric Optimization Calculation Flowchart[5]

created expectations of improvement in both the quality and speed of engine development.

3. 2. Electric motor systems

Problems specific to EV and HEV powertrain systems are emerging as features such as one-pedal driving and range extenders increase their diversity. Examples these issues include the worsening of transmitted noise due to changes in the engine mount vibration characteristics caused by the torque reaction force during regenerative braking, the exhaust noise from energy consumed by rotating the engine with the generator motor at full charge[8], and, in vehicles with a one-pedal EV system, torsional vibration in the drive system due to backlash during acceleration and deceleration, as well as torque ripple while the vehicle is stopped on an incline[9]. Although analysis technologies continue to evolve, the concern that unexpected phenomena will increase as these systems and controls become more complex remains. The independent development of each system makes accurate predictions difficult, increasing the need to construct prediction technologies for the entire system.

3. 3. Drive Power Transmission Systems

With respect to the driveline, hybrid systems combining the drive power of both the engine and the motors have been developed to make vehicles more environmentally friendly, and research on the vibration problems arising from the adoption of such systems is being conducted. One case addressing the major changes the torsional vibration characteristics of the drive system caused by the new hybrid systems involved the development of vibration damping control technology to suppress vehicle vibration at engine start[10]. Another report indicated that separating the individual damping elements before testing and verifying them improved the prediction accuracy of torsional vibration[11]. In the case of CVT belt and chain noise, the accuracy of CAE prediction technology and sub-assembly evaluation technology was improved by directly measuring the pin compression force, tension, and sheave vibration during actual operation and logically clarifying the CVT behavior and noise generation mechanism at that time (Figs. 3 and 4)[12][13]. The development process is expected to eventually be redesigned to allow the incorporation of noise performance during the first half of that process.

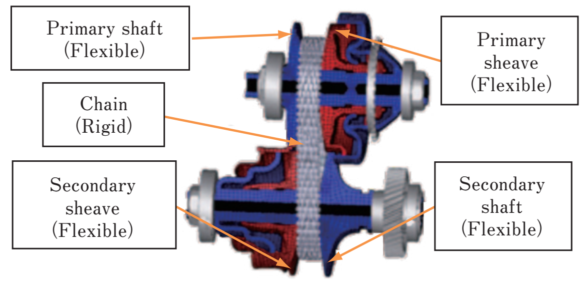


Fig. 3 CVT Analysis Model[11]

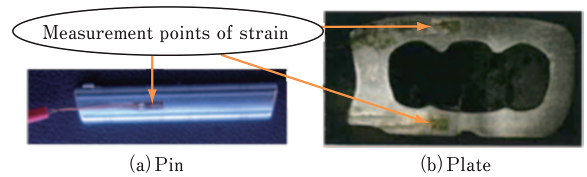


Fig. 4 Examples of Strain Measurement Points[11]

4 Tires, Suspension Systems, and Vehicle Bodies

4. 1. Tires and Suspension Systems

Pneumatic tires are likely to remain in use even if the sources of motive power and the vehicle layout change. The vibration transmission and acoustic radiation characteristics of tires are extremely important. However, in addition to having a wide frequency range, tires are made of composite materials and have strong nonlinearity. Tires also rotate during actual operation, making it difficult to take experimental measurements and modeling tire behavior. A wide range of studies, from the derivation of theoretical solutions to statistical energy analy-

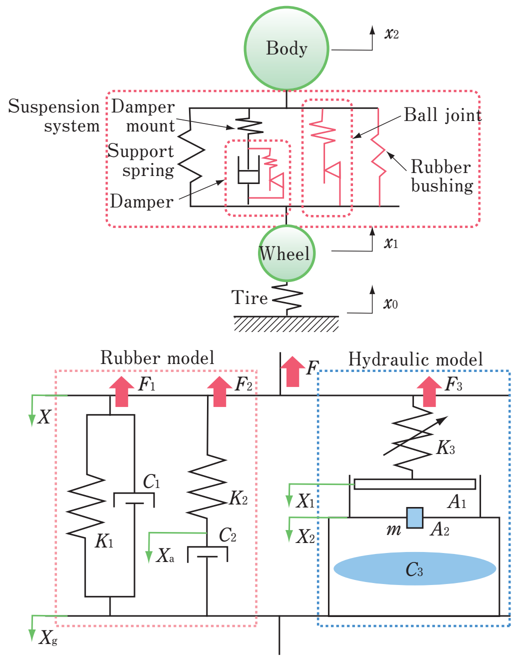


Fig. 5 Conceptual Diagram of a Suspension Component and Liquid-Sealed Engine Mount Model[16]

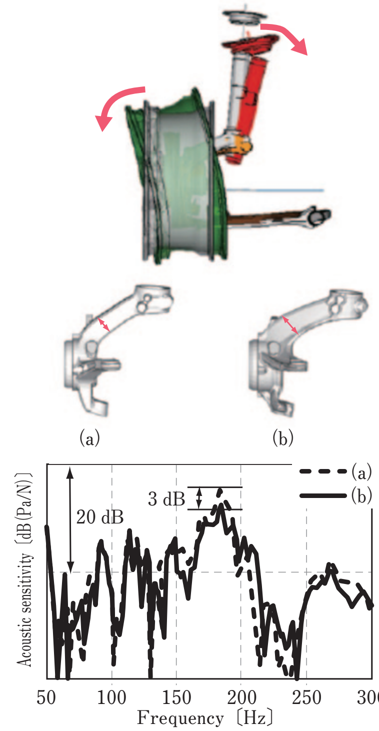


Fig. 6 Reduction of Road Noise by Improving Front Suspension Resonance Mode and Knuckle Rigidity[17]

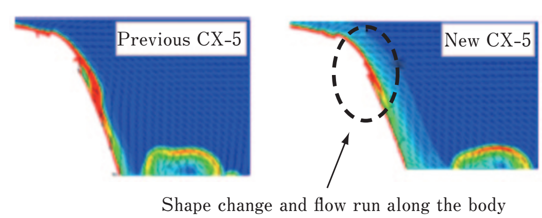


Fig. 7 Reduction of the A Pillar Aerodynamic Noise[19]

sis (SEA), are continuously conducted on tires[14][15]. The long history of multibody analysis in the field of steering stability has led to successful efforts to apply the multibody model to other factors, such as the frequency dependent characteristics of the suspension bushings, damper friction, liquid-sealed engine mounts, and drive system torsional vibration, as well as incorporating a commercial tire model package that approximates low order tire vibration mode with a small degree of freedom to balance vehicle dynamic performance with ride comfort and low frequency vibrations (up to approximately 20 Hz) (Fig. 5)[16]. However, there are still many technical problems to overcome, including the need for experimental measurements and fitting calculations to identify the tire model parameters, the need to select the proper parameters for each use, and the fact that the upper limit frequency is low.

The electrification of vehicles has increase the relative importance of vehicle road noise performance. The acoustic resonance of the air within the tires and the vehicle interior is one of the factors controlling the road noise, but this resonance frequency and mode are largely determined by spatial shapes and their characteristics are difficult to change (although devices such as resonators and active canceling do exist). In one case, the development of a new vehicle involved controlling the resonance frequency of the suspension system and the subframe to distance it from the acoustic resonance frequency[17], and optimizing the placement of the component eigenvalues greatly reduced road noise (Fig. 6).

4. 2. Vehicle Bodies

Noise (aerodynamic noise) caused by vortices of air generated around the vehicle body become a problem during high-speed driving. While the use of a microphone array or other devices in a wind tunnel is a common approach to identifying parts acting as noise sources and developing countermeasures[18], there are also reports that the detached air flows and vortices causing this noise effective were reduced effectively through computational fluid dynamics (CFD) simulations (Fig. 7)[19][20].

The transmitted sound from the door seal has been identified as a problem because it is the main route through which aerodynamic noise generated outside the vehicle enters the cabin. Since a large amount of rubber

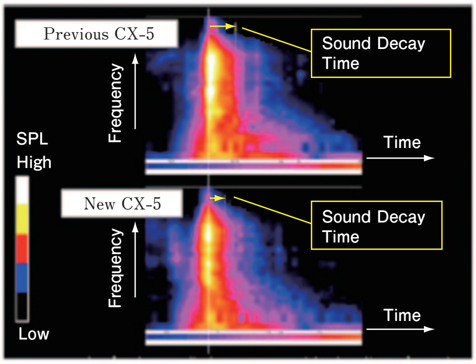


Fig. 8 Evaluation of Sound Decay Time when the Door is Closed[19]

and plastic deformation is applied to the door seal during use, verifying its noise performance before the vehicle is manufactured is difficult. Nevertheless, efforts to find alternative materials have prompted attempts to identify physical properties and perform nonlinear analyses[21][22]. Furthermore, the excitation of the entire vehicle surface by turbulent components generates low-frequency vibrations and booming noise. Since this dominates the interior noise level in the speed range around 160 km/h, there have been attempts to identify the vibration source using CFD and then analyze it in combination with a vehicle body structure finite element (FE) model[23]. The scope of CFD application is gradually expanding, as demonstrated by the example of calculating the aerodynamic noise of the radiator fan[24].

Until now, interior sound levels have been measured using sound pressure level (SPL), speech intelligibility (AI), and the psychoacoustic scale as evaluation indices, and a new evaluation index based on the reverberation time within the vehicle interior has been introduced (Fig. 8)[19]. The performance of sound absorbing and damping materials is very likely to improve and increase the need for modeling methods.

5 Sound Quality

For several years continuously variable transmission (CVT) vehicles, which offer good fuel economy and little shift shock, have grown increasingly popular due to their lower impact on the environment. However they present the drawback of falling short in providing the expected feeling of acceleration. In research aimed at compensating for this drawback, an acceleration feel estimation model that used a subjective evaluation to understand how changes in the acceleration sound parameters (time required for engine speed to increase and the rate of engine speed increase) altered the driver's impression was built, and evaluations in a driving simulator were carried out to assess the usefulness of this acceleration feel estimation model that takes driving operations into consideration[25].

Improving the engine combustion sound generated during acceleration is an important issue in terms of increasing product appeal, and the quality of the engine sound, not only how loud it is, strongly affects that appeal. However, because measures that improve the combustion sound tend to be in direct conflict with efforts to reduce weight or improve fuel economy and engine output performance, they have been kept to a minimum in the recent development of lightweight, fuel-efficient engines. To solve these problems assessing the quality of the combustion sound from the early stages of development, when the degree of design freedom is still high, and taking effective measures to improve this quality, are important. Consequently, a time series combustion sound contribution separation method was used to extract only the engine combustion sound from the actual sound measured during vehicle acceleration, and the quality of that extracted sound was quantified using a new objective evaluation method devised to evaluate combustion sound using psychoacoustic measures[26].

In contrast, with the growing popularity of quiet running vehicles such as plug-in hybrids and electric vehicles, noises that previously went unnoticed because they were masked by the engine noise, such as the operating noises of on-board actuators run by motors, gears, and mechanical parts, are becoming more obvious due to the reduced background noise in the vehicle interior and predicted to become problematic. However, reducing the operating noise of the on-board actuators will require increasing the manufacturing precision of component parts, which not only involves limits in terms of manufacturing and costs, but could also cause some products to be suspected of malfunctioning if no operating noise can be heard. These operating noises therefore need to be changed to more pleasant sounds, while retaining the characteristic sound of the products. Efforts to improve sound quality by applying the general theory of consonance from the music industry to the mechanical noise the actuator operating noise represents have been made[27].

Future sound design will likely be increasingly applied not only to driving sounds such as the sound of acceleration, but also to various other sounds, such as the operating sounds of devices and door closing sounds, to improve the product appeal and comfort of automobiles.

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