VIBRATION, NOISE AND RIDE QUALITY

1 Introduction

Global warming and other environmental issues are being further emphasized on a global scale and, in the context of realizing a more sustainable society, reducing CO_2 emissions has become a top priority in automobile development.

In Japan, electric vehicles (EVs), hybrid electric vehicles (HEVs), and clean diesel vehicles are becoming more widely available, and even fuel cell vehicles (FCVs) have been introduced to the market, raising the proportion of fuel-efficient vehicles. Even in Europe, which up to now had mainly relied on advances in diesel engine technology to reduce CO_2 emissions, a shift to more electric-powered vehicles, including mild hybrids, is underway.

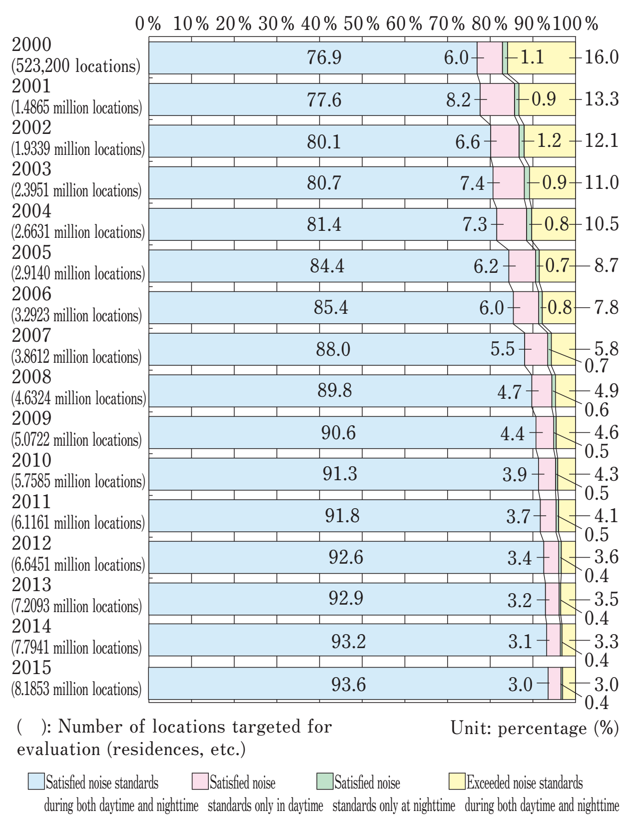
In addition, the efforts of automobile manufacturers in the U.S. and China to comply with the new Corporate Average Fuel Economy (CAFE) standards are having a major impact on the issues of vehicle vibration and noise. In conjunction with enhancing the efficiency of electric-powered powertrains and downsized internal combustion engines, there are calls for drastic reductions in vehicle weight. Consequently, innovative technologies that satisfy these demands while also continuing to ensure good vibration and noise performance are becoming more necessary.

At the same time, the introduction of UN regulations concerning vehicle noise emissions (R41-04 and R51-03) represent a major turning point in environmental noise requirements, and efforts to eliminate road traffic noise problems are accelerating. Automotive engineers will therefore be required to make further advances in the development of technologies drastic reduce both engine and tire noise.

In addition, the challenges ahead are not only limited to reducing environmental noise by making vehicles that operate more quietly, but also include the necessity of developing technologies that take safety into consideration when addressing the noise generated by vehicles.

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 some roads still do not meet either daytime or nighttime environmental noise standards, and continuous improvement is required (Fig. 1). The situation is similar in Europe, the strengthening of regulations concerning the noise produced by automobiles did not lead to a sufficient de-



Source: The Status of Motor Vehicle Traffic Noise during FY 2015, Ministry of the Environment homepage

Fig. 1 Status of Compliance with Environmental Noise Standard in Japan (nationwide change over time)[1)] crease in environmental noise, prompting renewed debate on revising the regulations to match actual circumstances.

In response, discussions were held at the UN and in 2016 a new testing method was issued in UN regulation R51-03. This regulation was then introduced (harmonized with existing standards) in both Europe and Japan. To reduce the noise generated during actual urban driving, the test method in R51-03 has been revised to use urban driving as a basis, and also includes steps to strengthen the noise regulations (Phases 1, 2, and 3). A noise off-cycle test (ASEP: Additional Sound Emission Provisions), which should be more effective at improving environmental noise conditions in urban areas, was also added.

Moving forward, important factors in constructing a roadside environment that is truly easy to live in will include not only reducing the noise generated from vehicles, but also measures against roaring mufflers that lead to direct complaints, road surface countermeasures to complement those for tires to address the noise generated between the tires and the road surface, and the addition of a noise insulation system along the road. In Japan, as the Central Environment Council prepares to issue its fourth report, the Vehicle Stand-alone Noise Technical Committee and other groups are holding discussions on how to strengthen the regulations concerning replacement mufflers, tire stand-alone noise, and vehicle external noise.

Work by Russia on revising its in-vehicle noise regulations is being followed up by an equivalent review of the related international ISO-5128 standard, Measurement of noise inside vehicles. The current ISO-5128 was established in 1980 and no longer corresponds to current automobile usage. Consequently, updates the testing methods that reflect actual usage conditions are being proposed.

This has led to investigations and analyses of actual conditions inside the vehicle during on-road driving, including the driving time, to identify frequent driving patterns and incorporate them into the testing method. At the same time, the cumulative level of noise exposure experienced by the occupants through those patterns is being calculated through vehicle interior noise simulations to assess noise levels that do not result in adverse health effects.

In Japan, Europe, North America, and elsewhere, progress made in improving vehicle quietness both inside and outside the vehicle has also brought to light the issue of pedestrians failing to notice an approaching vehicle, especially in the case of EVs and HEVs running on electric power alone. Consequently, the Working Party on Noise (GRB) and others held discussions on audible warnings to safely inform pedestrians the vehicle's approach, and UN regulation (R138) concerning these acoustic vehicle alerting systems (AVAS) has been enacted. It is expected to be introduced (harmonized with existing standards) in Japan in 2018 and in Europe in 2019.

Among its provisions, the R138 regulation stipulates that the audible warnings must be sufficiently loud to be perceived by pedestrians, must be emitted at two or more frequency bands to ensure they do not go unnoticed, and should change to make the acceleration or deceleration of the vehicle easy to understand. In addition, a revision prohibiting the inclusion of a pause switch for the audible warnings was added to avoid the risk of an accidental failure to emit the alert.

In the United States AVAS are regulated by FMVSS 141, which is different from R-138. Compared to R138, the FMVSS 141 standard stipulates that manufacturers can choose whether the alert is emitted at two of four frequency bands, imposes a larger vehicle speed range over which the warning must be emitted, and sets a louder sound volume. Consequently, it has now become crucially important to develop tones for this alert that will be acceptable not only to occupants, but also to citizens living along the roadways.

The concept of creating a regulation similar to that for AVAS for back-up alarms to cover blind spots that the driver cannot fully confirm as safe while the vehicle moves in reverse has been brought up. This issue is being examined in UN GRB meetings.

3 Noise and Vibration of Vehicle Components

3.1. Powertrains

In internal combustion engines, friction and weight are being reduced to improve fuel economy, and at the same time very fine improvements to prevent the worsening of vibration and noise are continuously being made. For example, the stiffness balance between the upper and lower portions of the piston skirt were examined to determine how it affected the piston striking sound referred to as slap noise. This indicated the importance of setting the stiffness in the skirt longitudinal direction during the process of determining the skirt shape(2). The

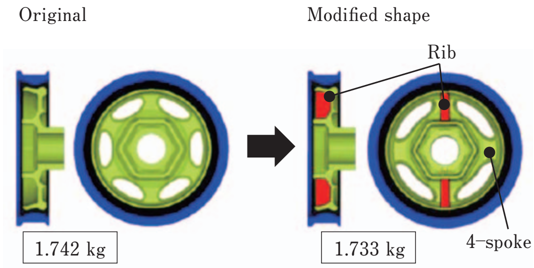


Fig. 2 Pulley Shape to Reduce Bending Vibration of Crankshaft[3]

diameter of the crankshaft was narrowed to reduce weight, but this in turn decreased bending stiffness, leading to an increase in engine vibration. A case where this was addressed by focusing on the coupled bending vibration of the crankshaft and crank pulley and changing the shape of the pulley to reduce crankshaft vibration without increasing mass has been reported (Fig. 2)[3]. Investigations such as these widely rely on using CAE analysis to ascertain behavior and on CAE-based optimization methods.

Cases where the efficiency of both gasoline and diesel engines was increased by reducing their size and equipping them with Turbocharger/Supercharger are increasingly numerous. Consequently, research on analytical techniques related to vibration and noise phenomena peculiar to Turbocharger/Supercharger is progressing. One reported case examined methods to reduce the friction of the bearings by combining the FEM calculation of the oil film of the fluid bearings with a mechanical analysis of an elastic body model of the rotational behavior of the rotor shaft of the turbocharger[4]. The results are proving useful in studies to reduce the whirl noise of turbochargers.

Start-stop systems are an increasingly common fuel-efficient technology, and technologies such as active engine mounts have been reported to reduce engine re-start vibrations in those systems as well as in HEVs. However, there are ongoing investigations to find a lower cost countermeasure, and engine control parameter optimizations along the lines of increasing the rotation speed of the starter or changing the compression ratio and amount of ignition retardation have been reported to reduce engine vibrations[5].

For diesel engines, research into Homogeneous Charge Compression Ignition (HCCI) as a means of simultaneously reducing NO_x and smoke emissions is being conducted. Also, methods to reduce the combustion noise caused by sudden combustion during high load operation continue to be studied[6].

Analysis methods that combine electromagnetic field simulations and structural simulations have been applied to address the high frequency electromagnetic noise produced by the electric motors used in EVs and HEVs. In one case, a two-dimensional electromagnetic field analysis taking the electromagnetic excitation force in the radial and tangential directions of the motor into account was expanded to focus on the vibration mode in the axial direction of the stator core in a three-dimensional electromagnetic field whose amplitude and phase change in the axial direction. Applying mode control to this situation was found to reduce motor noise[7].

In the drivetrain, the torsional stiffness of the clutch damper is being reduced to compensate for measures such as lowering the lock-up speed of the torque converter even further to improve fuel economy. However, this has led to cases of problematic vibration phenomena involving complex mechanisms, such as judder caused by the self-excited vibration of the clutch and subharmonic oscillation induced by the nonlinear characteristics of the damper. Consequently, research to clarify these phenomena and develop countermeasures is now underway[8][9].

Efforts to reduce engine noise and otherwise improve the quietness of vehicles are accompanied by research to further reduce the gear noise. Unlike helical gear sets which consist of a single pair of gears, planetary gear sets, one of the shifting mechanisms in automatic transmissions (ATs) or continuously variable transmissions (CVTs), have multiple meshing points, which has made it difficult to predict their vibratory force. A method to predict the vibratory force was developed by combining the variable loads of the meshing points of each pinion gear in the circumferential, radial, and axial directions, while accounting for the meshing phase differences between the pinion gears. This was then combined with the vibration analysis of the transmission to predict the planetary gear noise level when gear specifications were changed with respect to the meshing phase (Fig. 3)[10]. In researching that method, an analysis that took into consideration the change in the vibratory force due to variation in the gear machining precision was also carried out. The results demonstrated that controlling the variation in precision during gear manufacturing is an important factor in terms of gear noise.

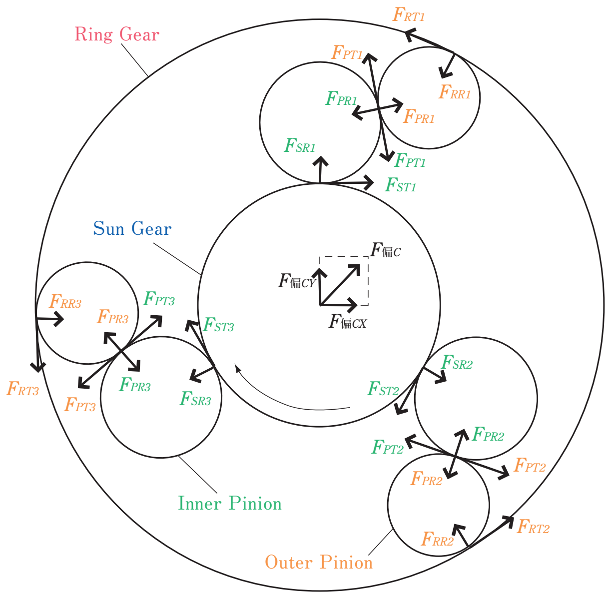


Fig. 3 Planetary Gear Load Vector Diagram[10]

Efforts are also being made to improve the prediction accuracy of engine mount vibration transmission in the medium frequency region where gear noise is a problem. Liquid-filled engine mounts use the resonance of their internal fluids to obtain a damping effect. To reproduce the dynamic behavior of the internal fluid at the frequency of interest, the dynamic pressure propagation of the fluid is expressed by an equilibrium equation of the pressure and the flow velocity. A modeling method in which the viscous force in the shear direction when a fluid passes through an orifice is expressed as a spring element has been introduced[11]. This method allows a reproduction of the storage spring and loss spring of the liquid-filled engine mounts accurate to approximately 1 kHz. Further progress in vibration isolation technology that covers the range from low- to high frequency is expected in the near future.

3. 2. Tires and the Suspension System

The recent rise in HEV and EV popularity has been leading to decreased noise from vehicle powertrains. However, this means that an increasingly large proportion of vehicle noise is being generated by road surface inputs, making it more important than ever to reduce such road noise. As regulations concerning the exterior noise of vehicles become stricter, reducing the amount of tire noise even further is becoming essential. Consequently, research is being actively pursued to clarify the mechanisms behind the noise radiated by tires, as well as to develop noise prediction technologies.

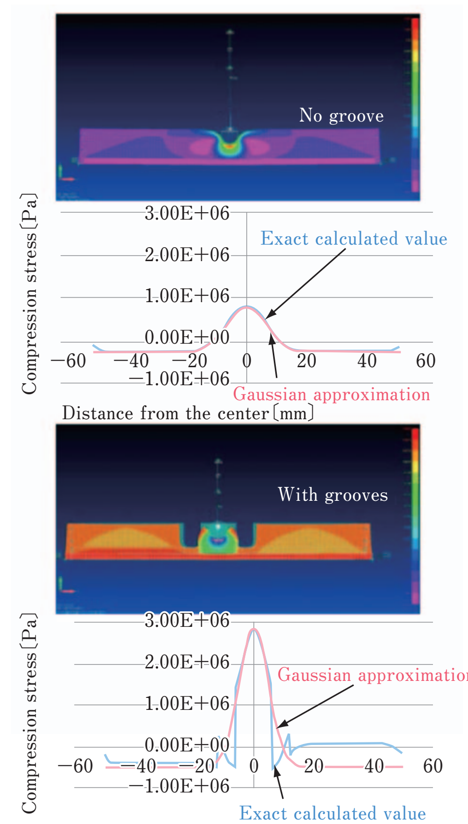


Fig. 4 Example of Estimating Tire Road Contact Surface Load[12]

In an effort to better define the dynamic behavior of tires, one reported case used a laser displacement meter to measure the high frequency vibrations on the tire tread as the tire radiated noise due to the impact inputs it received as it rolled over an uneven road surface, and then compared these measurements with the results of a FEM analysis[12]. The shape of the inputs at the time of impact can be approximated with a simple Gaussian function (Fig. 4). A better understanding of this phenomenon can be gained by clarifying how these inputs are transmitted as vibrations to the other portions of the tread surface, where the noise is generated. This is expected to lead to the development of even lower noise tires.

Beyond addressing vibration and noise issues, the suspension system is also required to provide high levels of steering stability and ride comfort. Reproducing the dynamic characteristics of the bushings used as coupling parts very precisely is critical in dynamic performance analyses of those characteristics. A bushing model with a small calculation load is also desirable when it is applied to a full vehicle model. One reported approach involved constructing a bushing model with a low degree of freedom that simultaneously for dynamic characteristics such as the amplitude dependence and frequency dependence of the bushing, as well as the anisotropy of the changes in stiffness[13].

Brake noise remains subject to a great deal of research and analysis. It has been shown that brake noise is generated when there is dynamic instability of the vibration system of the entire brake. Consequently, complex eigenvalue analysis via CAE has become widely used in the process of brake development. To carry this out further upstream in the design process, the brake system is expressed with a simplified functional model, and then the influence of design parameters such as the coefficient of friction, brake pad contact pressure, and contact position, on brake noise are examined[14].

3. 3. Vehicle Body and Interior Materials

As the demands for more fuel efficient and environmentally-friendly vehicles continue to grow, the demand for lighter weight automobile bodies and interior materials is also increasing commensurately. Development methods that can efficiently and rapidly examine means of achieving both good noise and vibration performance are required, making experimental technologies for automobile bodies and CAE technologies increasingly important.

Highly precise predictions of vibration and noise using large scale models have become possible as the computing power has improved. However, performance is known to vary due to individual differences that arise in the tolerance of parts included in the manufacturing process, and efforts to take this into consideration in predicting performance have been made[15][16]. The efforts assert that an automobile body hardly affected by the uncertain characteristics of parts was designed by applying a CAE-based large-scale Design of experiments (DOE), constructing a probabilistic prediction model from that data, and searching for a combination of design variables that reduces the error factor.

The statistical energy analysis (SEA) method, as well as the hybrid SEA method used in conjunction with other analyses and experiments, are now used to analyze the middle to high frequency range of noise. These methods have been widely applied to examinations of the proper placement of sound-insulating materials during product development. Studies of additional new methods have also been conducted. Dynamic energy analysis (DEA) is a method of analyzing the vibration energy that spreads through a structure using a finite element (FE) mesh. Position information is taken into consideration when the energy spreads, enabling the visualization of the energy flow. This method was applied to the floor vibrations of the cabin of a farm vehicle in an attempt to suppress the spread of the vibration energy (Fig. 5)[17]. Conducting vibration analyses focused on the energy flow, especially in frequency regions with a high mode density, is expected to become even more important.

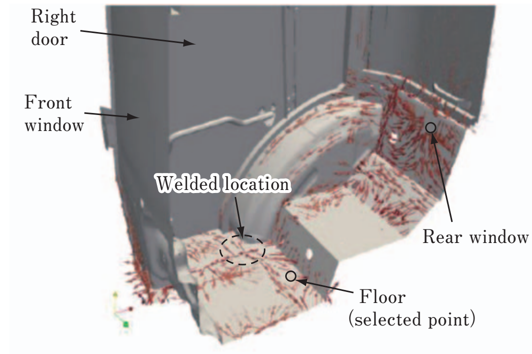


Fig. 5 Vibration Intensity Analysis Using DEA[17]

Until now the boundary element method (BEM) has been widely used to analyze acoustic radiation toward an external sound field. However, using an external sound field where the acoustic space around the vehicle body and the engine compartment was modeled with the finite element method (FEM), and applying coupled calculations for the structure and sound field, was reported to enhance the prediction accuracy of the sound pressure inside and outside the vehicle interior in cases involving a semi-open space like the engine compartment where a standing wave can be excited and the vibration of the structure greatly affects the sound field[18].

Progress is being made on finalizing a prediction method that combines computational fluid dynamics (CFD) with the SEA vibration noise analysis aimed at examining aerodynamic noise during high-speed driving. A wavenumber filtering is used to separate the sources of aerodynamic noise into the pressure fluctuation due to convection component and the sound wave component, but developing an identification method is proving difficult. A different method that defines these components as a single "force" without separating them, and then simply and quantitatively separates the phenomenon into input and transmission response systems, has also been reported[19].

Research on tangible methods of reducing the weight

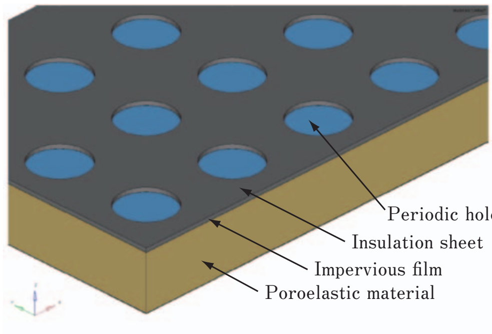


Fig. 6 Composition of Soundproofing Material with Improved Sound Insulation in the Medium Frequency Range[21]

of interior materials is also making progress. Based on the double wall acoustic theory, attempts to improve soundproofing in laminated panel structures consisting of a body panel and interior trim have involved increasing the thickness of the intermediate layer or increasing the material density to increase the airflow resistance of the intermediate layer. However, these changes ran counter constraining the layout and reducing weight. To address this, it has been reported that optimizing the airflow resistance of the internal material by focusing on the distribution of the acoustic particle velocities in each portion of the plane inside the structure can achieve further weight reduction and better sound insulation[20].

In addition, a new soundproofing material was proposed (Fig. 6)[21]. Periodically opening holes in a portion of conventional sound insulation soundproofing material was found to change the phase of the sound radiated from the surface of that material. This in turn canceled the radiated sound locally and improved sound insulation performance. In the context of limiting constraints, further research is expected to continue examining not only the layered structure of the material's composition viewed in cross section, but also attempt to improve the performance of the soundproofing material through spatial means.

4 Sound Quality

Active sound design systems, which apply active noise cancellation technology in an effort to improve sound quality by generating sound synchronized with the engine speed from the audio speakers, have become more prevalent. These systems offer a wide range of applications, including substituting the sound of an internal combustion engine in an EV or HEV or even allowing the driver of a regular internal combustion engine vehicle to obtain a sporty engine sound by selecting a driving mode. These systems use the existing in-vehicle audio systems and speakers to realize these functions at a relatively low cost. Furthermore, recent restrictions imposed by external vehicle noise regulations have limited the hardware options, typified by the air intake system and exhaust system, available for sound presentation. Therefore, sound production using electric signals is expected to expand further in the future.

In addition, attempts to apply stereophonic techniques and utilize auditory localization within the vehicle cabin are being actively pursued. The concept of a sound partition that would perform multi-domain sound field control using multiple speakers has been proposed[22]. This involves realizing individually controlled sound environments for multiple occupants in the driver's seat, front passenger seat, rear seats, or other area of the vehicle cabin. Eventually, vehicles might offer a moving space in which the driver enjoys a comforting engine sound, while the front passenger enjoys the comfort of a more quiet space, and the passengers in the rear seats enjoy watching a movie at high volume. These possibilities will undoubtedly be the object of further research.

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