Vibration, Noise and Ride Quality

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1 Introduction

The adoption of measures to help address environmental issues such as global warming and to reduce pollutants such as fine particulate matter smaller than 2.5 micrometers are some of the major challenges facing automotive engineers today. In addition, customers are calling for even more energy-efficient vehicles as crude oil prices have increased over the last year and fuel prices in Japan have risen due to the underlying depreciation of the yen.

At the same time, various developments are occurring in the field of vibration, noise, and ride quality (NVH). In Japan, there are plans to apply a new test method and regulatory values in the near future for road traffic noise to evaluate noise under more realistic urban driving conditions. Work is also continuing toward the establishment of uniform international standards for proximity warning sounds for hybrid electric vehicles (HEVs) and electric vehicles (EVs). The improvement of energy efficiency is an important goal in the power plant field to help reduce fuel consumption. However, many of these measures have a trade-off relationship with noise and vibration (NV). For example, various combustion devices and controls worsen NV in medium and high frequencies, and reducing or deactivating cylinders as part of the trend for engine downsizing facilitates low frequency vibration and increases vibration amplitude. Idling stop mechanisms are also becoming more widely available, which means that engineers have to consider product appeal in terms of performance on engine restart. In the transmission field, increases in the number of shift speeds and widening shift ratios are leading to the greater application of lock-up controls and lower engine speeds, thereby increasing both the amount of time that the engine runs at low speeds and the transmission of torque fluctuations. Recent reports have detailed measures to address these issues through engine mounts and the drive system. Furthermore, as engineers look for substantial weight savings in the body, reports have described efficient and fast methods of studying weight reduction methods while satisfying NVH performance requirements. With respect to road noise, efforts to reduce tire rolling resistance, weight, and the like have confirmed that tires have a major effect on vibration. At the same time, several case studies have been published that describe developments to enhance the added value of vehicles through sounds heard in the interior. In the sound quality engineering field, most of these developments relate to isolating the sound of acceleration to express the sensation of acceleration to the vehicle user. However, some also describe the steady popularization of devices that emit sounds from the audio system speakers synchronized with the engine speed.

2 Road Traffic Noise

Standards for individual vehicle noise, as typified by ISO 362, started to be introduced in the 1970s with the aims of preserving and reducing road traffic noise. Since then, the standards have grown steadily more stringent, resulting in an approximate 84% reduction in the acoustic energy emitted from passenger cars. Despite these efforts, however, environmental noise has not substantially improved [(1)].

For this reason, the Working Party on Noise (GRB) was started up in 2003 as part of the World Forum for Harmonization of Vehicle Regulations (WP 29) under the institutional framework of the United Nations Economic Commission for Europe (UNECE). GRB is studying ways of evaluating noise under more realistic urban driving conditions. Discussions regarding a test method for four-wheeled vehicles are almost complete and the group started discussing regulatory values with deliberation scheduled for 2013. WP 29 approved revisions to the test method and regulatory values for motorcycles in June 2012 and these will be adopted in Japan from January 2014.

In Japan, the Central Environmental Council was established as a consultative body of the Ministry of the Environment. Under this council, a vehicle noise committee began a fundamental review of test methods and regulatory values in June 2005. In April 2012, the committee adopted the UNECE regulations on the rolling sound emissions of tires (R117-02) and international standards for motorcycle noise (R41-04). In addition, the committee issued a second report outlining the replacement of current acceleration and steady-state driving noise regulations. Based on this report, the decision to adopt the motorcycle regulations (R41-04) in January 2014 was officially announced in January 2013. The adoption of independent tire regulations and four-wheeled vehicle standards (R51-03) remains under discussion pending reports from WP 29/GRB [2].

At the same time, recent discussions have also begun to focus more strongly on pedestrian awareness of silent vehicles such as HEVs. Visually impaired groups and other road users have expressed the opinion that hybrids and other vehicles that are powered by motors alone at low speeds are dangerous because these vehicles are too quiet. In response, the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) announced the world's first guidelines relating to HEVs and other silent vehicles. The National Federation of the Blind (NFB) in the U.S. also raised the same issue with WP 29/GRB, prompting the establishment of an informal working group under the umbrella of GRB in February 2010 and the start of global studies.

In the U.S., the President signed into law the Pedestrian Safety Enhancement Act in January 2011. The issue of warning noises for silent vehicles is now an urgent issue since the rules for vehicle noise under this Act are scheduled to go into effect in 2014. Consequently, Japan and the EU have set up a joint informal working group to discuss measures for silent vehicles with the aim of establishing uniform international standards. This working group is studying methods of emitting noises from vehicles and the appropriate noise levels and the like for alerting pedestrians while preserving the road noise environment. This group aims to make a proposal to WP29 in November 2014 [3].

3 Noise and Vibration of Vehicle Components

3.1. Powertrain

The key challenge in the powertrain field is developing energy-saving technology. Reflecting this trend, in addition to noise-reduction technologies for more fuel-efficient gasoline and diesel engines, a large number of reports have been published describing technology to reduce the particular NV phenomena of vehicles with electric powertrains, such as EVs and HEVs.

Reports covering gasoline engines have described solutions for the particular NV issues of engines incorporating technologies to improve fuel efficiency, such as cylinder deactivation [4–6] and idling stop [7–9]. Papers have also described ongoing analysis of detailed NV phenomena over a wide range of subjects related to combustion [10], pistons [11], and the intake of air [12][13]. This reflects the increasing complex nature of engine NV, which is caused by combinations of phenomena related to interactions between a growing number of related parts and conditions. Technology to address these NV phenomena includes new analysis methods focusing on time series waveforms [14][15].

A particular feature of recent research is the prevalence of reports about CAE analysis and cases of optimized research using CAE. In the same way as the reports analyzing NV mechanisms listed above, the topics of papers about CAE and optimized research are extremely varied. Examples include the overall stiffness of the power plant [16], piston noise [17][18], and intake and exhaust system noise [19–21].

This research is not just concerned with simply reducing engine noise. Fig. 1 shows some typical sound devices that have been developed to actively create sounds that emphasize particular frequency components to enhance the product appeal of new engines [22][23].

One complex challenge for diesel engines is simultaneously improving fuel efficiency, emissions, and combustion noise. Reports describing methods to help achieve this aim include papers about verifying the effectiveness of a boot-shaped fuel injection mode using direct acting piezo injectors [24] and multi-purpose automatic optimization using combustion simulations [25]. Reports of technology for simplifying the enhancement of combustion sound quality include new analysis methods such as sound quality matrix mapping using impulsiveness al-

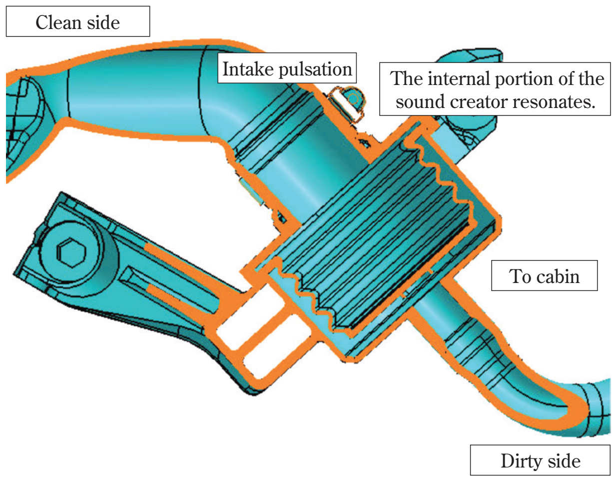

Fig. 1 Sound creator [22].

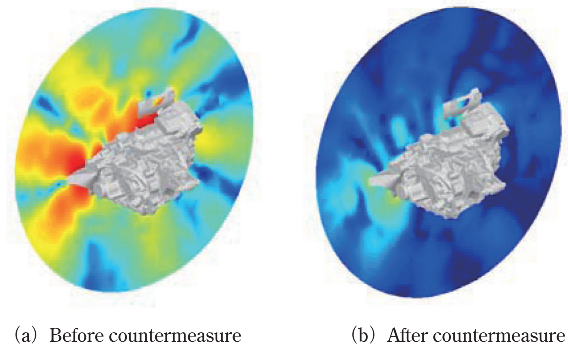

Fig. 2 Radiation noise analysis results at rotor torsional mode[30].

gorithms [26] and the identification of noise sources using cepstrum analysis [27].

In the field of electric powertrains, one published report addressed engine start vibration, which is a particular issue for HEVs. The reported method is capable of predicting changes in vibration on engine start based on changes in the control method and control values by incorporating a hybrid system control model into a full-vehicle mechanism analysis simulation that includes various non-linear elements [28].

Other reports examined the mechanism of high-frequency electromagnetic noise generated by the motors used in HEVs and EVs and described potentially effective countermeasures. One case focused on the attachment tolerance of rotor permanent magnets [29] and another focused on high frequency modes as shown in Fig. 2 [30]. To facilitate studies into these countermeasures, other reports described research into technology for predicting motor noise that couples electromagnetic and structural analysis simulations [30]–[32].

As described above, NV phenomena created by powertrains are becoming more complex as powertrains diversify. This is likely to continue in the future and the development of analytical technology for identifying these complex phenomena and increasing the efficiency of research into countermeasures will remain a critical engineering challenge.

3. 2. Mounting and drive systems

As a measure for improving fuel efficiency, turbochargers are being adopted to reduce the number of cylinders from six to four, and from four to three. Vehicles with two-cylinder engines have also been launched. The expansion of transmission ratio ranges has also reduced engine speeds and increased high-load operation.

As a result, there is a greater need for engine mounts with greater low-frequency vibration isolation performance. One challenge in developing such mounts is improving the engine vibration isolation performance of the mounts while maintaining support stiffness for driving reaction force. To help resolve this issue, one report described the development of active engine mounts and torque rods [33], demonstrating advances in active engine mount technology.

Research in the drive system field is examining ways of further reducing CVT belt noise and the like as vehicles become more silent due to efforts to reduce engine, road, and wind noise. Design requirements have been identified for belt alignment to simultaneously reduce the sound pressure of belt noise and resolve sensations of fluctuation, particularly under conditions with low background noise, such as gradual acceleration with an accelerator opening angle of 20% or less, braking, and the like. First, based on frequency characteristics, such as the frequency modulation of vibratory forces and the vibration transmission sensitivity of the transmission, research has identified the generation mechanism for fluctuation sounds (i.e., sound pressures with an amplitude modulation characteristic). As a result, technology has been developed to resolve sensations of fluctuation and lower sound pressure through a split structure that controls modulating frequencies and a combination of three types of elements that give the vibratory force order spectrum a trapezoid shape [34].

Another report describes studies into the automatic optimization of gear noise characteristics using the finite element method (FEM). As factor contributing to gear noise, meshing force causes vibration due to transmission error. This report identified the peak meshing force by modeling the gears, including the transmission case. Combining fluid and structural simulations using FEM with topometry optimization, this method achieves automatic optimization using acoustic power as a design target [35].

In addition to CVTs, the ratio range of automatic transmissions (ATs) is continuing to expand, a phenomenon that also includes increases in the number of shift speeds. One such example is the report of a nine-speed AT [36]. In the case of both CVTs and multi-speed ATs, an urgent task is the development of countermeasures for low-frequency NV that occurs at low-speed high-load engine operation in fuel economy test cycles. Many cases of research have been published related to countermeasures affecting the drive system. Research using multibody dynamics (MBD) has become common in recent years, and reported examples include the use of mechanism simulations to study drive system specifications under inputs caused by fuel-efficient driving. Although many reports describe lock-up dampers, dual mass dampers have also started to enter common use. One report describing the optimization of vibration dampers underlined the importance of the damper temperature characteristics and material selection [37]. Research into pendulum dampers is also advancing, including a study that incorporated these dampers at the initial phase of MBD analysis [38]. Drive system inputs are likely to continue increasing as fuel efficiency improves further, which will lead to more research into drive system technology capable of improving both fuel efficiency and NV.

3. 3. Suspension and tires

An ongoing challenge for suspension design is achieving targets for ride quality and road noise while ensuring stability and controllability. Consequently, this has required the construction of highly accurate CAE models and test environments. One particularly important research topic is simulating suspension behavior in actual use and various reports have been published about this subject.

Related to tires, recent substantial improvements in rolling resistance and the effects of tire weight reduction and the like have increased the importance of tire vibration as a factor affecting noise in the occupant compartment. Tire characteristics differ greatly depending on whether the tire is in contact with the ground, and whether it is moving or stationary. Identifying the vibration characteristics of tires when the vehicle is in use is particularly important. One reported case of vibration characteristic analysis in grounded and non-grounded states described how the natural frequency of the tire increases when in contact with the ground, causing the vibration mode shape to change [39].

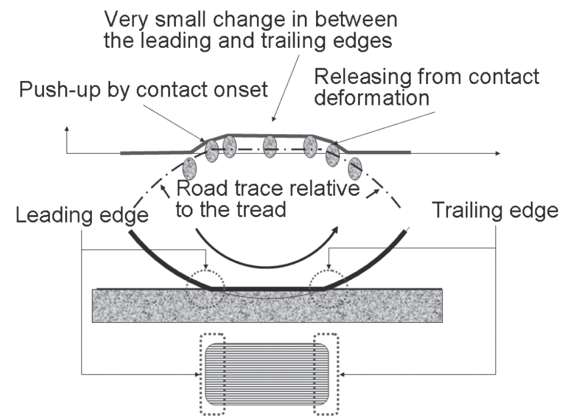

Fig. 3 Principles of torque, thrust, and chain tension measurement using shear strains on a disc [40].

Inputs from the road surface to tires when the vehicle is in use have been analyzed from experimental and theoretical standpoints in research to improve the accuracy of conventional knowledge (Fig. 3) [40].

Technology for predicting road noise performance is indispensable for research into the dynamic characteristics of tires in actual use. Efforts to develop and enhance this technology are likely to continue in the future.

Research into the dynamic characteristics of suspensions in actual driving conditions includes the creation of an experimental model from measurement data obtained using wheel attitude sensors and six-component force gauges capable of sampling at 100 Hz. The report into this research demonstrated that the non-linear characteristics of dampers have a major effect on the simulation accuracy of models [41].

Another report examined the relatively rare topic of bench evaluation technology for ride quality using three-direction road surface inputs of 30 Hz or more. A vibration generator acceleration input waveform was formulated to simulate unsprung acceleration during driving. The vibration mode of the vehicle passing over joints with a height difference was confirmed in bench tests to identify the vibration modes of the rear suspension members and body. After changing the actual insulator characteristics of the rear suspension members, both

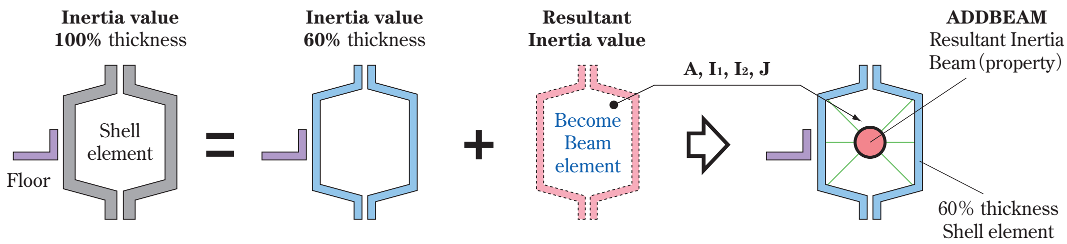

Fig. 4 Small degree-of-freedom model using beam elements [44].

driving tests and bench tests verified the reduction in floor vibration, thereby confirming the effectiveness of tests using a vibration generator [42]. As HEVs and EVs enter the mainstream of the market, vibration generated by powertrain inputs will decrease. One probable side-effect of this trend will be to increase the relative impact of vibration caused by road surface inputs on overall vehicle comfort. Consequently, research into this kind of vehicle vibration is likely to increase.

As an example of research describing the development of a mass-produced vehicle, a report detailed the suspension system in a new front-engine rear-wheel drive (FR) sports car. The location of the front suspension coil springs was changed from above the tires to the side, helping to lower the center of gravity. Hard bushings were adopted in the rear suspension to lower the spring constant of the coil springs, thereby improving ride quality as well as stability and controllability [43].

3. 4. Body and interior materials

Reducing the weight of the body is an important way of improving both fuel efficiency and environmental friendliness. Consequently, it is important to adopt efficient and fast methods for studying how to reduce weight while ensuring NVH performance. One effective means of accomplishing this with a small degree-of-freedom (DOF) model that expresses a shell body using beam and shell elements (Fig. 4). Research has examined the adoption of this method at the initial development stage [44]. In a conventional shell model, calculations are optimized using a genetic algorithm (GA), which causes massive increases in calculation time. However, the small DOF model means that a GA can be adopted without an excessive increase in calculation speed, enabling weight to be reduced while ensuring NVH performance.

One report about highly accurate predictions of NVH performance describes research into improving the accuracy of CAE models assuming prototype-less development relying on CAE. This report focuses on the major impact of acoustic model accuracy on the prediction accuracy of sound levels within the occupant compartment, particularly the effects of slight gaps in interior materials on calculation results [45]. Another report described the development of elements for acoustic gaps to enable the modeling of these slight spaces in air paths [46]. The accuracy of the created acoustic model can only be verified by properly identifying the acoustic modes from experiment results. Consequently, reports have been published describing research that applies a maximum-likelihood approach using the non-linear least squares method [47] and research that applies multi-point variation [48].

Acoustic research in higher frequency regions has been reported using statistical energy analysis (SEA). These reports described the validity of a model for sound insulation specifications with complex structures (two or more layers) [49] and model accuracy improvement by application to an EV [50].

Other research has examined the effects of vibration on the human body. These include vibratory analysis of human body and seat systems [51] and subjective evaluations of human discomfort due to seat vibrations [52]. Since prototype-less development also involves the judgment of performance related to human sensitivity based only on CAE results, it is likely that research into such subjective evaluations will become more important in the future.

4 Sound and Sound Quality Evaluation

Each automaker is continuing sound development to improve the added value of vehicles through sounds heard in the interior. Proposed sound development cases include conventional approaches for reducing discomforting noise under various driving conditions and for emphasizing dynamic performance by isolating order sounds in tune with the engine speed when accelerating in accordance with the vehicle concept [5][22][53]. However, in recent years, mass-produced systems have also been introduced that emit sounds from the audio system speakers synchronized with the engine speed obtained via vehicle electronic control signals. Research has been published that makes greater use of these methods to propose new types of sounds for motor-powered EVs [54)-(56].

Due to the complex auditory characteristics of humans and the wide range of subjective values, it is still difficult to apply sound quality evaluation technology to unambiguously assess the quality of sounds. However, objective evaluation methods are being adopted based on subjective sound audition evaluations, psychoacoustic indices, and so on. Reported objective evaluation methods include one that uses a new calculation algorithm for roughness, which is a known psychoacoustic index [57], and one that proposes an index for quietness calculated using an algorithm that reflects human auditory characteristics [58]. These objective sound quality evaluation technologies should be effective ways of improving vehicle development efficiency but are still only at the research stage.

The market share of EVs and predominately motor-driven HEVs is predicted to increase in the future. Since many people are unaccustomed to hearing motor noise, clear definitions of motor sound quality have yet to be laid out. Therefore, it is likely that automakers will put greater efforts into exploratory research into sounds that add value to the vehicle, objective evaluation indices for these sounds, as well as sound-generation software and hardware.

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