Vibration, Noise and Ride Quality

1 Introduction

Environmental issues such as abnormal weather around the world due to global warming and pollutants such as fine particulate matter smaller than 2.5 micrometers are growing more and more serious. Furthermore, in Japan, customers are calling for even more energy-efficient vehicles as fuel prices increase due to the escalating cost of crude oil, the depreciating yen, and the higher consumption tax. At the same time, countermeasures against noise, vibration, and harshness (NVH) remain a critical part of automotive engineering.

In Japan, recent developments in the field of road traffic noise include the publication of the second report from the Central Environmental Council, which announced the decision to adopt regulations determined by the United Nations Economic Commission for Europe (UNECE) with regard to motorcycle noise (R41-04) and the rolling sound emissions of tires (R117-02).

Outside Japan, the standard for four-wheeled vehicles (R51-03) remains under discussion, with standard values and implementation periods likely to be decided in the middle of 2014. The U.S. is still making steady progress in studying regulations for proximity warning device installation.

In the powertrain field, various systems have been proposed and practically adopted. In particular, as electric vehicles (EVs) and hybrid electric vehicles (HEVs) become more widespread, more research has focused on unpleasant noise generated by motors and other components. Several reports were published about combined electromagnetic and structural analysis methods. In addition, since more internal combustion engine (ICE) powertrains are adopting idling stop systems as well as HEVs, a growing number of reports described research into reducing vibration when the engine is stopped.

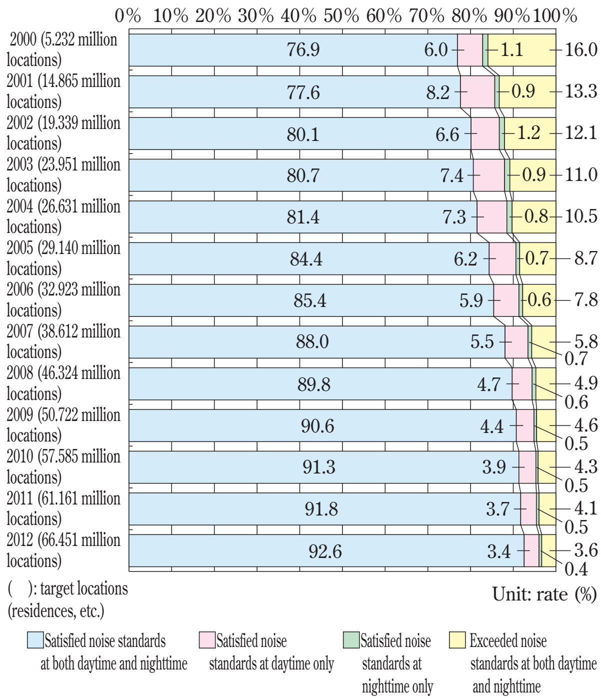
In the materials field, composite materials such as carbon fiber reinforced plastics (CFRPs), which have a greater specific strength and specific stiffness than metal are becoming more widespread. The number of reports describing analytical research related to these materials is also likely to increase in the future.

Vehicle sound expression is also an important part of automotive engineering. A system has been proposed that adds sound through the speakers using an active noise cancellation system. This system can also be used to express sound in an HEV or EV. In addition, a quantitative sound quality evaluation case study was reported that used physiological data obtained by neuromagnetic field measurement. This has potential application in various aspects of sound design.

2 Road Traffic Noise

Japan implemented its first noise regulations in 1951 against steady-state driving noise and exhaust noise. Since then, acceleration noise regulations have also been introduced and the standards described in the regulations have grown more stringent. At the same time, various roadside countermeasures against noise have also been implemented. According to The Status of Motor Vehicle Traffic Noise during FY 2012, a report issued by the Japanese Ministry of the Environment, the standards for environmental noise were met at 92.6% of locations tested at both daytime and nighttime (Fig. 1). This figure has improved by at least 12% over the last ten years. However, further noise reduction countermeasures are still required along main roads in some regions.

In 2012, the Central Environmental Council published a report called The Future Measures to Reduce Noises from Individual Automobiles (2nd Report), which announced the decision to adopt UNECE regulations for motorcycle noise (R41-04) starting from January 1, 2014. The same report also announced the decision to adopt the regulations for the rolling sound emissions of tires



Source: The Status of Motor Vehicle Traffic Noise during FY 2012, Ministry of the Environment homepage (http://www.env.go.jp/air/car/noise/noise_h24.pdf)

Fig. 1 Noise standard compliance status in Japan (nationwide, historical trend).

(R117-02). The adoption of an acceleration noise test method for four-wheeled vehicles (R51-03) remains under consideration. Outside Japan, R51-03 is being examined by UNECE/WP 29 GRB, i.e., the UNECE Working Party on Noise (GRB) as part of the World Forum for Harmonization of Vehicle Regulations (WP 29). At the earliest, standard values and implementation periods may be decided by the middle of 2014.

This regulation proposes changing the test method considering more realistic driving urban road conditions, and it also incorporates a gradual tightening of the standard values. Furthermore, the Additional Sound Emission Provisions (ASEP) will be introduced as a new test method to eliminate inappropriate increases in sound levels outside the test conditions. Another standard that has been adopted is ISO 10844-2011, which includes modifications to the specifications for road surface measurement, including a higher road surface roughness upper limit to reduce sound level differences due to different road surfaces.

In contrast to the strengthening of external noise regulations, some countries are studying regulations regarding the installation of proximity warning devices

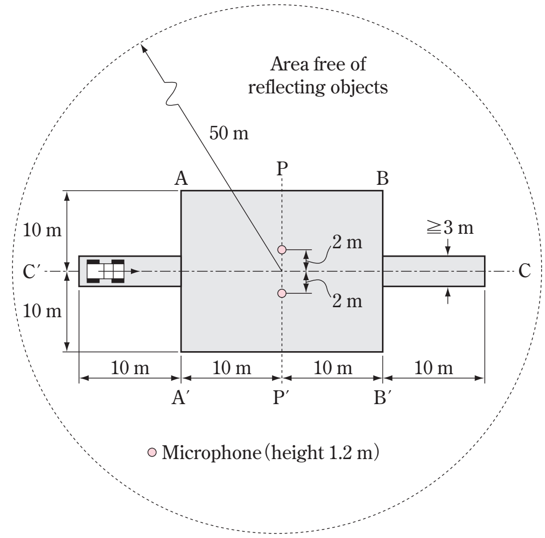


Fig. 2 Test site dimensions: the shaded area is the minimum area to be covered with a surface complying with ISO 10844.

to ensure the safety of pedestrians against HEVs and EVs driving silently at low speeds. The U.S. plans to introduce regulations by 2015, and research is examining the wavelength characteristics of the generated sounds toward establishing a Global Technical Regulation (GTR) (Fig. 2).

As a new method of evaluating vehicle noise, Europe is leading efforts to study the compatibility between indoor and outdoor testing of road vehicles (ISO 16255). This standard aims to establish a certification test method that is unaffected by the effects of weather conditions. This standard is attracting attention since indoor testing may become a feasible option as a certification site.

In the proposed test method, a vehicle is driven on a chassis dynamometer in a semi-anechoic chamber. The vehicle noise is then measured using a microphone array provided parallel to the vehicle. This test method allows highly repeatable measurement that is less affected by ambient weather conditions and the measurement environment. However, it is difficult to use chassis dynamometer rollers to reproduce the tire noise characteristics generated on an external ISO road surface. Therefore, a method is being studied that adds tire noise measured in a separate external ISO road surface test. In addition, since the vehicle is not actually moving, it is possible to use various measurement instruments. Since analysis results obtained using these instruments may enable the design of optimum noise countermeasures, this standard has a wide range of advantages for vehicle development and its future application is highly antici-

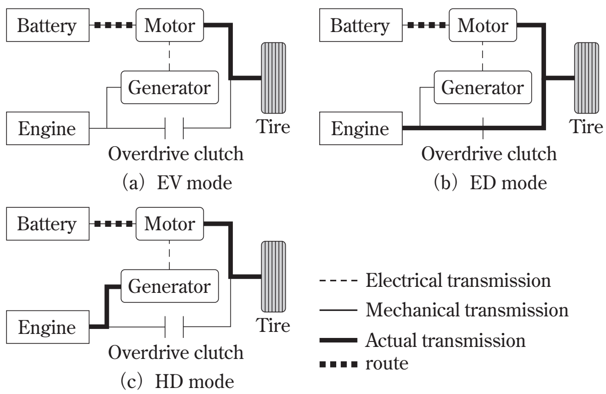


Fig. 3 Power transmission paths in each drive mode.

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3 Noise and Vibration of Vehicle Components

3. 1. Powertrain

A key trend in recent years is the rising demand for vehicles with a lower environmental load. Various powertrain systems have been proposed and adopted to help improve fuel efficiency, most typically motor-powered EVs and HEVs. As shown in Fig. 3, an HEV that combines a series-type HEV system with a conventional parallel-type HEV system has been practically adopted. Countermeasures against vibration in this system were described in a report that detailed the differences between conventional vibration transfer paths and the vibration transfer paths when this system is driven in series mode. The same report also described countermeasures for the mounting system and vehicle body to optimize the fuel efficiency of this system, as well as future issues.

Research is also making progress into range-extended electric vehicles (REEVs), which have a greater single-charge range than a conventional EV. Since REEVs are generally compared with EVs, noise-reduction is a very important development requirement. Research into systems that combine an ICE as an auxiliary power unit proposed the adoption of an inline 6-cylinder engine or horizontally opposed 2-cylinder engine as an effective means of reducing vibration noise.

It is well-known that the high-frequency motors used to power EVs and HEVs generate unpleasant noise. Several reports were published about the continuing development of combined electromagnetic and structural analysis methods. These analysis methods are likely to

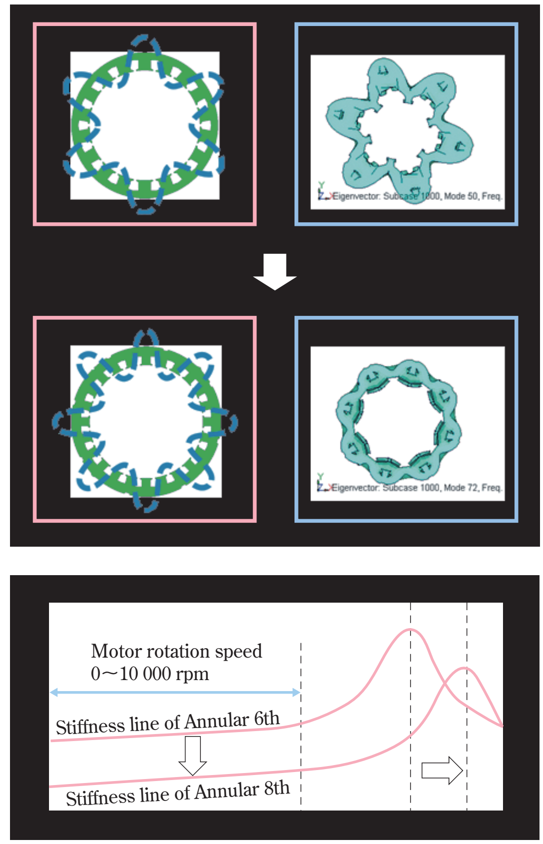

Fig. 4 Reducing vibration by increasing annular modes of electromagnetic excitation force.

become more precise with further development in the future. In a similar fashion, controlling vibration input modes as shown in Fig. 4 is an effective countermeasure against vibration. A key point is proposing countermeasures at the initial stage of development.

From the standpoint of systems using an ICE as a power source, following the trend of diesel engines, more downsized gasoline engines are being developed with a turbocharger that utilizes exhaust gases or a mechanically driven supercharger. Progress is being made in analyzing NVH phenomena in these engines. One report about reducing turbocharger-related noise described a simulation technique that combined the analysis of mechanisms, structures, and acoustics in response to the necessity of making improvements at the initial stage of development.

The development of systems aiming to reduce pumping loss, such as lean combustion and cylinder-deactivation, is also working to improve the NVH performance of the whole powertrain, including the drivetrain components.

In addition, the adoption of idling stop systems to help improve real-world fuel efficiency has spread to ICE powertrains as well as HEVs. The number of ICE powertrains with idling stop systems has increased dramatically and reports have been published describing studies to help reduce unpleasant vibration when the engine is stopped. For HEVs, one report described the reduction of excitation force by decreasing pumping pressure through retardation control of the intake valves on engine start. For ICEs, another report described the reduction of vibration levels by shortening the engine stop time, and the starting up of the engine in a short period of time by actively controlling the starter position by alternator generation and controlling the combustion timing when the engine is re-started.

Furthermore, each automaker in Japan has announced the launch of fuel cell vehicles (FCVs) around 2015 as another step toward the development of the ultimately environmentally friendly means of transportation. The number of reports describing new NVH phenomena in these vehicles is likely to increase in the future.

3. 2. Mounting and drive systems

Reports have described the application of model-based development to new transmissions and the simultaneous achievement of high levels of fuel efficiency, dynamic, and NVH performance. In NVH development, failure mode and effect analysis (FMEA) is used as a basis for identifying the parts, vibratory forces, and vibration phenomena related to NVH performance, which need to be designed at the initial stage of development. This type of analysis helps to visualize trade-off relationships and is carried out at the planning stage for system and part design related to NVH in consideration of the whole lineup. To help improve booming noise, transfer path analysis (TPA) is used to calculate the contribution ratios of vibration inputs. Torque fluctuations in accordance with these contribution ratios and vehicle-side sensitivity targets can then be set and measures taken to resolve issues. Gear noise mechanisms are identified through tests with respect to joints that cannot be modeled from geometrical information, boundary conditions, and material vibration characteristics. The results of these tests are then reflected in computer-aided engineering (CAE) simulation technology, which can be used to revise development processes and optimize system design. Consequently, this approach achieves targeted gear noise performance while reducing weight.

Wet clutches are frequently a source of transmission vibration. A report described the creation of a clutch finite element model (FEM) to predict the vibration behavior of a wet-type multiple-plate clutch. A plant model including the damping characteristics of the drivetrain was then adopted to develop a behavior analysis technique capable of simulating torque transmission characteristics when vibration occurs. This technique identified the mechanism that determines the torque transmission characteristics of the drivetrain, which allowed the qualitative prediction of self-excited vibration as well as the prediction of forced vibration affected by structural factors.

Another report focused on improving gear engagement noise, which is a more general NVH issue related to drivetrain vibration transfer. A drivetrain vibration transfer mechanism analysis model was created to study the correlation between gear engagement behavior and the first stage hysteresis torque of the clutch damper. The analysis results confirmed the existence of a hysteresis torque region that generates large gear engagement noise, even under hysteresis torque conditions in which small variations in angular velocity are transmitted to the driveshaft. This research also found that the waveform of the gear angular velocity, which depends on the attachment phenomenon of the clutch disc components, hysteresis torque, and drag torque, contributes to gear engagement noise.

Various means of improving vehicle fuel efficiency have been suggested, such as the replacement of gasoline engines with diesel engines and cylinder deactivation, which shuts off some of the cylinders under low load conditions, such as deceleration and steady-speed driving. However, these measures create disadvantageous conditions for NVH performance. Consequently, active engine mountings are being researched as a means of improving both NVH and fuel efficiency. Although adaptive controls are generally adopted to achieve these mounting systems, changing the filter coefficients of the controllers during acceleration and deceleration when the engine frequency changes is not sufficient to respond to variations in frequency. As a result, it is necessary to construct optimum controllers capable of responding to the frequency variations that occur. A report proposed model-matching control based on a characteristic transfer function matrix (CTFM) and confirmed the vibration damping performance of this method during idling and acceleration. Furthermore, combining model-matching control with conventional adaptive control enables a controller that generates fewer error signals in steady-state driving and that responds rapidly during acceleration and deceleration.

3. 3. Suspension and tires

As HEVs and EVs become more widespread, the number of driving scenarios with zero engine system noise is increasing. As a result, there is a rising need for countermeasures against road noise, which is becoming relatively more noticeable.

In addition to NVH performance, suspension development must also achieve a strong balance between ride comfort and stability and controllability. Several reports have described activities to achieve these performance aspects in actual vehicle development.

Progress is also being made in the development of basic technologies to improve the performance of each component in the suspension.

In addition to the performance aspects described above, tire development is facing increasing demands for lower rolling resistance and noise. A large number of reports have described the identification of phenomena and prediction techniques for dynamic behavior and radiation noise considering the effects of road surface contact and tire rotation. Research is likely to continue in the future into ways of achieving multiple requirements and improving performance.

Cavernous resonance is a type of road noise that is generated by the resonance of the air inside the tires. A report described the reduction of this noise by creating a disc wheel with a hollow rim, providing communicating passages for the air inside the tire, and using the hollow rim as a Helmholtz resonator. This also had the effect of reducing the weight of the wheel (Fig. 5).

Most previous research into shock absorbers has focused on ride comfort, handling, and stability. Although there has been little research into the NVH performance of shock absorbers, a report was published describing the creation of a numerical model capable of predicting the transfer force of piston rods as means of studying structure-borne noise up to high-frequency regions (700 Hz) in the case of a double-tube shock absorber.

Tire requirements are likely to become tougher in the future and research will probably continue into NVH reduction technologies from the twin standpoints of the overall suspension, including controls, and structural elements.

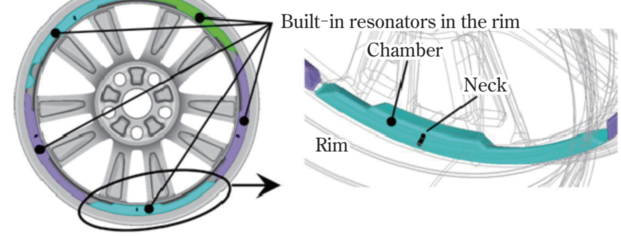

Fig. 5 Wheel structure with in-built resonators.

3. 4. Body and interior materials

Reducing the weight of the vehicle body continues to grow in importance as customers demand vehicles with improved fuel efficiency and environmental performance. Development techniques are required that can satisfy both NVH performance and weight reduction requirements efficiently and in a short period time. One proposed method for this is called running TPA, which analyzes the contribution of vibration and noise of components such as the engine and suspension from the source of the vibration to the response points, using only vibration in an actual operational state. Reports have described research in which the transfer functions obtained from the principal components regression method (i.e., principle component analysis + multiple regression analysis) carried out in the running TPA process were analyzed to identify the most effective components for reducing vibration, and research in which the frequency regions of the components requiring modification and the modification amounts were identified by processing the response point signals for each driving condition after implementing running TPA to achieve target response point signals and then re-calculating improved target transfer functions. With the aim of shortening the time required for TPA analysis, another report described a measurement case that demonstrated the feasibility of identification using an assembled vehicle without having to disassemble the connecting springs (bushings) from the vibration sources (engine and suspension) and body.

Another consequence of the increase in HEVs and EVs to help improve fuel efficiency is the need to improve both the characteristic high-frequency noise of motors and mechanical operation noise. However, since conventional acoustic materials for reducing vibration and for absorbing and insulating noise have the trade-off effect of increasing weight, development to improve mass effectiveness is gaining greater significance. Conventionally, design studies for highly mass-effective acoustic ma-

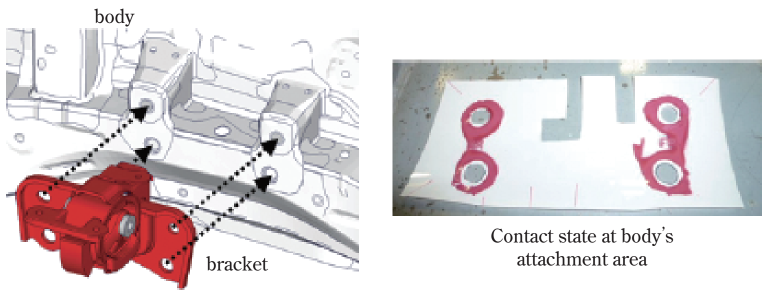

Fig. 6 Engine mounting bracket contact area.

terial specifications have used acoustic analysis based on hybrid statistical energy analysis (SEA), which combines tests and theory related to air-borne noise. In contrast, a report has described the analysis of mid- to high-frequency noise including structure-borne noise using a hybrid FEM/SEA technique. This report also verified the effectiveness of the developed method. The accuracy of the analysis was validated by comparing analysis and test results. In the presented research case, flat dash and floor panels were analyzed using SEA and other portions were modeled using FEM. There are high expectations for this method as an accurate analysis technique.

Background road and booming noises in the interior have decreased in accordance with the reduction in overall interior noise levels in recent years. As a result, sounds that were conventionally difficult to detect have become relatively more prominent, necessitating further countermeasures. Two examples are airflow noise and gear noise from the transmission, which are noticeable under localized conditions. Air flow noise is conventionally assessed by subjective evaluations. However, a report described a possible replacement method that simultaneously measures air flow noise using an external planar microphone array and an internal spherical microphone array. This method then used beam forming for correlation analysis and attempted to identify the sources of the air flow noise with the largest direct contribution ratios affecting prominent localized noises in the interior. This technique enables measures to improve interior comfort that include these prominent localized noises. Due to the high target frequencies, there have been few cases of research into gear noise using CAE to study the rubber used by engine mountings and body-side brackets. However, a technique has been reported that factors in the dynamic characteristics of engine mounting rubber. This technique predicts the surging of the mounting rubber and simulates the contact state of the transmission-

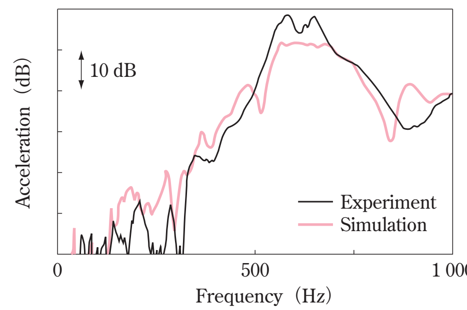

Fig. 7 Vibration characteristics between engine mounting brackets.

side and body-side bracket, thereby enabling prediction of vibration characteristics up to high-frequency regions with both brackets and engine mounting rubber in an attached state (Figs. 6 and 7). Another report described a method for optimizing engine mounting bracket shapes and the reduction of gear noise.

In the materials field, composite materials such as CFRPs, which have a greater specific strength and specific stiffness than metal, have been introduced. One report described how sound pressure is amplified by particular membrane vibration modes due to the anisotropic properties of CFRP that change depending on the fiber direction. In this research case, an analysis model was created using the physical properties of a laminated CFRP sheet. FEM-based eigenvalue analysis and boundary element method (BEM)-based radiation sound analysis were performed to propose a method of reducing the sound pressure through vibration mode analysis of the laminated CFRP sheet. These types of materials-related analysis are likely to become even more important in the future.

4 Sound and Sound Quality Evaluation

The development of vehicle sound is not just related to adding value to the interior sound. Sound is an expression of the brand image of each manufacturer and can be used to differentiate between different brands.

In general terms, conventional sound development has focused on the intake or the exhaust system. For example, development has mainly worked to create linear increases in sound pressure synchronized with the engine speed or, depending on the concept of the vehicle, to emphasize the order components of engine combustion to express a certain sound when accelerating. However, due to modern restrictions on exterior noise, there are limitations to expressing sounds through the intake or exhaust system. One proposal for resolving this issue is a system that adds sound through the audio speakers. This system uses the active noise cancellation system to express the desired sound by addition or subtraction of the desired elements. This technology can also be used to express sound in HEVs and EVs.

Acceleration sound is not the only expression of brand image. Other targets of sound design include door closing and locking sounds. Instead of a sensory-based subjective assessment of sound quality, this design approach adopts a sound quality evaluation using psychoacoustic indices, investigates sound preferences, and then creates the required sound. However, it is not easy to obtain stable evaluation results by subjective evaluations alone. In recent years, basic research has been conducted into objective sound quality evaluations using physiological data obtained by neuromagnetic field measurement. The establishment of sound quality evaluations based on neurophysiology has promising engineering applications related to various aspects of sound design.

Sound development and the creation of objective evaluation indices for sound will continue in the future. In addition to the development of hardware and software for expressing the designed sounds, it is likely that quantitative technologies using psychoacoustic indices such as loudness and sharpness will be proposed in the future alongside further research into sound quality measurement technologies.

5 Ride Comfort Related

Ride comfort is a critical element of dynamic quality. Every automaker is continuing to work on improving ride comfort performance to enhance vehicle appeal.

Recent years have seen an increase in user-oriented evaluations and analysis. With respect to the low-frequency (1 to 2 Hz) sprung behavior of the vehicle, ride comfort development is not simply focusing on the vehicle motion. This behavior also affects the motion of the head and eye-line of the driver. Research has identified the physical body controls and actions that are carried out by vehicle occupants for gaze stabilization. Evaluation and analysis considering human sensitivity has also been applied to vehicle components, including the seats, in addition to the conventional approach of qualitatively evaluating the vibration level of the vehicle body. A report analyzed the mechanism by which vertical vibration of the seats is excited by longitudinal vibration of the floor, and suggested an improvement method.

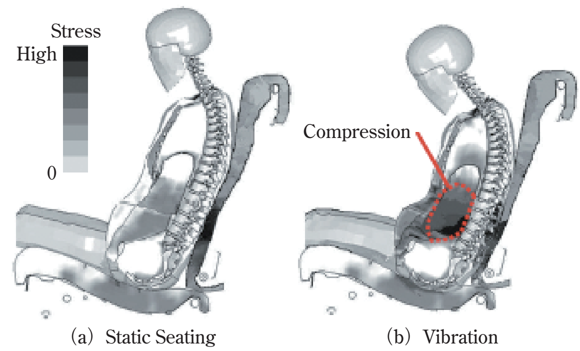

Fig. 8 Deformation of body structures (4 Hz vertical vibration).

At the same time, research is also continuing into the prediction of phenomena inside the body using human models. One report used a human FEM to analyze sensations of discomfort felt in the stomach region due to 4 Hz vertical vibration. This research simulated the physical behavior and discussed the compression of the stomach, which is thought to have a major influence on this sensation (Fig. 8).

Analyzing the mechanisms of phenomena felt by vehicle occupants is a promising means of advancing activities to identify ideal vehicle characteristics from the standpoint of the user. For this reason, user-oriented analysis is likely to gain further momentum in the future.

As a part of this trend, research is continuing into vehicle-based analysis technology. One report focused on transient vibration generated when the vehicle drives over a bump. This research predicted the transfer force from components to the vehicle body using a mechanism analysis model and carried out vector analysis on frequency axes using sound pressure sensitivity calculated from vehicle models. This efficient analysis method then uses inverse Fourier transformation to obtain the time domain response.

Other reports focused on shock absorbers, which have an extremely strong influence on ride comfort performance. Examples of research into next-generation ride comfort technologies include a study into the performance of a newly structured colloidal damper that integrates the spring and damper into a single part, and a study into a structure that substantially lowers the damping force in high mechanical piston speed regions.

Finally, various research is being carried out to improve ride comfort performance by making skillful use of existing systems as a way of achieving high-performance at a reasonable price. For example, one report described a method of estimating vertical acceleration of the vehicle, which is a key part of ride comfort control, using existing wheel speed sensors rather than additional sensors. This method focuses on the increase in suspension wear when braking force is applied and uses actuators that control the braking force at each wheel to suppress low-frequency vertical body motion caused by road surface inputs. Another report focused on cameras used for driver assistance systems. This research obtained accurate estimates of road surface profiles using a monocular camera and light source, which are easy to install on a vehicle, and verified the effect of using these profiles for active suspension control. The re-utilization of sensors used by existing sensors like this helps to minimize cost and weight increases, and is likely to be an active research field for all automakers in the future.