Noise, Vibration, and Harshness Analysis Technique Using a Full Vehicle Model

Hideto NISHINAKA*, and Noritaka MATSUOKA

Automakers have launched environment-friendly and fuel-efficient cars into the market. In such cars, decreased number of cylinders and expanded lock-up range are used to improve fuel efficiency. However, particularly in a vehicle with a 3-cylinder engine and continuously variable transmission, vehicle body vibration is aggravated by the influence of suspension resonance at the start of lock-up. To propose anti-vibration products that reduce the vibration, an analysis technique that covers drivelines and suspension systems is essential. Therefore, we have built a full vehicle analysis technique for evaluating a whole vehicle. With this technique, the reduction of vibration at the time of lock-up was examined using hydraulic strut mounts and the effects were confirmed in the actual vehicle evaluation. This full vehicle analysis technique is one of the fundamental technologies for our future product development.

Keywords: anti-vibration product, full vehicle analysis, NVH, hydraulic strut mount

1. Introduction

Vehicle manufacturers have enhanced the environmental friendliness of their vehicles after making every effort to improve fuel efficiency, and have put them onto the market. As a means of improving the fuel efficiency of vehicles, manufacturers downsize the engine by reducing the number of cylinders, and expand the lock-up*[1] range of the continuously variable transmission (CVT). A vehicle equipped with a 3-cylinder engine and a CVT with an expanded lock-up range starts locking up the CVT when the engine speed is low, making the suspension resonate at low engine speeds and aggravates the vehicle body vibration.[(1)]

Meanwhile, our conventional analysis technique for the noise, vibration, and harshness (NVH) phenomena of vehicles is targeted in analyzing engine mount-related systems. In particular, this analysis technique has been used to evaluate the vibrations being transmitted to the systems through the engine mounts. To analyze the NVH phenomenon of a vehicle equipped with a 3-cylinder engine and a CVT and thus to suppress the vibration of the vehicle, it is necessary to spread the analysis objects to a whole vehicle including drivelines and suspension systems.[(2)]

In this research study, we developed a full vehicle analysis technique that models a vibration transmission path that has not been considered in the conventional analysis technique. This paper reports a case example where the new analysis technique verified that a hydraulic strut mount*[2] is effective in reducing salient low-frequency vibrations of the suspension system at the time of lock-up of a vehicle equipped with a 3-cylinder engine and a CVT.

2. Overview of Full Vehicle Analysis Model

Vibration noise is roughly classified into air-borne noise and solid-borne noise. Air-borne noise includes engine sounds and exhaust sounds that are transmitted through gaps in the vehicle body and body panels, while solid-borne noise includes vehicle interior vibrations and noises that are caused by the vibration noises that are transmitted from vibration noise sources through the power plant, exhaust system, suspension system, and other transmission paths. The full vehicle model described in this paper is utilized in developing new products which can reduce solid-borne vibrations. Figure 1 shows an outline of the propagation mechanism of solid-borne vibrations.[(3),(4)] This figure also shows the range of the vibration noise transmission paths the conventional technique covers when analyzing engine mount systems.

As shown in Fig. 1, vehicle body vibration and noise are induced by engine vibration that is transmitted to the chassis through not only the engine mount but also the suspension bush and strut mount via the transmission, drive shaft, and suspension.

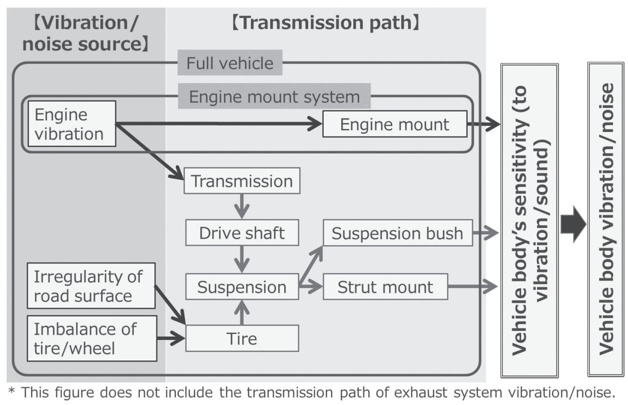


Fig. 1. Outline of vehicle body vibration/noise generation mechanism

To reproduce the vibration noise that is transmitted through these paths, we built a full vehicle analysis technique by integrating the subsystems shown in Fig. 2. This

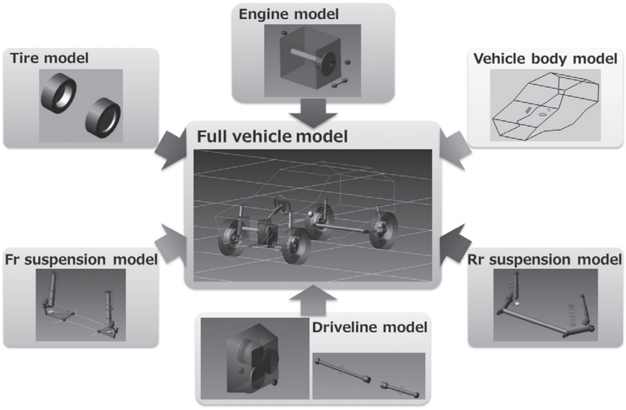


Fig. 2. Schematic illustration of full vehicle analysis model

time, we constructed a full vehicle model that represents a vehicle equipped with a 3-cylinder engine and a CVT. The NVH phenomena that can be evaluated using the full vehicle model include idling vibration, engine shake, lock-up vibration, cranking vibration, and harshness (vibration generated by a vehicle when riding over a bump). Meanwhile, we constructed the above model so that it can be used for a multibody dynamics analysis that can evaluate steady/unsteady NVH phenomena.

3. Detailed Description of Full Vehicle Model Construction Technique

This Section selects the front (Fr) suspension model and driveline model among the subsystems described in Section 2 and details these models. A hydraulic mount model that was constructed after taking into account its dependence on frequency/amplitude is also detailed in this section.

3-1 Suspension model

Vibration induced by the irregularities on the road surface and imbalance of the tire/wheel is transmitted to the vehicle body through the suspension system, a vibration transmission member. Engine vibration is also transmitted to the vehicle body through the suspension system via the drive shaft. To accurately express the suspension system, a vibration transmission member, we built a suspension model having a 3-dimensional geometry and mechanism equivalent to those of the suspension used in an actual vehicle. This suspension model consists of rigid components connected together by springs and damping elements.

To check the appropriateness of this suspension model, we analyzed the vertical vibration of a right wheel knuckle that will be induced when the front wheel tread is oscillated and compared the analysis result with the measured values. The result is shown in Fig. 3. In the measurement, the vertical vibration of the Fr suspension peaked at a frequency of 28 Hz. The analysis reproduced the peak vibration at the same frequency, verifying the appropriateness of the analysis model.

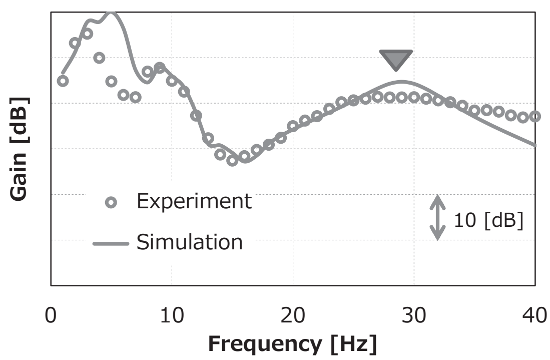


Fig. 3. Vertical vibration of right wheel knuckle that is generated when front wheel tread is oscillated

3-2 Driveline model

We built a driveline model to reproduce the phenomenon in which engine vibration is transmitted to the suspension through the transmission and drive shaft. This model consists of a drive shaft, transmission, torque converter, and lock-up damper. We enhanced the accuracy of the model by identifying the torsional rigidity of the drive shaft, the characteristics of the torque converter, and the characteristics of the lock-up damper using the following methods.

We first measured the wheel hub turning angle and drive shaft torque by conducting a torsional rigidity measurement test as shown in Fig. 4, and incorporated the test results into the analysis model as the static torsional rigidity of the drive shaft. The measured and analytically

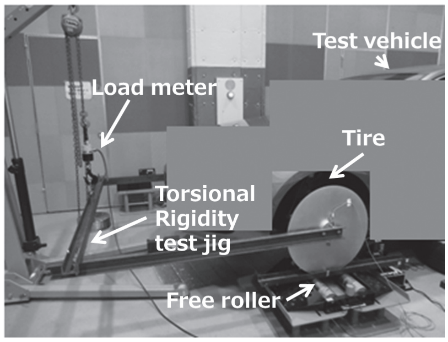


Fig. 4. Measurement test for torsional rigidity of driveline

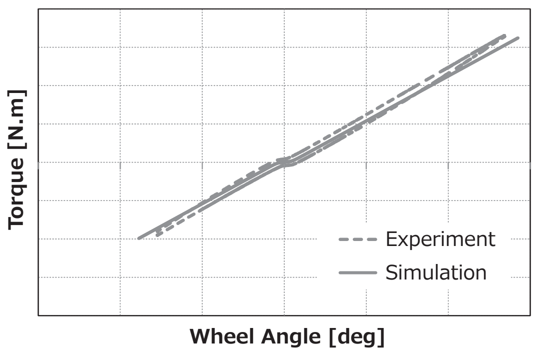


Fig. 5. Torsional rigidity of drive shaft

determined torsional rigidities of the drive shaft are compared in Fig. 5. The measurement and analysis results closely agreed with each other.

For the characteristics of torque converter and lock-up damper, we measured the variation of drive shaft torque when the shift lever is in the "drive" position*3 and at the time of lock-up. Then we adjusted the relevant parameters so that the analytical values would become nearly equal to the measured values. The results obtained after the above adjustments are shown in Figs. 6 and 7. Figure 7 shows that the analytical values differed significantly from the measured values in the rotational speed range below the lock-up speed of approximately 1400 rpm. The probable reason for the above is that the analysis model cannot represent the slip lock-up control. However, it is possible to study anti-vibration products on the basis of relative comparison in place of taking into account the above slip characteristics.

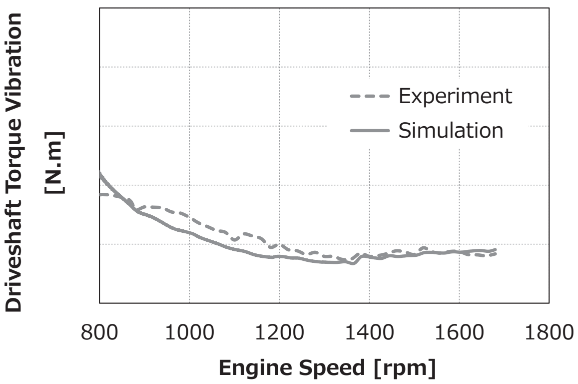
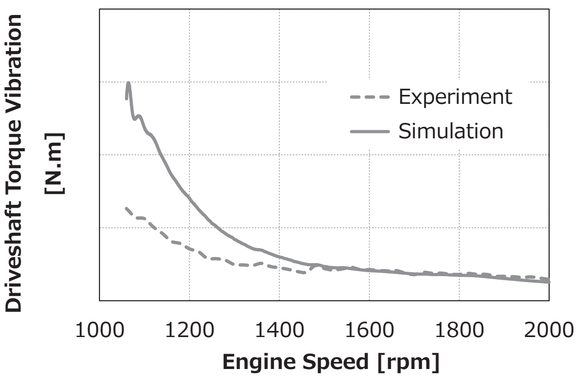


Fig. 6. Variation of drive shaft torque at the time of idling with shift lever in D



Fig, 7. Variation of drive shaft torque at the time of lock-up

The torsional rigidity of the drive shaft, the characteristics of the torque converter, and the characteristics of the lock-up damper have been properly incorporated into the driveline model as discussed above, verifying the appropriateness of this model.

3-3 Frequency/Amplitude dependence model of hydraulic mount for full vehicle analysis

An engine mount with an excellent damping performance is indispensable for a vehicle to suppress engine vibration when moving and thus to enhance ride comfort. On the other hand, the spring constant of the engine mount needs to be reduced to suppress the vibration at the time of idling. The hydraulic mount shown in Fig. 8 is conventionally used as an engine mount that satisfies the above two conditions by having appropriate frequency dependence and amplitude dependence.(5)

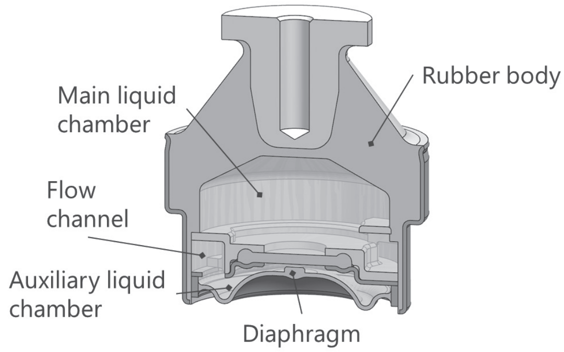


Fig. 8. Construction of conventionally used hydraulic mount

Since this full vehicle model is required to reproduce a variety of NVH phenomena of vehicles with a high degree of accuracy, we incorporated into the full vehicle model a hydraulic mount model capable of reproducing the required frequency dependence and amplitude dependence.

This hydraulic mount model consists of mass, spring, and damping elements. Using measured values, we identified the parameters of these elements. The characteristics of the hydraulic mount determined from the model and the characteristics measured are shown in Fig. 9. As this figure shows, this analysis model expressed the characteristics of the hydraulic mount with a high degree of accuracy, verifying the appropriateness of the estimation of the model parameters.

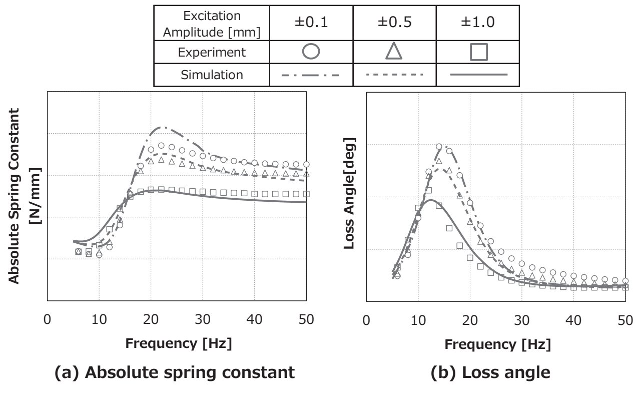


Fig. 9. Characteristics of hydraulic mount

4. Study on the Reduction of Vibration at the Time of Lock-Up

In a vehicle equipped with a 3-cylinder engine and a CVT that was used to construct a full vehicle model, the suspension has a resonance point near the number of engine revolutions at the start of lock-up. The suspension vibrates in resonance with the engine vibration that is transmitted through the drive shaft and aggravates the vibration of the vehicle. We conducted a study on the reduction of the above vibration at the start of lock-up by using the newly developed full vehicle analysis technique. This section describes the study results.

4-1 Transfer path analysis (TPA) of vibration at the time of lock-up

Using the full vehicle model, we analyzed the vibration at the time of lock-up and examined the 1.5th order component of vehicle floor vibration, a problem raised by the vehicle near the lock-up start speed. The vibrational response analysis results for the vehicle floor are shown in Fig. 10 and the TPA results for the engine mount, suspension bush, and strut mount are shown in Fig. 11. Figure 10 shows that the vehicle floor maximized its vibration acceleration near the engine speed range of 1200 to 1300 rpm. It can be seen from the TPA results, which are shown in Fig. 11, that the right and left strut mounts connecting the upper end of the suspension to the body affected significantly the vibration acceleration in the above vehicle speed range. Since the vertical vibration of the suspension resonates with the engine vibration near the above speed range as described in Section 3-1, we estimated that the resonance of the suspension aggravated the vibration level of the vehicle.

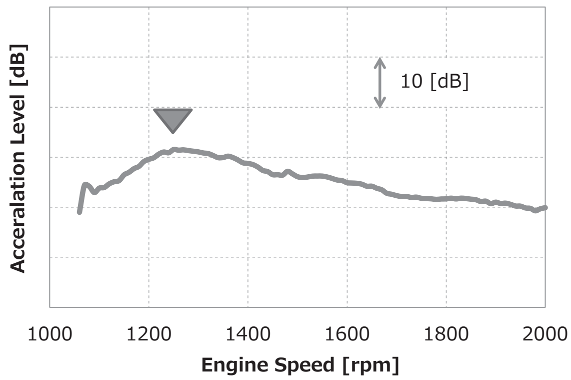
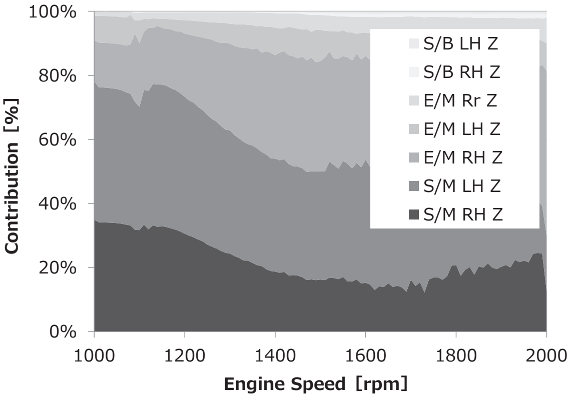


Fig. 10. Vertical vibration of vehicle floor at the time of lock-up



* S/B: suspension bush S/M: strut mount E/M: engine mount
Fr: front Rr: rear RH: right side LH: left side

Fig. 11. TPA of vehicle floor's vertical vibration at the time of lock-up

4-2 Proposal of Anti-vibration product that reduces vibration at the time of lock-up

The TPA revealed that suppressing the vertical resonance of the suspension, which significantly affects vehicle body vibration, is effective in reducing the vehicle floor vibration. Based on the above finding, we conducted a study on a hydraulic strut mount as an anti-vibration product having a large vibration damping performance.

In particular, we set the loss angle peak frequency of the hydraulic strut mount to 28 Hz, which was the resonance frequency of the suspension. Figure 12 shows the configuration of the hydraulic strut mount[6] we designed based on the above study results. Figure 13 shows the measured characteristics of a prototype hydraulic strut mount.

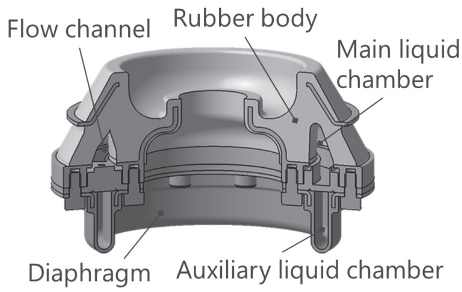


Fig. 12. Configuration of hydraulic strut mount

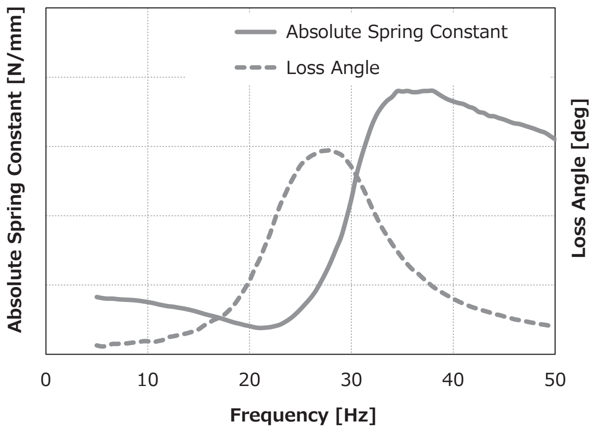


Fig. 13. Characteristics of prototype hydraulic strut mount (Absolute spring constant and loss angle)

4-3 Full vehicle analysis and verification of its appropriateness using actual vehicle

For a mount having no liquid-sealing structure and the newly proposed hydraulic mount, the analysis results and vehicle test results for the strut mount vibrations on the suspension side are shown in Figs. 14 (a) and 14 (b), respectively. The vehicle test results, which are shown in Fig. 14, verified the effect of the hydraulic strut mount in suppressing suspension vibration as estimated by the analysis. It was also confirmed from the vehicle test results that the newly proposed strut mount reduced the intensity of vehicle floor vibration by a maximum of 6 dB, as shown in Fig. 15.

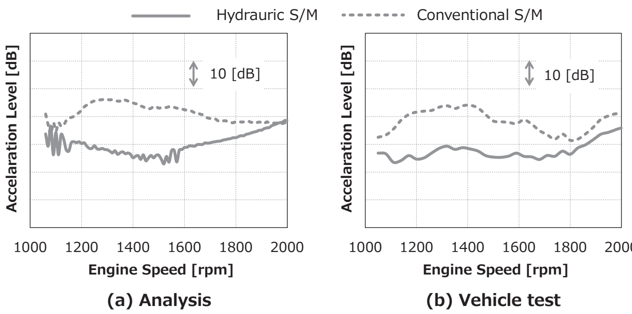


Fig. 14. Vertical vibration of strut mount on suspension side

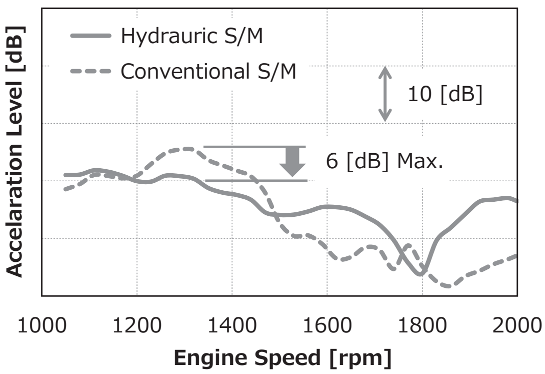


Fig. 15. Vertical vibration of vehicle floor at the time of lock-up (vehicle test)

5. Conclusion

We have developed a new full vehicle analysis technique that makes it possible to analyze the NVH phenomenon of a whole vehicle. Vehicle test results have verified that analyzing the characteristics of hydraulic strut mounts using this technique is effective in reducing vibration at the time of lock-up.

The full vehicle analysis technique we have built in this research study is useful not only for improving engine mounts but also for developing other anti-vibration automotive products, and is one of the fundamental technologies indispensable for our future product development.

6. Acknowledgments

We would like to express our appreciation to INFORMATION SERVICES INTERNATIONAL-DENTSU, LTD. and ESTECH CORP. for their cooperation in the development of this full vehicle analysis technique.

Technical Terms

*1 Lock-up: A state where a torque converter lock-up clutch is energized.

*2 Strut mount: A component that affixes the upper end of a strut type suspension to a vehicle body.

*3 The “drive” position: In the case of an automatic transmission or CVT vehicle.

References

(1) Hiromichi Tsuji et al., “Transfer path contributions for Engine Mounting and Driveshaft of CVT Lock-up vibration,” JSAE Annual Congress Proceedings, 20156083 (2015)

(2) Yuusuke Satou et al., “Technical development of total engine mounting design for NVH, drivability and ride comfort,” JSAE Annual Congress Proceedings, 20156087 (2015)

(3) JSAE, “Automotive Technology Handbook Vol.1 Fundamentals and Theory,” JSAE (1990)

(4) JSAE, “Automotive Technology Handbook Vol.3 Test and Evaluation,” JSAE (1991)

(5) JSAE, “Automotive Technology Series 11 Vibration Noise Reduction Technology for Automobiles,” Asakura Publishing Co., Ltd. (1996)

(6) Japanese Unexamined Patent Application Publication No. 2018-001797, “STRUT MOUNT AND SUSPENSION MECHANISM IN WHICH SAME IS USED”

Contributors

The lead author is indicated by an asterisk (*).

H. NISHINAKA*

• Sumitomo Riko Company Limited

N. MATSUOKA

• Sumitomo Riko Company Limited