

Prediction Technology for Vibration at Takeoff and Acceleration in AWD Vehicle Fitted with CVT

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ABSTRACT

A vibration prediction technology for the early examination of noise and vibration performance at development stages prior to the manufacture of a prototype vehicle has been developed. CVT belt resonance and differential rotation and the fluctuation component in the rear differential clutch were modeled and incorporated in a multi-body analysis model for use in noise and vibration performance design in vehicle development. The torsional vibration transfer characteristic of the CVT belt and the rear differential clutch vary in response to driving conditions in driving scenarios involving vehicle takeoff and acceleration. Parameters to be applied in the model are therefore identified in unit tests of the CVT and all-wheel drive system, which are developed in advance of the vehicle body. The developed technology is effective in performance design at development stages prior to the manufacture of a prototype vehicle, and reduces the man-hours involved in repeating performance validation using actual vehicle tests.

1. Introduction

The number of SUVs sold is increasing worldwide. Many SUVs are fitted with all-wheel drive (AWD) systems that allow them to display a high level of driving performance even on snow-covered roads and other low- μ roads, and unpaved roads. The number of these vehicles fitted with high-fuel-efficiency CVT as an environmental measure is also increasing.

The need to enhance noise and vibration (NV) performance in order to increase comfort is also growing, but at the same time, there are other strong demands on automakers, including the realization of weight reductions in order to reduce fuel consumption and the achievement of reduced cost, making vehicle development an increasingly complex process. Similarly, it is also necessary to shorten the development period and reduce the number of prototypes manufactured. As a response to these demands, the use of simulation technologies at stages of development prior to the manufacture of the vehicle is an effective means of increasing development efficiency.

There has been a recent tendency among automakers to increase the allocation of torque to the rear wheels at takeoff and in driving scenarios involving acceleration as a means of enhancing driving performance. In order to control the consequent displacement of the rear differential unit (RDU) mounts in response to the drive reaction force from the tires, it is necessary to increase the support stiffness of the RDU

mounts. However, when the stiffness of the RDU mounts is increased, the amount of vibration from the RDU mounts isolated to the vehicle body is reduced, resulting in a decline in NV performance. At the same time, because the lockup domain of the torque converter in a vehicle fitted with a CVT is broader than that of one fitted with an AT, the amount of vibration isolated by the lockup damper is lower. As a result, vibration input from the engine to the propeller shaft, known as torque fluctuation input, is higher. Because the specifications of the propeller shaft and RDU mounts are highly dependent on the layout and the support method, it is not easy to vary them after the prototype vehicle has been manufactured.

In addition, because the torsional vibration transfer characteristics of the CVT belt and the RDU clutch vary transiently at vehicle takeoff, reproduction using conventional simulation models that assume steady-state conditions is challenging. A vibration prediction technology was therefore developed that was capable of predicting, prior to the manufacture of a prototype vehicle, the increase in vibration input from the RDU mount to the vehicle body with the realization of increased AWD driving performance, and assisting in the examination of specifications that would enhance NV performance. A multi-body analysis model incorporating a CVT belt and RDU clutch was created, with the FF based AWD vehicle provided with an inline 4-cylinder engine shown in Fig. 1 as the subject of the study.

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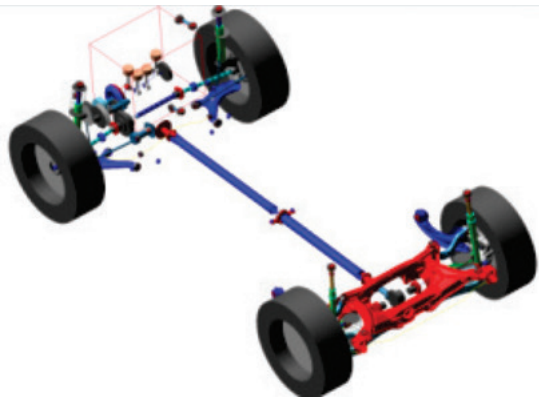


Fig. 1 Vehicle multi-body simulation model

2. Research Issues and Goals

This chapter will consider the issues associated with a technology for the prediction of vibration at takeoff and acceleration in an AWD vehicle fitted with a CVT.

In the conventional AWD NV performance design simulation models employed in vehicle development, CVT are modeled using rigid body elements. In addition, RDU clutches are modeled using static friction characteristics that do not include differential rotation or a fluctuation component.

In the case of the belt CVT forming one of the subjects of the research under discussion, the excitation force and resonant frequency of the CVT belt vary with driving conditions, for example the shift ratio or the input torque from the engine at takeoff and acceleration. CVT belt simulations conducted to date⁽¹⁾⁻⁽³⁾ have not considered energy loss through friction, and have not been able to reproduce the damping coefficient or excitation force in relation to changes in driving conditions such as the shift ratio or the input torque.

In addition, the electronically controlled hydraulic RDU clutch under study in this research produced a speed differential between the front and rear wheels at takeoff and acceleration, resulting in differential rotation. The torsional vibration transfer characteristic of RDU clutches varies in response to differential rotation and the fluctuation component. Because the models employed in RDU clutch simulations conducted to date⁽⁴⁾ have reflected only dynamic friction characteristics measured under conditions without a fluctuation component, they have not been able to reproduce the torsional vibration transfer characteristics of the RDU clutch at takeoff and acceleration. With regard to methods of measuring the friction characteristic, it is not possible to measure the clutch friction characteristic in a state in which differential rotation is occurring or a fluctuation component is acting under actual driving conditions. Because of this, it is not possible to accurately reproduce the torsional vibration transfer characteristic of an AWD

system provided with a propeller shaft using conventional simulation technologies.

These examples of simulation technologies are almost all examples of reports involving single CVT or clutch units. There are almost no examples to date of research on the prediction of input vibration to the vehicle body using combinations of complex systems.

The research discussed in this paper developed a method of identifying the damping coefficient of a CVT belt, which varies with factors such as the shift ratio, and the coefficient of dynamic friction of an RDU clutch, which varies in response to differential rotation and the fluctuation component, based on unit test results for each of the systems, which are developed in advance of the actual vehicle. The project then went on to develop a technology for the prediction of RDU mount vibration in an AWD vehicle fitted with a CVT (Fig. 2).

The target vibration frequency range for the research was 90 Hz to 120 Hz, which encompasses CVT belt, propeller shaft, and RDU mount resonant frequencies that represent a considerable issue in terms of realizing NV performance at vehicle takeoff. The target driving conditions were those at vehicle takeoff and acceleration. The research sought to make it possible to predict the level of vibration of the RDU mounts by creating a model using only data available at development stages prior to the manufacture of a prototype, with CVT belt speed fluctuations employed as input in addition to engine torque fluctuations, and employing it in combination with a vehicle response model.

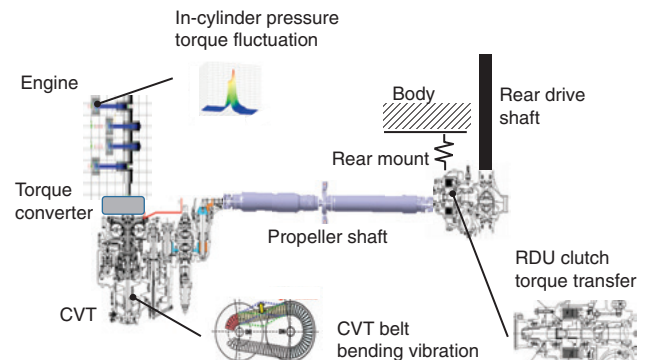


Fig. 2 Transfer mechanism

3. Modeling: Overview and Concept

The simulation model was a multi-body analysis model encompassing the engine, CVT, propeller shaft, rear drive shaft, RDU clutch, RDU mounts, and vehicle body. This chapter will discuss the modeling of the CVT belt and RDU clutch using the technology developed in this research.

3.1. Modeling of CVT Belt

Because the CVT belt undergoes elastic deformation in the target frequency range, it was expressed using mass elements, spring elements and damping elements. Figure 3 shows a schematic diagram of the CVT belt model. In order to reproduce the string vibration of the belt in the 100 Hz range while reducing the calculation load, rather than using a finite element model, the CVT belt was modeled using one spring element and one damping element. The primary and secondary pulleys were modeled using mass elements. When the CVT belt is in motion, it loses energy through contact between the elements, rings, and other metal parts. Equation (1) shows the relationship between the equivalent viscous damping coefficient between the mass elements and energy loss⁽⁵⁾. C' is the equivalent viscous damping coefficient, E is energy loss per cycle, ω is angular velocity, and A is amplitude.

$$C' = \frac{E}{\pi\omega A^2} \quad (1)$$

As Eq. (1) shows, the theoretical viscous damping coefficient can be calculated from the actually measured energy loss and amplitude, but it is no simple matter to directly measure the amplitude of each element, ring, and other part while the rotating belt is resonating. In the research under discussion, torsional torque fluctuation tests of the CVT unit were conducted under conditions simulating actual driving, and the damping coefficient was identified from the measured degree of fluctuation in pulley rotation. The combination of this coefficient with the mass and spring characteristic determined by the design specifications made it possible to create a model that could reproduce elastic deformation in the CVT belt under differing shift ratios and other conditions.

3.2. Modeling of RDU Clutch

In an RDU clutch, a wet-type multi-disc clutch is coupled between the input-side shaft, which is directly connected to the propeller shaft, and the output-side shaft, which is directly connected to the hypoid gear. In the target frequency range, the clutch is not subject to elastic deformation, and can be expressed using mass elements and friction elements. Figure 4 shows a schematic diagram of the AWD system model including the RDU clutch. Because the lubrication

state of the clutch varies with differential rotation and the load acting on the clutch, it is not easy to calculate the clutch friction characteristic for numerical analysis. The clutch friction characteristic was therefore determined experimentally in the project under discussion. The friction characteristic was measured using a low-velocity friction apparatus (LVFA). The LVFA measures the dynamic friction characteristic by applying a thrust load to the clutch unit and imparting a forced rotation that does not include a fluctuation component. Figure 5 shows the dynamic friction characteristic against differential rotation as measured in the LVFA. Equation (2) is a relational equation for the pressing force on the clutch and the transmitted torque. T is transmitted torque, μ_d is the dynamic friction coefficient, n is the number of clutches, R is the dynamic radius of the clutch, and F is the pressing force acting on the clutch.

$$T = \mu_d n R F \quad (2)$$

When the vehicle accelerates at takeoff, the RDU clutch experiences differential rotation, and in addition receives torque fluctuation from the engine and CVT on the input side. It has been reported that the dynamic friction characteristic in relation to the torsional vibration that formed the subject of this research differs from states in which there is no fluctuation component⁽⁶⁾. It is not possible to accurately express the torsional vibration transfer characteristic of an RDU clutch at vehicle takeoff and acceleration via a conventional model expression that uses the dynamic friction coefficient μ_d measured in an LVFA that does not consider the fluctuation component. It is therefore necessary to

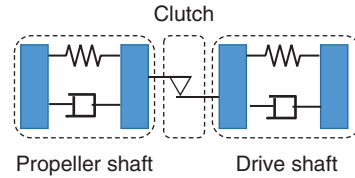


Fig. 4 Modeling of AWD unit

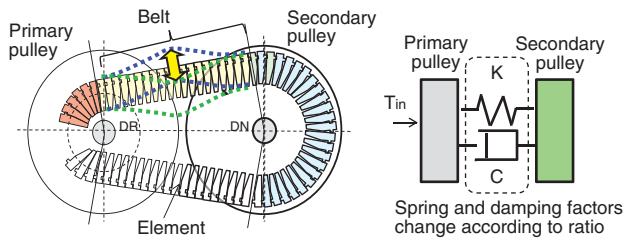


Fig. 3 Modeling of CVT belt

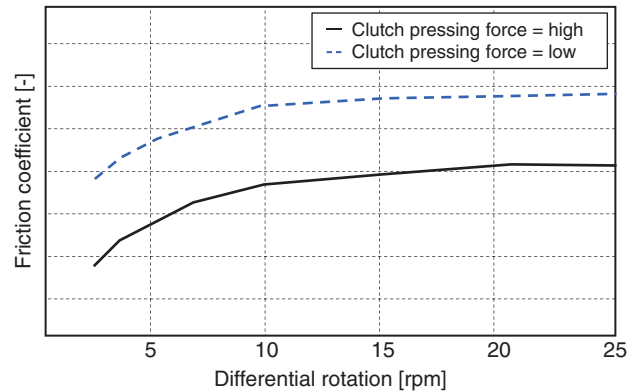


Fig. 5 Clutch friction coefficient in response to differential rotation

consider the dynamic clutch friction characteristic in a state that includes a fluctuation component.

In the research under discussion, torsional torque fluctuation tests were conducted with a unit AWD system as the subject, and the dynamic friction coefficient with consideration of the fluctuation component produced by differential rotation was identified from the measured degree of fluctuation in rotation. Equation (3) is a relational equation proposed by the research. $d\mu_d/dV$ is the dynamic friction coefficient fluctuation characteristic identified from the fluctuation component. By expressing the relationship between the pressing force on the clutch and transmitted torque with consideration of average torque and the fluctuation component, it is possible to express the torsional vibration transfer characteristic of the RDU clutch.

$$T = \left(\mu_d + \frac{d\mu_d}{dV} \cdot dV \right) nRF \quad (3)$$

4. Method of Identification and Results of Verification

4.1. Method of Identification of CVT Parameters

For identification of the CVT belt parameters, the spring coefficient and damping coefficient were identified with the mass as constants and the objective function as the fluctuation in pulley rotation speed measured in a unit test apparatus.

Figure 6 shows a schematic diagram of the CVT unit test apparatus. The CVT was attached to a drive dynamometer, and to an absorption dynamometer by means of a left-right driveshaft. The range for each parameter for the test conditions was set as shown in Table 1 based on the use domain in an actual vehicle and the domain of occurrence of CVT belt resonance. In addition, the fluctuation of the pulley rotational speed was measured under steady-state conditions for each of the conditions shown in Table 1.

Figure 7 shows results for the identification of the damping coefficient against rotational speed and input torque at a low pulley ratio as a representative condition.

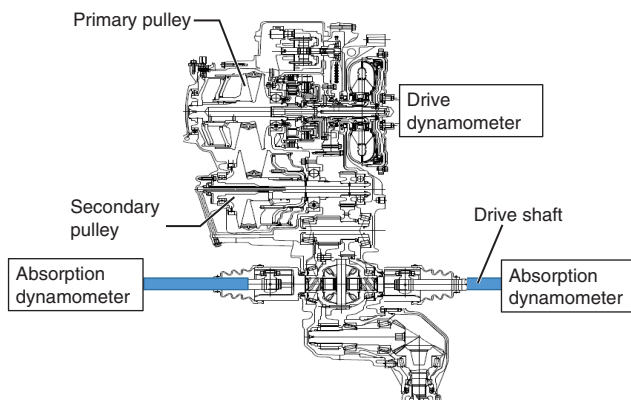


Fig. 6 CVT unit test

Table 1 CVT unit test parameters

Rotational speed	1000 to 4000 rpm
Input torque	0 to 200 Nm
CVT pulley ratio	0.5 to 2.65

Figure 8 shows the results of a simulation of the rotational speed of the secondary pulley at vehicle takeoff and acceleration as results for verification of the reproducibility of the identified parameters. Based on the fact that the change in the resonant frequency of string vibration and the degree of fluctuation in the speed of rotation of the secondary pulley were reproduced, it was judged that the simulation possessed sufficient accuracy.

4.2. Method of Identification of RDU Clutch Parameters

For identification of the RDU clutch parameters, the friction coefficient was identified with the mass as constants and the objective function as the fluctuation in the rotational speed of the propeller shaft measured for each condition in a unit test apparatus.

Figure 9 shows a schematic diagram of the AWD system test apparatus. A drive dynamometer was attached to the end of the propeller shaft, and absorption dynamometers were attached to the left-right driveshaft via the RDU. In order to measure the RDU clutch torsional vibration transfer characteristic during torsional resonance of the propeller shaft, a low-inertia dynamometer capable of fluctuating input in the 100 Hz range, simulating CVT belt vibration, was employed as the drive dynamometer. The range for the test condition parameters was set as shown in Table 2, based on the use domain in an actual vehicle.

Next, the method of identification of parameters and the results of parameter identification will be discussed.

Based on the results of previous tests, it was found that the rotating propeller shaft displays hysteresis in relation to

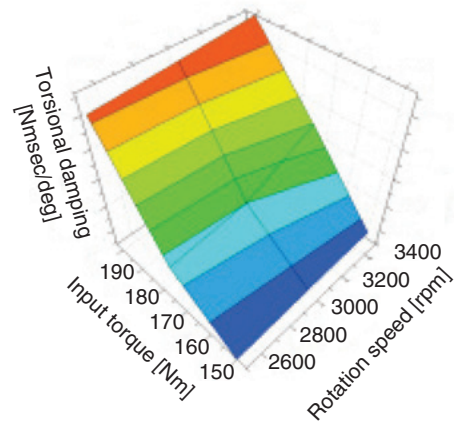


Fig. 7 Verified belt damping parameters at low pulley ratio

Table 2 AWD unit test parameters

Input rotation speed	500 to 2000 rpm
Input torque	50 to 150 Nm
Torque fluctuation amplitude	10 to 80 Nm
Differential rotation speed of clutch	0 to 20 rpm

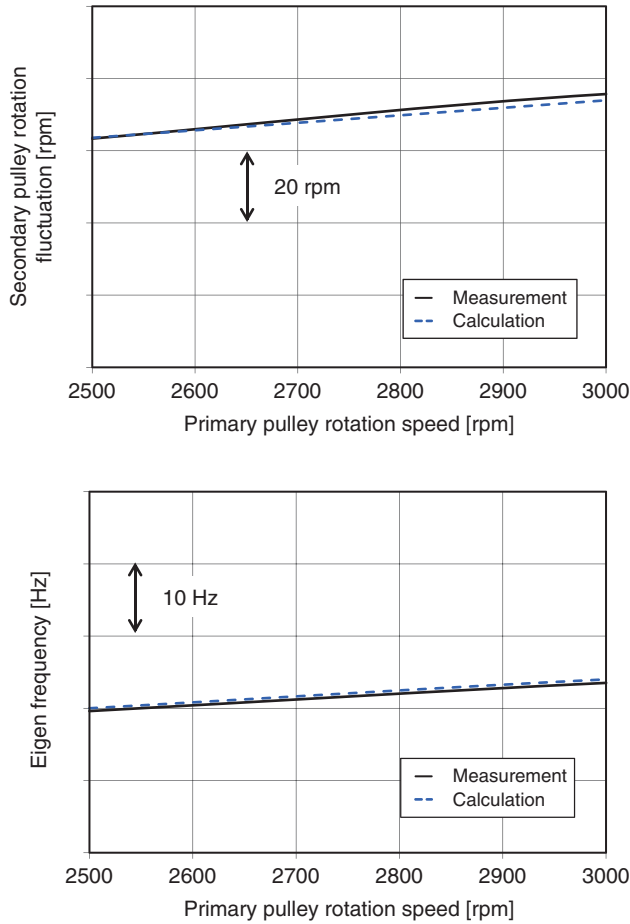


Fig. 8 Simulation results for CVT belt at vehicle takeoff and acceleration

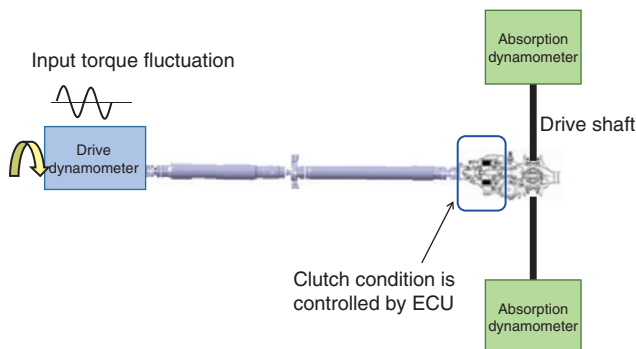


Fig. 9 AWD unit test of torsional vibration

the torsion angle and input torque characteristic. The energy loss produced by hysteresis is considered to be an effect of factors including the sliding resistance and looseness of the joints and bearings, and calculating the damping characteristic for numerical analysis is a challenge. In order to identify the damping coefficient of the propeller shaft, measurements were therefore conducted in the test apparatus shown in Fig. 9 with no differential rotation of the clutch. The damping coefficient was identified with the mass and spring as constants and the rotation speed of the propeller shaft measured in tests as the objective function. Figure 10 shows the results of identification of the damping coefficient. The modeling of the RDU clutch was conducted using Eq. (2), and the model reflected the dynamic friction coefficient μ_d with no fluctuation component.

Next, the measurements were conducted with differential rotation of the RDU clutch using the test apparatus shown in Fig. 9 in order to identify the coefficient of friction of the RDU.

Average torque transfer was expressed as the conventional dynamic friction coefficient μ_d measured using the LVFA, and torque fluctuation transfer was defined as the dynamic friction coefficient fluctuation characteristic $d\mu_d/dV$ that varies with differential rotation speed. Figure 11 shows the results of parameter identification of the dynamic friction coefficient fluctuation characteristic $d\mu_d/dV$ against the fluctuation component, with actually measured fluctuation

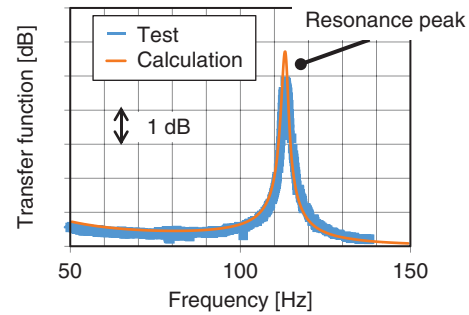
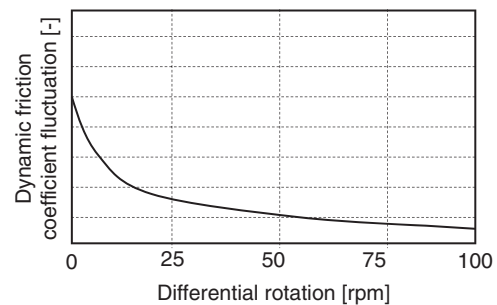


Fig. 10 Simulation results for transfer function of torque fluctuation without clutch differential rotation


 Fig. 11 Verified dynamic friction coefficient fluctuation parameters $d\mu_d/dV$

in the propeller shaft rotation speed as the objective function, and Fig. 12 shows simulation results for the torque fluctuation transfer characteristic. Considering the dynamic friction coefficient fluctuation characteristic made it possible to reproduce the torsional vibration transfer characteristic in the target frequency range (solid line) with sufficient accuracy even with differential rotation of the clutch, by comparison with simulation results that did not consider the dynamic friction coefficient fluctuation characteristic (broken line).

4.3. Results of Verification of Prediction of RDU Mount Vibration

The CVT belt model and RDU clutch model for which parameters had been identified based on the results of unit tests were incorporated in a vehicle model, and the vibration of the RDU mounts at vehicle takeoff and acceleration was predicted. The target accuracy for the prediction technology was set as the ability to calculate the peak level of vibration within the target frequency range to an accuracy of ± 3 dB, which would not hinder studies at development stages prior to the manufacture of a prototype. Figure 13 shows actual

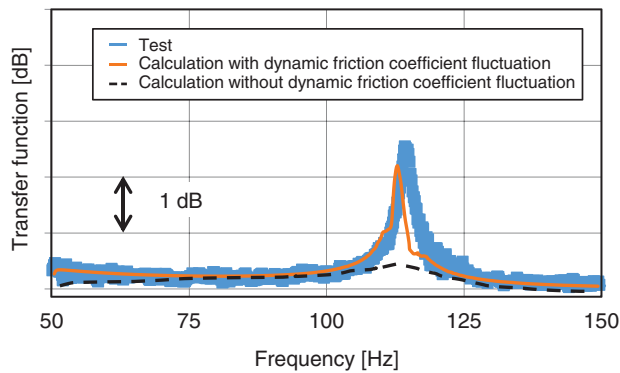


Fig. 12 Simulation results for transfer function of torque fluctuation with clutch differential of 10 rpm

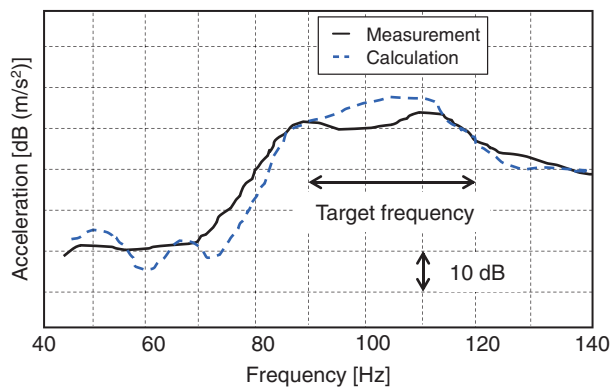


Fig. 13 Spectrum accuracy of rear differential mount vibration

vehicle test results and simulation results for the vibration of the RDU mounts at WOT acceleration from a stationary state. The calculation results realized the target accuracy for RDU mount vibration in the 90 Hz to 120 Hz frequency range under analysis, demonstrating that the method possesses sufficient accuracy for application in vehicle development.

5. Example of Application

This chapter will discuss an example of a study of NV performance in a prototype vehicle assuming a development process utilizing the modeling technique developed in this research.

Increased allocation of drive force to the rear wheels in order to enhance driving performance on snow-covered roads and hill-climbing performance was set as the condition, and NV performance was examined.

Figure 14 shows the results of a simulation of transfer load input to the vehicle body from the RDU when AWD performance is enhanced, in this case by increasing the allocation of drive force to the rear wheels, using the prediction technology developed in this research. The calculation results show that the transfer load input to the vehicle body under this condition (dotted line) increases against the current model (broken line). While methods that respond to the excitation source are also available, the research under discussion studied the reduction of in-cabin sound pressure with the RDU mounts considered as changeable parts. The target for the transfer load input to the vehicle body shown in Fig. 14 (solid line) was achieved by increasing the support span in order to increase support stiffness in relation to drive reaction force, reducing the spring characteristic of the RDU mounts under a drive force load.

Figure 15 shows results obtained by manufacturing a prototype and reflecting the examined specifications in a vehicle. The performance targets for interior noise were realized.

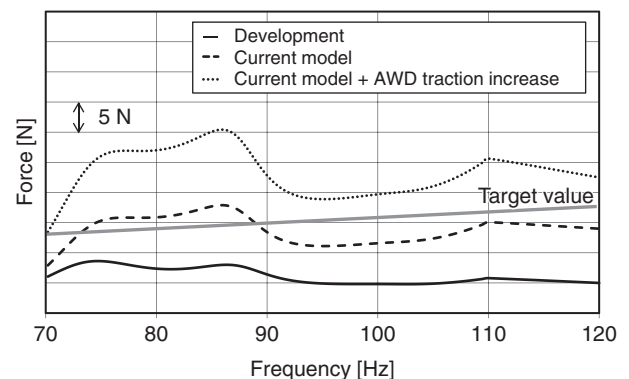


Fig. 14 Simulation results for input force from RDU to vehicle body at vehicle takeoff and acceleration

The results discussed above indicated that it had been possible to develop a prediction technology able to be used in the study of system characteristics that satisfy AWD driving performance and NV performance targets assuming vehicle development demands.

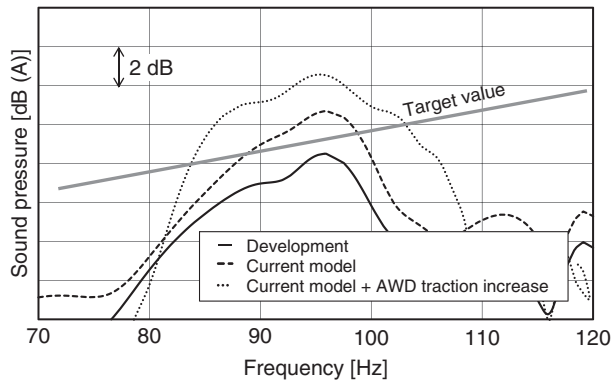


Fig. 15 Vehicle test results for in-cabin sound pressure

6. Conclusion

A simulation model able to be employed in the study of NV performance has been developed based on the conventional simulation model used in AWD NV performance design, in order to expand the range of frequencies and driving conditions analyzed, and balance NV and driving performance in systems combining a CVT and AWD.

- (1) A method of modeling the CVT belt was developed in which the damping coefficient, which varies with driving conditions including the shift ratio and input torque, is identified experimentally in CVT unit tests.
- (2) A method of modeling the RDU clutch was developed in which the dynamic friction coefficient fluctuation characteristic, which varies with differential rotation speed and the fluctuation component, is identified experimentally in AWD system tests.

The reflection of these developments in a simulation model has made it possible to predict RDU mount vibration at development stages prior to the manufacture of a prototype vehicle, and to study specifications for NV and AWD driving performance at the initial stage of development.

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