

Research on Simulation Method for Predicting Rattling Noise in Manual Transmission Drivetrain

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ABSTRACT

The level of rattling noise in a Manual Transmission (MT) drivetrain system is closely related to the transmission input shaft rotational speed fluctuation. In this research, the loudness of noise, which is proportional to the impact force of the rattling idle gears caused by the rotational speed fluctuation, and the conspicuousness of noise, which is caused by the existence of drivetrain resonance, were clearly identified. Furthermore, a drivetrain simulation method for predicting the rotational speed fluctuation was developed. In this simulation method, a clutch torsional characteristic defined by the dynamic torsion constant and equivalent damping force coefficient is used as the parameter to improve accuracy. Consequently, it is now possible to obtain the optimum specifications of clutch, moment of inertia and torsional rigidity characteristic of the drivetrain to reduce the rattling noise level at an early stage of the development program.

1. Introduction

Gear rattling noise in MT vehicles is an important issue that affects the product appeals of comfort and quietness. The source of vibration for this rattling noise is the torque fluctuation caused by engine combustion. This torque fluctuation is inputted into the transmission via the clutch and causes idle gears to impact, producing a rattling noise. In order to reduce the gear rattling noise, it is necessary to suppress the transmission of the torque fluctuation from the engine to the drivetrain. This requires measures to dampen the torsional vibration of the drivetrain in the practical vehicle speed range, and to reduce the rotational speed fluctuation of the transmission input shaft, which causes the rattling noise.

The rotational speed fluctuation of the input shaft is closely related to the torsional characteristics of the clutch^{(1), (2)}. Therefore various measures are implemented to reduce this rotational speed fluctuation, such as reducing the torsional stiffness characteristics of the clutch and changing the hysteresis by displacement of the fluctuation angle. However, these measures are limited by the clutch structure, as they require increased spring stress, widening of the

operating angle, the addition of a variable hysteresis torque mechanism, etc. Therefore, in order to ensure adequate measures, torsional characteristics of the clutch that can suppress rotational speed fluctuation of the input shaft must be studied and set in the initial design stages. Simulations are conducted to study the rotational speed fluctuation of the input shaft^{(3), (4), (5)}, but in some cases the results do not match with measured values and the desired effects are not achieved. Therefore, various specifications are currently tested using actual vehicles to determine the specifications.

This paper reports the development of a simulation method that defines and reflects the dynamic torsional characteristics of the clutch in the operating state to accurately predict the rotational speed fluctuation of the input shaft.

2. Rattling Phenomenon

The rattling noise of concern becomes noticeable during full-throttle acceleration in high gear and when coasting (natural deceleration) in low gear. Figures 1 (a) and (b) show the actual values for rattling noise measured near the transmission case, engine combustion primary rotational

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speed fluctuation, and transmission input shaft rotational speed fluctuation during full-throttle acceleration in 5th gear and when coasting in 3rd gear.

Rattling noise was observed to change in conjunction with the input shaft rotational speed fluctuation. The sum total of the forces during idle gear impact can be considered as an index for the rattling noise loudness, and this is defined as the force of tooth impact F derived from the angular speed fluctuation and moment of inertia of each idle gear as shown in Eq. (1).

$$F = \sum_{i=a}^b I_i \frac{d\omega_{Gi}}{dt} \quad (1)$$

$$= \sum_{i=a}^b I_i \frac{d \left(\frac{\Delta N_{IS}}{60} \times 2\pi \times \frac{1}{r_i} \right)}{dt}$$

Here,

I : Moment of inertia of idle gear

$\Delta\omega_G$: Idle gear rotational speed fluctuation

ΔN_{IS} : Input shaft rotational speed fluctuation

r : Ratio

a to b : Each idle gear step in the running state

Figure 2 shows the relation between sensory ratings and tooth impact force obtained by Eq. (1) using measured values of the rotational speed fluctuation during resonance of torsional vibration of the drivetrain. This figure shows that the proximate noise level and tooth impact force have a proportional relationship with a high correlation. Conversely, a worsening tendency can be observed for sensory ratings as tooth impact force increases. However, there were a number of cases that received lower ratings even though the tooth impact force was small and the proximate noise level was

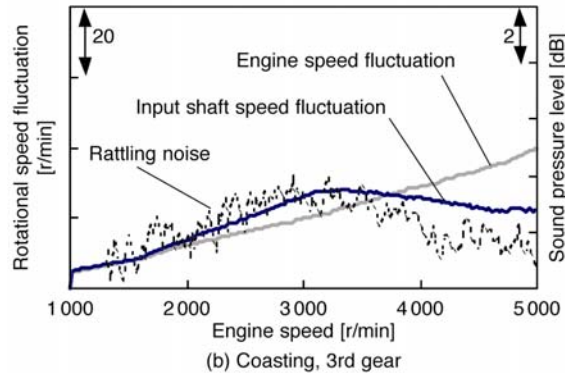
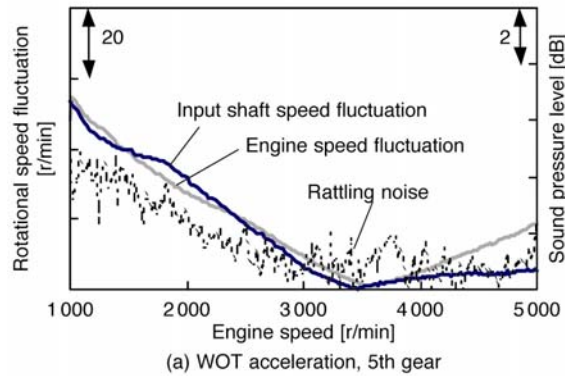


Fig. 1 Rotational speed fluctuation and sound pressure level

low.

Therefore, an index of the rattling noise conspicuousness was defined as the amplification of rotational speed fluctuation, r_{amp} , which is the ratio of the input shaft rotational speed fluctuation to the engine rotational speed fluctuation during resonance of torsional vibration of the drivetrain, as shown in Eq. (2).

$$r_{amp} = \Delta N_{IS} / \Delta N_E \quad (2)$$

Here,

ΔN_E : Engine rotational speed fluctuation

This amplification of rotational speed fluctuation was confirmed to correlate closely with sensory ratings as shown in Fig. 3, with the rating tending to worsen as the rotational speed fluctuation transmission ratio increased. The rating is presumed to worsen because the difference between the rattling noise inside and outside the area of torsional vibration resonance of the drivetrain increases and the rattling noise becomes more conspicuous as the amplification of rotational speed fluctuation increases. Thus, the reason for the poor rating even when the rattling noise is low is thought to be due to the rattling noise conspicuousness.

Based on the above, rattling noise can be rated in terms of loudness, which depends on the absolute value of the sound pressure level, and conspicuousness, which is caused by resonance of torsional vibration of the drivetrain. Furthermore, these characteristics can both be judged by obtaining the input shaft rotational speed fluctuation value.

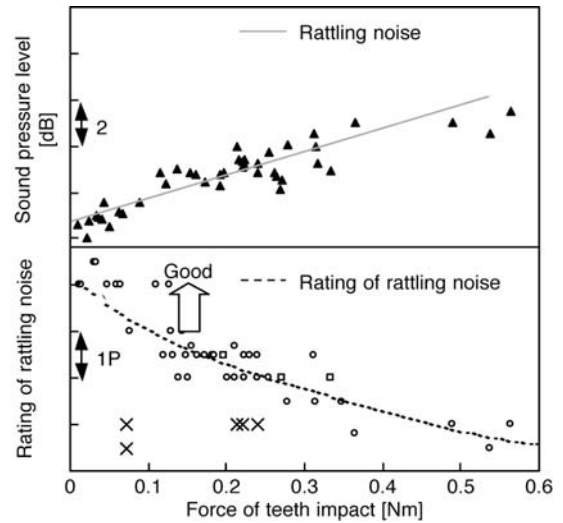


Fig. 2 Relation between rating of rattling noise and force of teeth impact

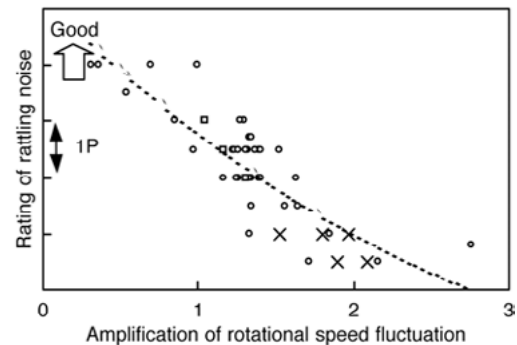


Fig. 3 Relation between rating of rattling noise and amplification of rotational speed fluctuation

3. Modeling the Drivetrain Rotation Transmission Mechanism

3.1. Simulation Model

Figure 4 (a) and (b) shows an outline of the simulation model used to predict transmission input shaft rotational speed fluctuation. The model configuration was set as the range from the crank shaft to the flywheel, clutch, transmission, drive shaft, tire, and body. Equations (3) through (7) show the equations of motion for torsional vibration of the drivetrain used in the simulation model.

Measured values for the input shaft, counter shaft, and differential and calculated values for the drive gear and shaft deflections were used for the torsional stiffness of the transmission.

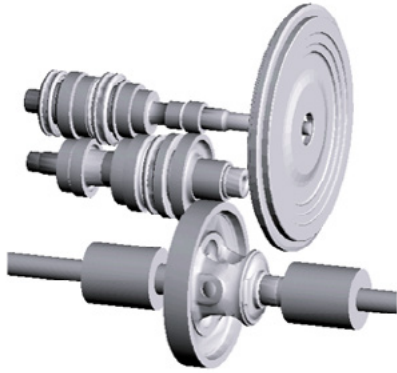
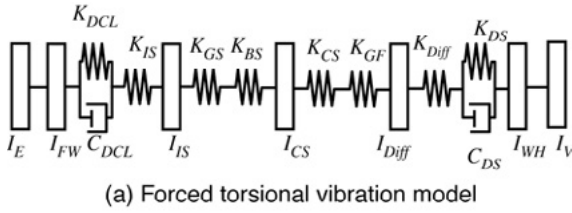


Fig. 4 Simulation model for rotational speed fluctuation

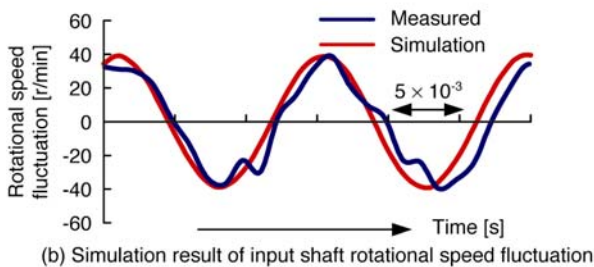
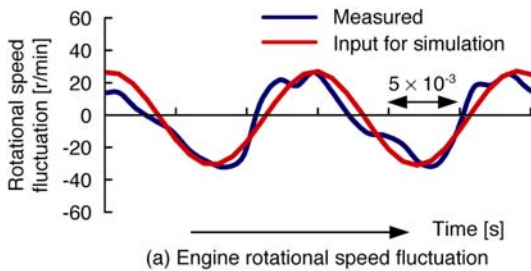


Fig. 5 Input wave and simulation result

The measured torsional stiffness and the damping coefficient calculated from experimental equations were used for the drive shaft characteristics.

The torsional characteristics of the clutch reflected the dynamic torsional characteristics in the operating state. These details are described in section 3.2.

The input was a vibration applied in the form of a sine wave that fluctuated at the primary frequency of engine combustion using the measured value of the engine rotational speed fluctuation as the amplitude as shown in Fig. 5 (a). The results reproduced the input shaft rotational speed fluctuation as shown in Fig. 5 (b).

$$I_1 \ddot{\theta}_{FW} + C_{DCL} (\dot{\theta}_{FW} - \dot{\theta}_{IS}) + K_1 (\theta_{FW} - \theta_{IS}) = 0 \quad (3)$$

$$I_2 \ddot{\theta}_{IS} + C_{DCL} (\dot{\theta}_{IS} - \dot{\theta}_{FW}) + K_1 (\theta_{IS} - \theta_{FW}) + K_2 (\theta_{IS} - \theta_{CS}) = 0 \quad (4)$$

$$I_3 \ddot{\theta}_{CS} + K_2 (\theta_{CS} - \theta_{IS}) + K_3 (\theta_{CS} - \theta_{Diff}) = 0 \quad (5)$$

$$I_4 \ddot{\theta}_{Diff} + K_3 (\theta_{Diff} - \theta_{CS}) + C_{DS} (\dot{\theta}_{Diff} - \dot{\theta}_{WH}) + K_4 (\theta_{Diff} - \theta_{WH}) = 0 \quad (6)$$

$$I_5 \ddot{\theta}_{WH} + K_4 (\theta_{WH} - \theta_{Diff}) + C_{DS} (\dot{\theta}_{WH} - \dot{\theta}_{Diff}) = 0 \quad (7)$$

$$I_1 = I_E + I_{FW}$$

$$I_2 = I_{IS}$$

$$I_3 = I_{CS} / i^2$$

$$I_4 = I_{Diff} / i^2 / i_f^2$$

$$I_5 = (I_{WH} + I_V) / i^2 / i_f^2$$

$$1/K_1 = 1/K_{DCL} + 1/K_{IS}$$

$$1/K_2 = 1/K_{GS} + 1/K_{BS}$$

$$1/K_3 = 1/(K_{CS}/i^2) + 1/(K_{GF}/i^2)$$

$$1/K_4 = 1/(K_{Diff}/i^2 / i_f^2) + 1/(K_{DS}/i^2 / i_f^2)$$

Here,

I_E : Moment of inertia of engine

I_{FW} : Moment of inertia of flywheel

I_{IS} : Moment of inertia of input shaft

I_{CS} : Moment of inertia of counter shaft

I_{Diff} : Moment of inertia of differential

I_{WH} : Moment of inertia of wheel and tire

I_V : Moment of inertia of vehicle body equivalent

K_{DCL} : Clutch dynamic stiffness

K_{IS} : Input shaft torsional stiffness

K_{GS} : Gear meshing stiffness

K_{BS} : Shaft deflection stiffness

K_{CS} : Counter shaft torsional stiffness

K_{GF} : Final gear meshing stiffness

K_{Diff} : Differential torsional stiffness

C_{DCL} : Clutch equivalent damping coefficient

C_{DS} : Drive shaft damping coefficient

i : Running gear ratio

i_f : Final gear ratio

3.2. Dynamic Torsional Characteristics of the Clutch

The simulation reflected the torsional characteristics of the clutch as the dynamic torsional characteristics in the operating state. Figure 6 shows an example of the dynamic torsional characteristics of the clutch when it is rotating, and the static torsional characteristics when it is not rotating.

The centrifugal force presses the torsion spring toward the outside, which increases the friction force and causes the hysteresis torque of the dynamic torsional characteristics to become larger than the static torsional characteristics. When running, in addition to this increased hysteresis torque, the clutch vibrates with a minute amplitude angle at the engine combustion primary cycle, and can be assumed to operate in a loop form such as shown in Fig. 7.

The clutch stiffness in the running state, the loop shown in Fig. 7, is thought to operate at a higher dynamic stiffness K_d than the static stiffness, and this is defined in Eq. (8). In contrast with the static stiffness, which is a constant value under all conditions, the dynamic stiffness is determined by the hysteresis torque and the fluctuation angle, which change according to the rotational speed and the rotational speed fluctuation, respectively. As a result, the dynamic stiffness changes continuously according to the running state.

Figure 8 shows an example of the dynamic stiffness characteristics calculated by Eq. (8) using the dynamic torsional characteristics of the clutch at each rotational speed.

The damping coefficient produced by the hysteresis torque is defined as the equivalent damping coefficient C_{eq} ⁽⁶⁾ from the area enclosed by the loop shown in Fig. 7, and is calculated as shown in Eq. (9). This equivalent damping coefficient is determined by the hysteresis torque, the

fluctuation angle, and the fluctuation frequency caused by engine combustion, so, like the dynamic stiffness, it changes continuously according to the running state.

Figure 9 shows an example of the equivalent damping coefficient characteristics at each rotational speed calculated by Eq. (9), using the dynamic torsional characteristics of the clutch at each rotational speed in the same manner as the dynamic stiffness.

The dynamic stiffness and equivalent damping coefficient characteristics shown in Fig. 8 and Fig. 9 were calculated for each engine rotational speed, rotational speed fluctuation, and operating torque range, and compiled into a simulation database. The simulation continuously varied the characteristics by obtaining the dynamic stiffness and equivalent damping coefficient from this database based on the calculated states and then substituting these values to the clutch characteristics in the simulation model shown in Fig. 4 (a).

$$K_d = \frac{H + K_s \times 2 \times A}{2 \times A} \quad (8)$$

$$C_{eq} = \frac{S}{\pi \times \omega \times A^2} = \frac{H \times 2 \times A}{\pi \times 2\pi f \times A^2} \quad (9)$$

Here,

- K_s : Static stiffness
- H : Hysteresis torque
- A : Crank fluctuation angle
- f : Fluctuation frequency
- S : Loop area

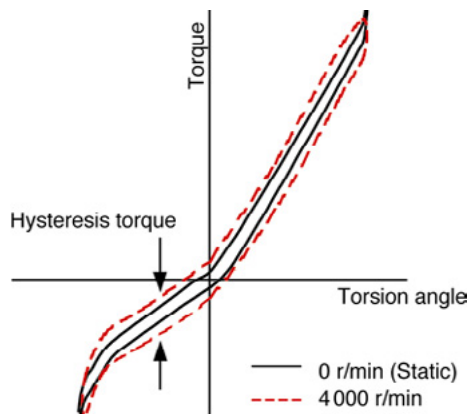


Fig. 6 Rotational characteristics of clutch at 4 000 r/min

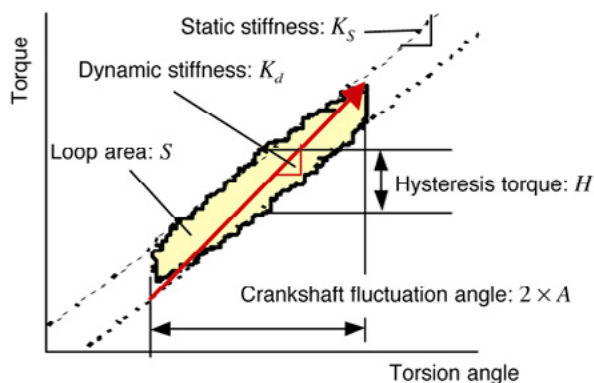


Fig. 7 Dynamic characteristics of clutch

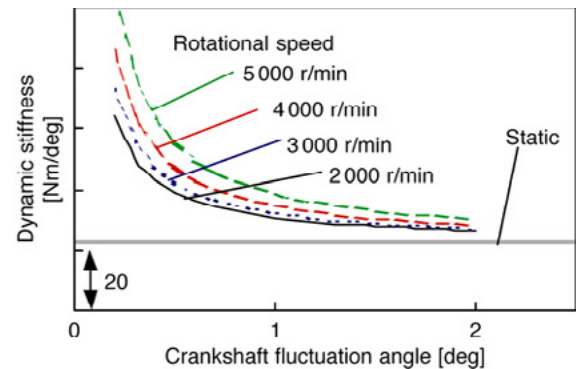


Fig. 8 Calculated results of dynamic stiffness of clutch

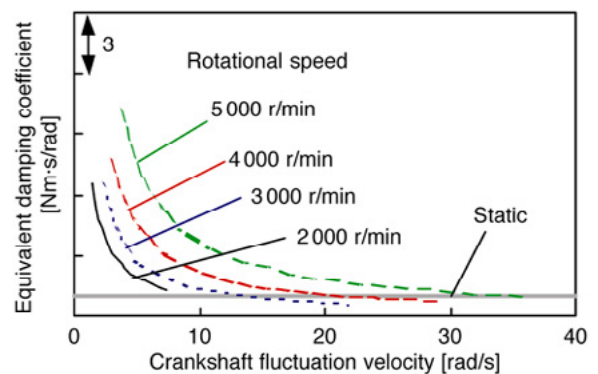


Fig. 9 Calculated results of dynamic damping of clutch

4. Analysis Examples

4.1. Correlation between Measured Values and Simulation Results

The newly constructed simulation model was applied to a 1.4-liter, 5-speed manual transmission drivetrain, and the results were compared with measured values of the input shaft rotational speed fluctuation.

Figure 10 (a) and (b) shows the simulation results and measured values during full-throttle acceleration in 5th gear and when coasting in 3rd gear.

During full-throttle acceleration in 5th gear, the measured values of the input shaft rotational speed fluctuation increased in amplitude compared to the engine rotational speed fluctuation due to resonance of torsional vibration of the drivetrain at an engine rotational speed of around 2 300 r/min, and the peak value was 40 r/min. The simulation results matched closely with the measured values in terms of the peak value and the engine rotation speed at which that peak occurs due to resonance of torsional vibration of the drivetrain, thus confirming the correlation.

When coasting in 3rd gear, the measured values of the input shaft rotational speed fluctuation increased in amplitude at an engine rotational speed of around 4 000 r/min. In this case as well, the simulation results were to reproduce the same phenomena as the measured values.

These results confirmed that the newly constructed simulation model can accurately reproduce measured phenomena related to input shaft rotational speed fluctuation during both acceleration and deceleration.

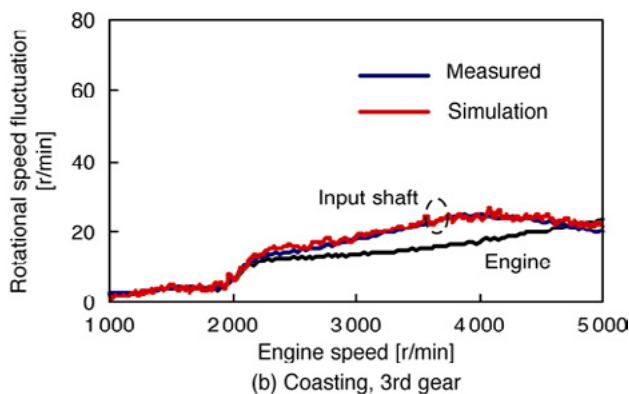
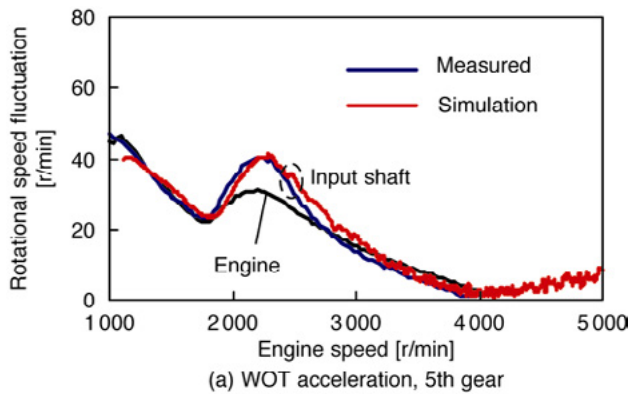


Fig. 10 Comparison of rotational speed fluctuation between measured results and simulation results at 1.4L 5MT

4.2. Investigation of Specifications for the Torsional Characteristics of the Clutch

Simulations were conducted to investigate specifications for the torsional characteristics of the clutch during development of a 2.4-liter, 6-speed manual transmission drivetrain. These results were then compared with the results of confirmation testing an actual vehicle.

Figure 11 shows the torsional characteristics during rotation for the two types of clutches investigated. The acceleration side shows the characteristics at 2 000 r/min, and the deceleration side shows the characteristics at 4 000 r/min. On the acceleration side, the same static stiffness characteristics were set for both Type 1 and Type 2, but the hysteresis torque when rotating was set larger for Type 2 than for Type 1. On the deceleration side, the static stiffness was set the same as the acceleration side for Type 1, and half that value for Type 2. In addition, the hysteresis torque when rotating was set smaller for Type 2 than for Type 1.

Figure 12 (a) and (b) shows the simulation results of the input shaft rotational speed fluctuation using the above torsional characteristics of the clutch during full-throttle acceleration in 5th gear and when coasting in 3rd gear.

During full-throttle acceleration in 5th gear, the input shaft rotational speed fluctuation for Type 1 was confirmed to peak due to resonance of torsional vibration of the drivetrain at an engine rotational speed of around 1 850 r/min. The peak value at that time was 55 r/min. Type 2 had reduced rotational speed fluctuation compared to Type 1, and a peak was not observed. For this reason, Type 2 was confirmed to have better characteristics for rattling noise during full-throttle acceleration.

When coasting in 3rd gear, the input shaft rotational speed fluctuation for Type 1 was confirmed to peak due to resonance of torsional vibration of the drivetrain at an engine rotational speed of around 4 000 r/min. The peak value at that time was 40 r/min. Type 2 had reduced rotational speed fluctuation compared to Type 1, and a peak was not observed. For this reason, like full-throttle acceleration in 5th gear, Type 2 was confirmed to have better characteristics for rattling noise during coasting deceleration.

Figure 13 shows the measurement results for input shaft rotational speed fluctuation when these two types of clutches were mounted in an actual vehicle.

The measured values and the simulation results exhibited nearly the same characteristics, and Type 2 was confirmed to achieve the same rotational speed fluctuation and fluctuation reduction effects in an actual vehicle.

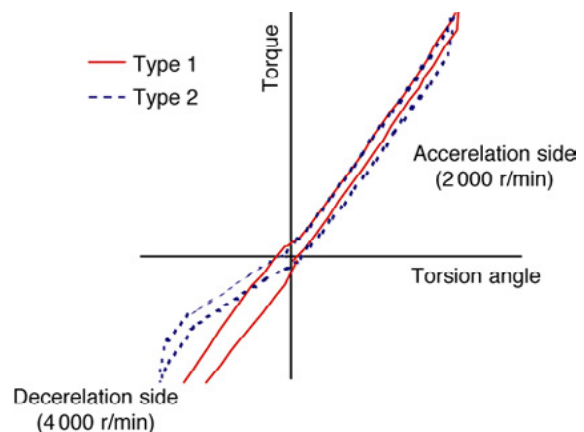


Fig. 11 Rotational speed characteristics of clutch for 2.4L 6MT

Based on these results, the newly constructed simulation model was confirmed to be an effective means for accurately predicting the input shaft rotational speed fluctuation, which is necessary when determining the torsional characteristics of the clutch and the drivetrain specifications.

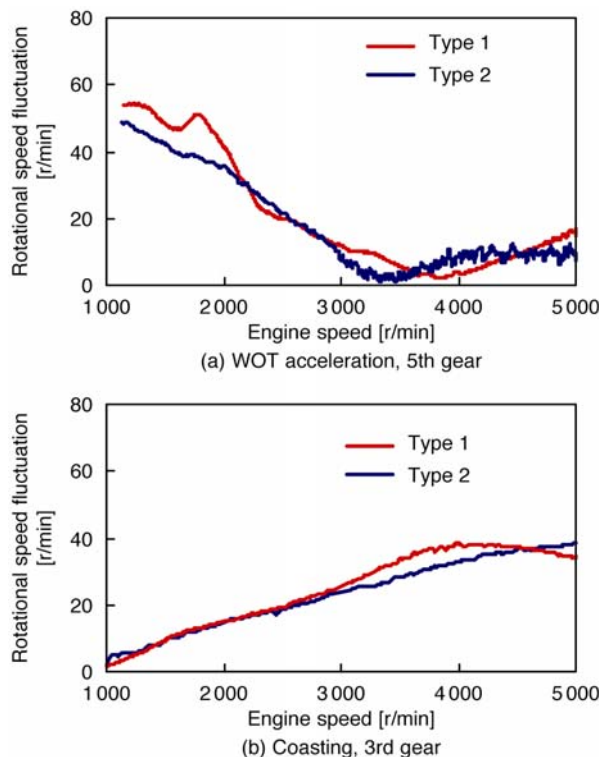


Fig. 12 Simulation results of input shaft rotational speed fluctuation at 2.4L 6MT

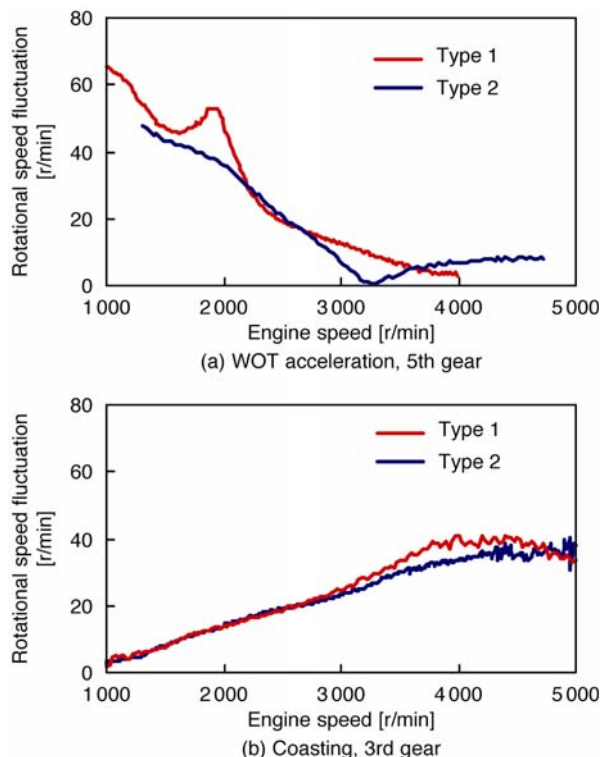


Fig. 13 Measurement results of input shaft rotational speed fluctuation at 2.4L 6MT

5. Conclusion

A method for predicting rattling noise in MT vehicles was studied, and the following results were obtained:

- (1) Rattling noise can be rated in terms of loudness, which depends on the absolute value of the sound pressure level, and conspicuousness, which is caused by resonance of torsional vibration of the drivetrain. Furthermore, it was shown that both of these characteristics can be judged according to the input shaft rotational speed fluctuation.
- (2) The measured values of the input shaft rotational speed fluctuation could be reproduced by defining the dynamic torsional characteristics of the clutch during operation as the dynamic stiffness and the damping coefficient, estimating the characteristics for each engine rotational speed, rotational speed fluctuation, and operating torque range, and then reflecting these values to the simulation model.
- (3) Using the newly constructed simulation model made it possible to investigate the optimum specifications for the clutch torsional characteristics and the drivetrain that reduce the input shaft rotational speed fluctuation in each drivetrain.

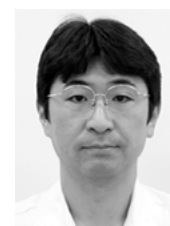
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