

Research on Longitudinal Vibration of MT Vehicle during Acceleration

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ABSTRACT

Waveforms of longitudinal vibration during acceleration in MT vehicles have been used to develop five evaluation indices corresponding to sensory evaluations. The mechanism of longitudinal vibration during acceleration was clarified in each part of the system through which it is transmitted: engine, drive train, tires, engine mounts and suspension. A simulation model was constructed employing design values as the main elements, enabling specifications to be tested in the initial development phase, before the construction of an actual vehicle. This method was utilized in the development of the new model Accord, enabling suspension characteristics and engine torque control, among other design elements, to be optimized at an early stage, and resulting in the reduction of development time by half.

1. Introduction

Recently, performance areas evaluated by human sensitivity, such as the comfort and responsiveness of the driver, became as important as dynamic performance, noise, fuel economy and other performance areas that are evaluated numerically. However, it is difficult to accurately quantify these types of performance areas, so vehicle development must rely on sensory evaluation using actual vehicle tests, which means that vast amounts of manpower are used through trial and error testing.

Body longitudinal vibration that occurs when the accelerator pedal is depressed is a source of discomfort for the driver, and is an important area that must be improved for MT vehicles. Cases of improving this phenomenon by methods such as optimization of the engine mount stiffness⁽¹⁾ have been reported in the past.

This type of vibration concern is rooted in various properties of large numbers of components, and at the same time often has a trade-off relationship with other areas. This means that the related items are complexly intertwined and there are few cases where the issue can be solved simply by

improving the characteristics of a single part. In addition, it is extremely difficult to clarify the generation mechanism and degree of effect through actual vehicle tests, so accurate analysis technology is needed.

This paper reports the results of constructing and applying evaluation indices and a simulation model to the development of mass production vehicles.

2. Development Goals

In order to shorten the development time for MT vehicles, it is important to improve the specifications as much as possible in the initial development phase and reduce trial and error in actual vehicle tests.

The accumulation of vehicle behavior simulation know-how has made it possible to accurately analyze transient behavior. However, actual vehicle measurement data concerning element characteristics is needed to accurately reproduce behavior, which makes this difficult to use in the initial development phase. In addition, thus far evaluation has been determined by sensory evaluation

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through actual vehicle test rides, so there are no substitute evaluation indices, and it would be difficult to make a grade judgment even if vehicle behavior could be simulated.

Therefore, the three main goals of this study were as follows.

- (1) Constructing evaluation indices capable of substituting for sensory evaluation
- (2) Constructing a simulation that can be utilized from the initial development phase
- (3) Applying these indices and simulation to the development of mass production vehicles to shorten the development time

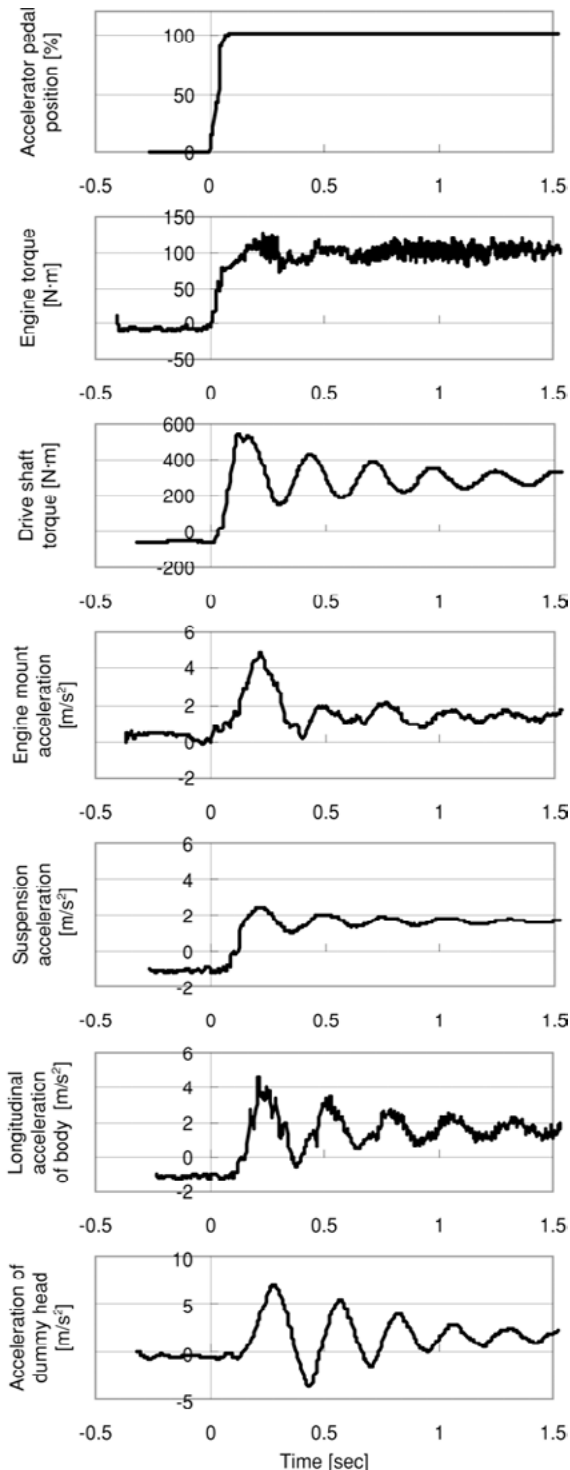


Fig. 1 Time history of body vibration by acceleration shock WOT acceleration, 2nd gear, 1500rpm

3. Construction of Evaluation Indices

To investigate evaluation indices, test ride comparisons of market vehicles were performed with multiple drivers, and sensory evaluation was conducted using the ten-point method. These results and measurement values were then compared and analyzed, and evaluation indices were constructed.

3.1. Test Method

The body longitudinal vibration frequency during acceleration differs according to the gear ratio, and the frequency increases at higher speed gear steps. In addition, the vibration when accelerating again from the state after deceleration fuel cut is larger than when accelerating from the steady cruising state.

The feeling is particularly worsened by the 3 to 8 Hz vibration that occurs when cruising at the low speed of 20 to 40 km/h in 1st through 3rd gears. Figure 1 shows some measurement examples. The body longitudinal vibration process during acceleration was confirmed through actual vehicle tests in which the accelerator pedal was pressed from the fully closed position to the fully open position to accelerate at the prescribed engine speed, and the torque and vibrations were measured. These measurements were taken for over ten types of vehicles with different shift steps, engine speeds and accelerator pedal openings. The engine torque during actual cruising used the net torque obtained by measuring and processing the internal pressure of all four cylinders in consideration of the combustion variance of each cylinder. Also, body longitudinal vibration during acceleration is felt as rocking of the head relative to the seat and neck, so a sensor was attached to the head of a dummy to measure the longitudinal acceleration. When the accelerator pedal is pressed to the fully open position, the engine generates sudden torque which produces torque fluctuations on the drive shaft. A short time thereafter, fluctuations occur almost simultaneously in the engine mount and the suspension, followed by overshoot and low cycle fluctuations in the body longitudinal direction. Then, after another short delay, fluctuations occur as measured by the instrumented dummy.

Figure 2 shows the frequency analysis of the dummy head acceleration and the body longitudinal vibration. The dummy head acceleration is amplified around 4 Hz, and attenuated at 11 Hz and higher.

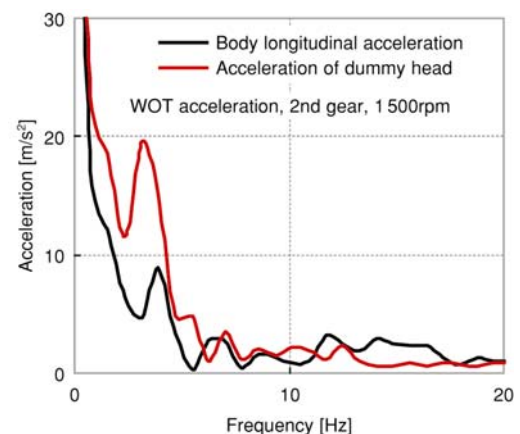


Fig. 2 Results of frequency analysis of dummy head acceleration

3.2. Creation of Indices

On the other hand, it was assumed from the questionnaire results that drivers feel the overshoot of the first peak as shock, and the subsequent vibrations as jerking. At the same time they feel the response speed (response) of the first peak, that is to say, a quick acceleration rise as comfort and acceleration that does not drop as smoothness. These subjective driving sensations were expressed as numerical values and compared with the results of sensory evaluation to construct five evaluation indices. Figure 3 shows the approach to each index, and the formulas used to calculate each numerical index are defined as follows.

(A) Shock: Non-dimensional value of the overshoot relative to the acceleration expected by the driver

$$\text{Overshoot} = \ddot{X}_A / \ddot{X}_{AVE} \quad (1)$$

(B) Jerking: Fluctuation energy amount obtained by integrating the low frequency fluctuation relative to the acceleration expected by the driver

$$\text{Swing energy} = 1/2 \cdot m \cdot \left\{ \int |\ddot{X}_B - \ddot{X}_{AVE}| dt \right\}^2 \quad (2)$$

(C) Response: Response speed relative to the driver's acceleration pedal operation

$$\text{Delay time} = t_p + t_N \quad (3)$$

(D) Quickness: Comfortable acceleration rise linked with the driver's acceleration pedal operation

$$\text{Torque increase} = (\ddot{X}_A - \ddot{X}_B) / t_p \quad (4)$$

(E) Smoothness: Minimum acceleration produced by the fluctuations during acceleration

$$\text{Minimum acceleration} = \ddot{X}_C \quad (5)$$

Nomenclature :

$\ddot{X}_A$: Peak of acceleration [m/s^2]

$\ddot{X}_{AVE}$: Average acceleration [m/s^2]

$\ddot{X}_B$: Real acceleration [m/s^2]

$\ddot{X}_C$: Bottom of acceleration [m/s^2]

t_p : Time until peak [sec]

t_N : No reactive time [m/s^2]

Figures 4 to 8 show the results of confirming the correlation of the five evaluation indices obtained by the above formulas with sensory evaluation by actual vehicle test rides, and show a high correlation in each case.

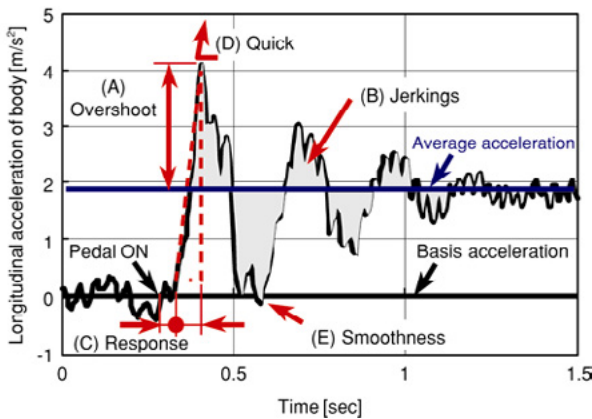


Fig. 3 Definition of index

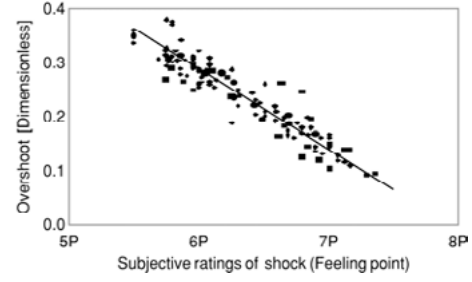


Fig. 4 Subjective ratings of shock characteristic against objective parameter

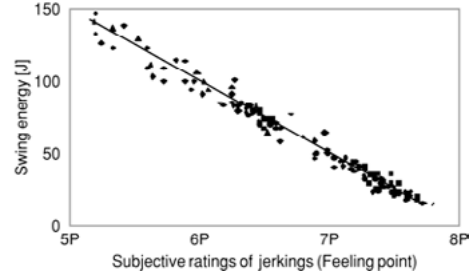


Fig. 5 Subjective ratings of jerkings characteristic against objective parameter

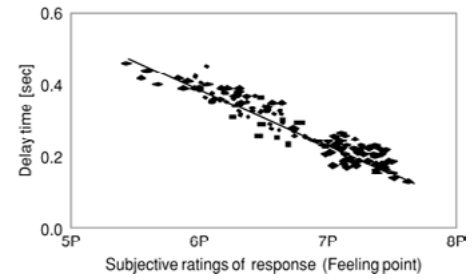


Fig. 6 Subjective ratings of response characteristic against objective parameter

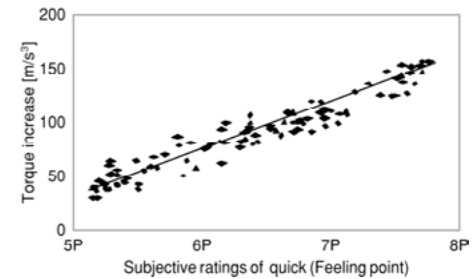


Fig. 7 Subjective ratings of quickness characteristic against objective parameter

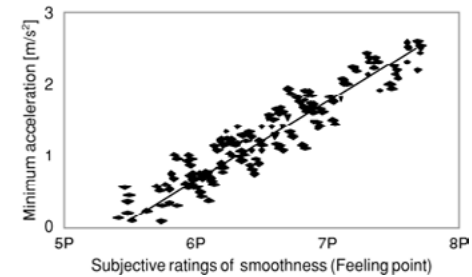


Fig. 8 Subjective ratings of smoothness characteristic against objective parameter

4. Creation of a Simulation Model

A simulation model was constructed with the body longitudinal vibration during acceleration as the coupled vibration from the engine to the transmission, drive shaft, tires, engine mount, suspension and body. The calculation formulas are shown below.

$$T_E - I_{FW} \ddot{\theta}_{FW} - T_{CL} = 0 \quad (6)$$

$$T_{CL} - C_{CL} (\dot{\theta}_{FW} - \dot{\theta}_{GB}) - K_{CL} (\theta_{FW} - \theta_{GB}) = 0 \quad (7)$$

$$T_{CL} - I_{GB} \ddot{\theta}_{GB} - T_{GB} / i = 0 \quad (8)$$

$$T_{GB} - K_{GB} (\theta_{GB} / i - \theta_{DS}) = 0 \quad (9)$$

$$T_{GB} - I_{DS} \ddot{\theta}_{DS} - T_{DS} = 0 \quad (10)$$

$$T_{DS} - C_{DS} (\dot{\theta}_{DS} - \dot{\theta}_{WH}) - K_{DS} (\theta_{DS} - \theta_{WH}) = 0 \quad (11)$$

$$T_{DS} - I_{WH} \ddot{\theta}_{WH} - T_{WH} = 0 \quad (12)$$

$$T_{DS} - I_E \ddot{\theta}_E - T_{EM} = 0 \quad (13)$$

$$F_{WH} - T_{WH} \theta_{SUS} / X_{SUS} = 0 \quad (14)$$

$$F_{WH} - M_{WH} \ddot{X}_{SUS} - F_V = 0 \quad (15)$$

$$F_V - C_{SUS} (\dot{X}_{SUS} - \dot{X}_V) - K_{SUS} (X_{SUS} - X_V) = 0 \quad (16)$$

$$F_V - M_V \ddot{X}_V - M_{PP} \ddot{X}_{EM} = 0 \quad (17)$$

Nomenclature :

T : Torque [N·m]

I : Inertia [N·m·s²]

θ : Torsional angle [rad]

C : Damping property [N·m·s/rad]

K : Torsional stiffness [N·m/rad]

F : Force [N]

M : Mass [kg]

X : Displacement [m]

Subscripts :

E : Engine

F : Flywheel

CL : Clutch

GB : Gear box

i : Gear ratio

EM : Engine mount

DS : Drive shaft

WH : Tire wheel

V : Vehicle

SUS : Suspension

PP : Power plant

The characteristic data of each element used in the simulation all used the design values. The body elastic vibration frequency range is lower than 20 Hz, so the power plant and the body were treated as rigid bodies. The frequency for this phenomenon is relatively low and the

dynamic magnification of rubber is close to 1, so it was thought that the load-displacement dynamic characteristics of the engine mount, suspension, tires and other elements could be replaced with static characteristics in the same manner as the clutch torsion and the drive shaft torsional stiffness. Non-linearity of these load-displacement dynamic characteristics was taken into account by applying a table function. Also, the engine torque input values used the values obtained by bench tests.

Figure 9 shows an example comparing the simulation results of body longitudinal vibration during full acceleration with actual vehicle measurement data.

This figure shows that in addition to the 3 Hz low frequency vibration which is the main fluctuation, the 15 Hz frequency component occurring on the first peak can also be calculated.

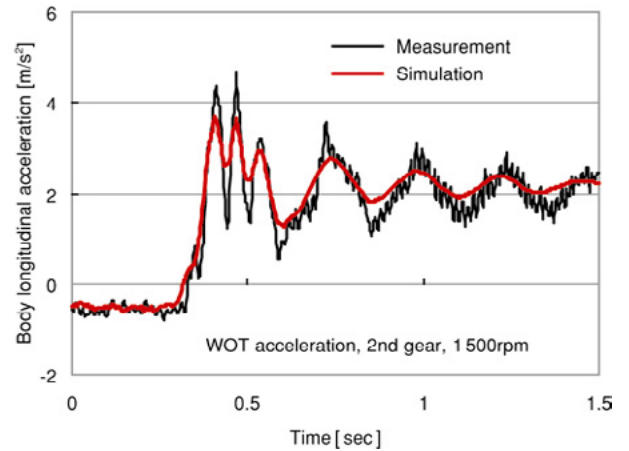


Fig. 9 Results of verification of simulation

5. Application to Development

5.1. Analysis of Contribution

The above simulation was conducted in the initial development phase of the new model Accord, and the results of analyzing the contribution of each evaluated part to body longitudinal vibration are shown in Fig. 10. This shows that the drive shaft stiffness, suspension stiffness, engine torque control, engine rotation inertia and body inertia have a significant effect. Therefore, suspension stiffness and torque control measures were investigated.

5.2. Countermeasure Effects

5.2.1. Suspension characteristics

Of the various suspension characteristics, the front and rear compliance characteristics are determined to simultaneously achieve the conflicting required performances of riding comfort and handling and stability. These characteristics are necessary when backward force acts on the vehicle, and it was found that changing the forward characteristics, which are a cause of shock during acceleration, had no effect on these performances. Therefore, the characteristics were changed to asymmetrical characteristics in the forward and backward directions as shown in Fig. 11 to reduce the shock during acceleration while maintaining riding comfort.

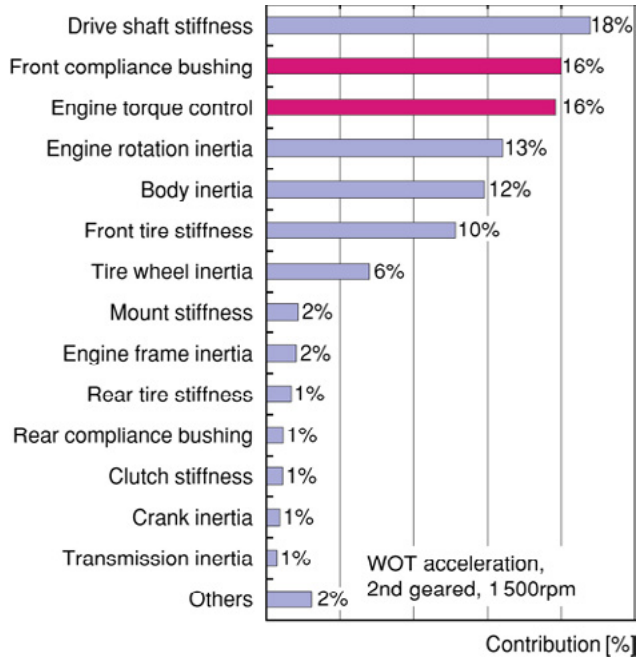


Fig. 10 Analysis of contribution of each part

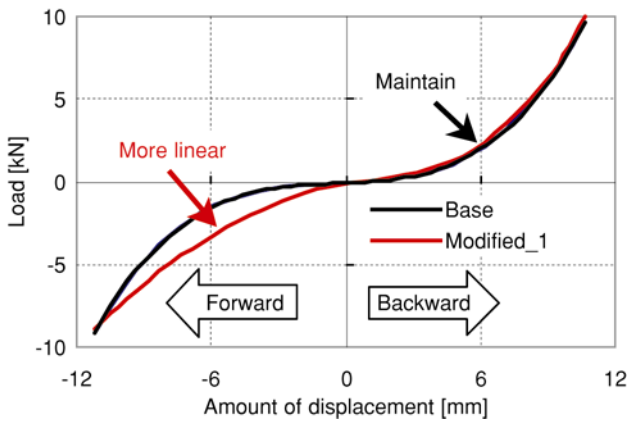


Fig. 11 Compliance bushing characteristic

Figures 12 and 13 compare the results before and after changing the compliance bush characteristics of the suspension. These figures show that the first suspension displacement peak during acceleration has been reduced, and at the same time the 15 Hz overshoot seen on the first peak has also been improved.

5.2.2. Engine torque control

Analysis of contribution showed that shock and jerking are the most affected by engine torque control, so improvement of these two items was investigated.

Conventional engine torque control methods include delaying the ignition timing angle or reducing the intake air volume and fuel injection amount to limit the engine torque rise speed, thus reducing overshoot and low frequency fluctuations.

First the optimum engine torque rise for improving shock was investigated. Figure 14 shows the changes in the evaluation index scores. Increasing the engine torque rise speed was found to improve response and quickness, but to worsen shock, jerking and smoothness, with shock in particular changing significantly. The optimum scores were achieved by reducing the speed by approximately 20% relative to the initial setting data.

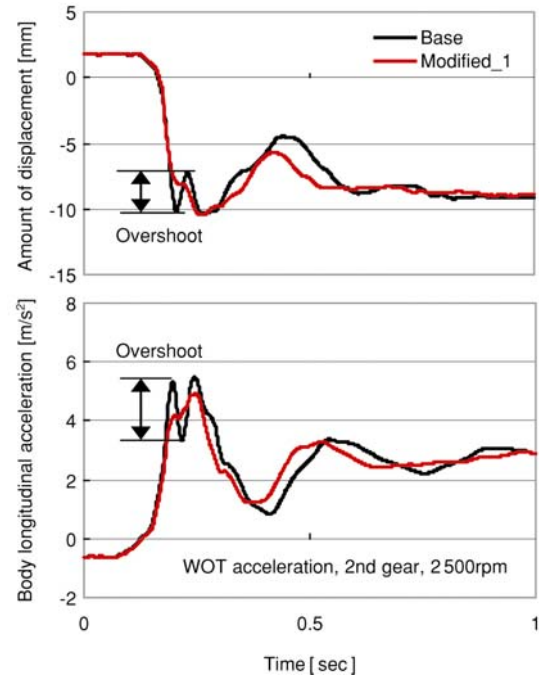


Fig. 12 Influence of compliance bushing (Simulation)

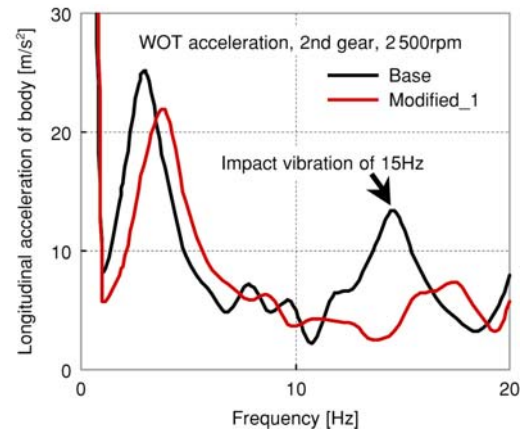


Fig. 13 Result of frequency analysis of body longitudinal acceleration of body (Simulation)

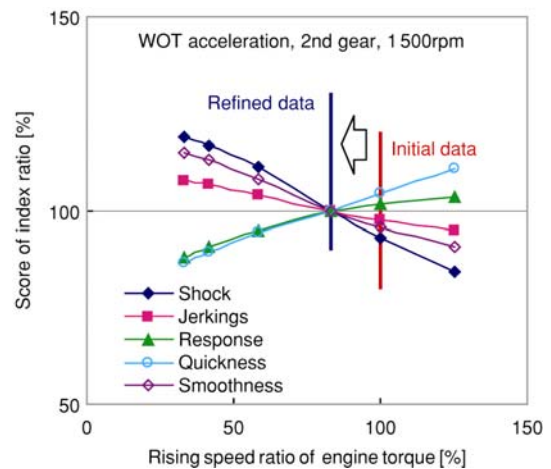


Fig. 14 Comparisons of speed of increase of engine torque (Simulation)

Next the optimum engine torque control timing for improving jerking was investigated. The control timing delay at various engine speeds was measured. The allowable timing delay was the value obtained using the aforementioned indices. As the engine speed decreased, the control delay became more pronounced and jerking worsened. The cause of this control delay was the longer arithmetic processing interval for engine rotation sync control. Changing the program reduced this control timing delay in the low speed range as shown in Fig. 15.

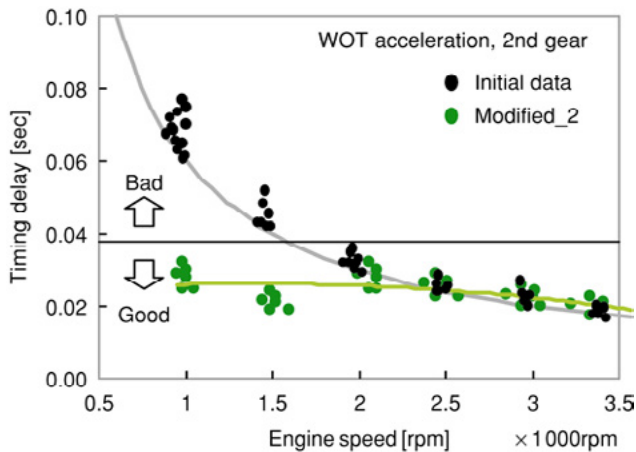


Fig. 15 Engine timing delay characteristics (Simulation)

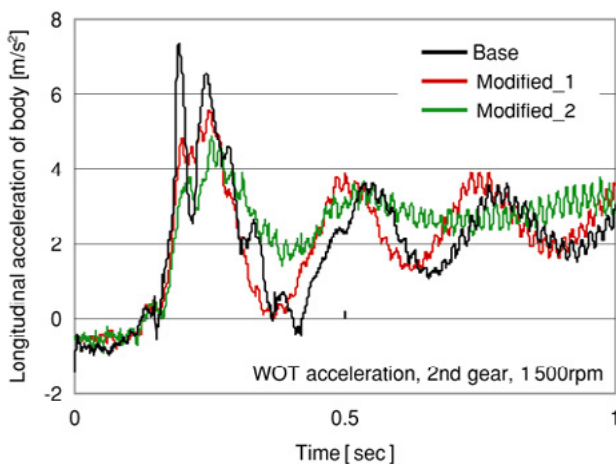


Fig. 6 Test results

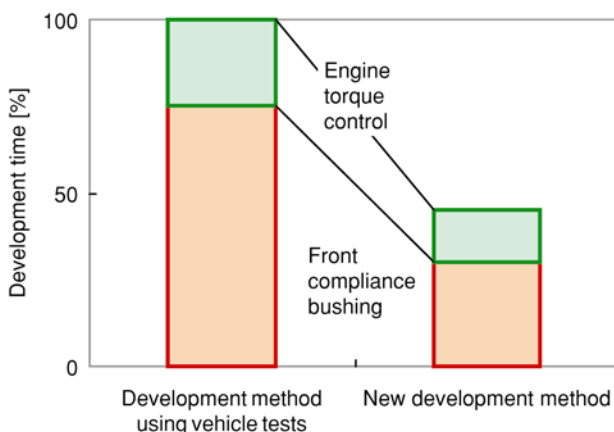


Fig. 17 Development time for acceleration feeling

Figure 16 shows the measurement results for body longitudinal vibration that reflects these countermeasures. Modified_1 with improved suspension characteristics and Modified_2 with engine torque control added show vast improvements to shock and jerking.

5.3. Effects of Application to Development

The newly developed method reduced trial and error in actual vehicle tests, and halved the development time as shown in Fig. 17.

6. Conclusion

Body longitudinal vibration of MT vehicles during acceleration was studied, and the following results were obtained.

- (1) Five evaluation indices for shock, jerking, response, quickness and smoothness were constructed to take the place of sensory evaluation of body longitudinal vibration during acceleration.
- (2) Using the design values for all the characteristics data of each element used in the simulation made it possible to investigate specifications in the initial development phase before an actual vehicle exists.
- (3) The development time of mass production vehicles was cut in half.

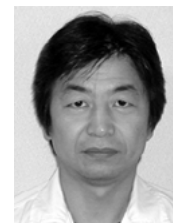
Reference

- (1) Inoue, M.: Analysis on Acceleration/Deceleration Shock and Vibration in FF Vehicle, Proceedings Journal of Society of Automotive Engineers of Japan 921087 (1992)

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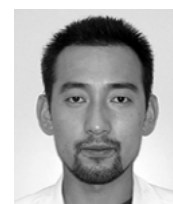
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