

Enhancement of Feeling in Turn Focusing on Pitching Behavior

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ABSTRACT

In order to provide a natural feeling in turn for general drivers in daily driving, a method was examined for adjusting the pitching behavior produced by steering in control of acceleration and deceleration linked with lateral motion. In consideration of the characteristic that the pitch angle response is twice the steering frequency, a control law was devised to reduce unnatural feeling in turn. The effect of the control law and the controlled variable was verified by simulation, and it was confirmed that the timing at which the pitching behavior occurs can be adjusted without impacting the rolling behavior. Next, actual vehicle tests were conducted, and the vehicle behavior was confirmed to be similar to that in the simulation. In addition, sensory evaluation showed that the method is effective in enhancing the feeling in turn, and that there is an appropriate value for the control strength.

1. Introduction

Numerous control devices are applied to the chassis area to enhance vehicle dynamic performance. Typical examples include control of the front and rear wheel steering angles to enhance maneuverability at low vehicle speeds and stability at high vehicle speeds^{(1), (2)}, ABS control that helps decrease tire locking in sudden braking, and yaw moment control by lateral distribution of the braking and driving forces^{(3), (4)}, all of which have increased stability and responsiveness.

In control by braking, the yaw moment control installed as standard equipment has enhanced stability performance, and application is also spreading to various areas other than emergency avoidance^{(5), (6)}. However, increasing the usage frequency of braking devices necessitates consideration of factors such as durability and quietness, so it has not been widely applied to the operation area used by general drivers in daily driving (Fig. 1).

In control by the power plant, it is known that when acceleration and deceleration are performed in turning, a yaw moment is generated due to weight transfer between the front and rear wheels⁽⁷⁾, and technology has been reported that provides driving enjoyment and a good driving feel in the daily operation area by controlling acceleration and deceleration linked with lateral motion⁽⁸⁾ to assist the turning operation and realize a “smooth G connection”⁽⁹⁾.

With the electrification of power plants, the application range of vehicle dynamic control that makes use of the good responsiveness of the motor is expanding. This makes

it also necessary to consider the unnatural feeling produced by control intervention.

In addition, it has been reported that pitching behavior also occurs along with yaw and rolling behavior in turning, and that the temporal difference between rolling and pitching behavior impacts the turning sensation⁽¹⁰⁾.

This study therefore defined the sensation of turning without unnatural feeling in response to the driver’s steering wheel operation as “feeling in turn,” and examined a method to enhance the feeling in turn and reduce the unnatural feeling produced by control intervention, focusing on pitching behavior in turning within the aforementioned technology to control acceleration and deceleration linked with lateral motion.

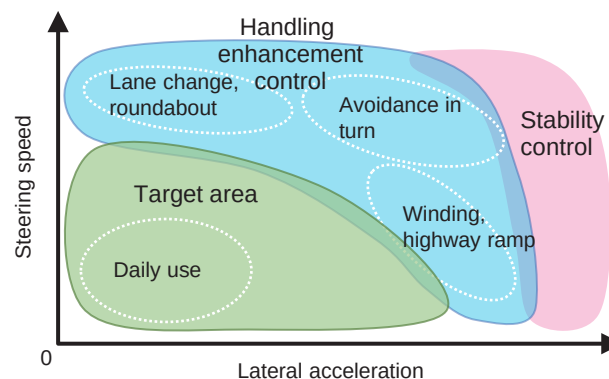


Fig. 1 Target scene

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2. Pitching Motion Produced by Steering

It is known that when acceleration and deceleration occur in turning, weight transfer occurs between the front and rear wheels, and a yaw moment is generated⁽⁷⁾. In longitudinal force control linked with lateral motion, a yaw moment that promotes turning is generated by the longitudinal force on the deceleration side. However, a pitching moment is also generated at the same time, which also contributes to pitching behavior.

Figure 2 shows an example of the lateral acceleration and the roll angle and pitch angle responses in sinusoidal steering input. Here, the lateral acceleration and roll angle can be seen to respond symmetrically to the left and right steering directions. In contrast, the pitch angle has characteristics such that it responds independently to the steering direction and has a response frequency twice the steering frequency.

It was therefore thought that if the temporal difference between the rolling and pitching behavior could be adjusted by controlling the longitudinal force to adjust the phase of the pitching behavior, this would be effective to enhance the feeling in turn.

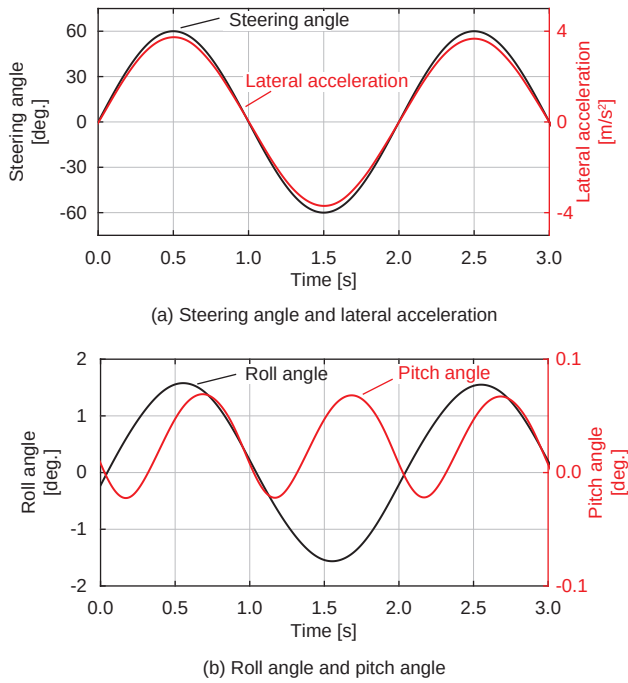


Fig. 2 Example of vehicle motion during sinusoidal steering input

3. Control for Enhancement of Feeling in Turn

3.1. Modeling of Pitching Motion

In order to perform control that adjusts the phase of the pitching behavior by longitudinal force control, it is

necessary to incorporate the pitching motion characteristics into the control law. However, taking the pitching motion into account increases the complexity of the vehicle model.

An approximate equation was thus derived that reproduces the aforementioned pitching motion characteristics with a minimum model, and a control law based on that approximate equation was examined.

First, the pitching motion produced by steering is summarized as Eq. (1).

$$I_y \ddot{\theta} = -hF_x + M_{YJ} + M_{YS} \quad (1)$$

On the right side of Eq. (1) here, F_x is the longitudinal force, and M_{YJ} and M_{YS} are the respective pitching moments generated by the jacking force and the suspension. The pitching moments are positive in the forward downward direction as shown in Fig. 3, and the gyro moment, tire vertical spring stiffness, unsprung mass, and anti-dive/lift/squat that contribute little to steering and pitching motion were ignored.

The longitudinal force F_x is the force acting in the x-axis direction of the vehicle body, and only the longitudinal force generated by turning is targeted. In steering, the cornering drag generated by the lateral force of the front wheels acts as the longitudinal force F_x , so longitudinal acceleration occurs in the direction to decelerate the vehicle body.

As the side-slip angle is small, by treating the lateral and cornering forces as equal, the longitudinal force due to cornering drag can be written as shown in Eq. (2) using the front wheel cornering force and the front wheel steering angle.

$$F_x = -F_{yf} \delta \quad (2)$$

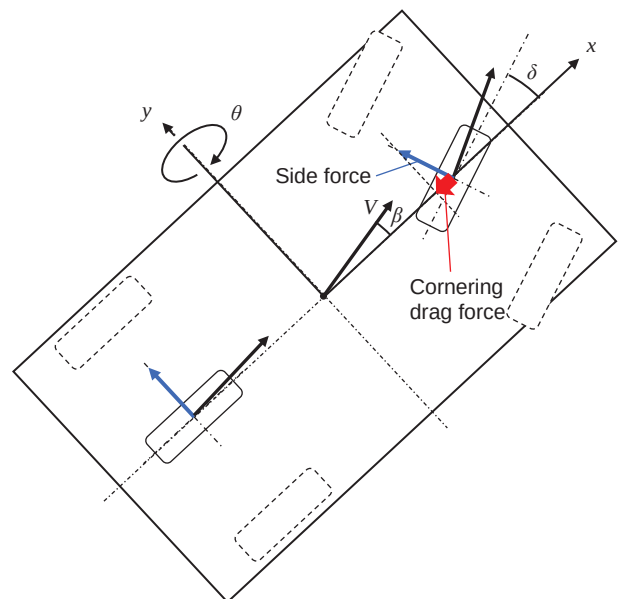


Fig. 3 Cornering drag force

The front wheel cornering force is described concisely using the lateral acceleration Y_G in the steady state as Eq. (3).

$$F_{yf} = \frac{l_f}{l} m Y_G \quad (3)$$

By substituting Eq. (3) into Eq. (2), the cornering drag becomes as shown in Eq. (4).

$$F_x = -\frac{l_f}{l} m Y_G \delta \quad (4)$$

Here, if the lateral acceleration gain G_Y relative to the front wheel steering angle is used, Eq. (4) can also be described as Eq. (5).

$$F_x = -\frac{l_f}{l} m G_Y \delta^2 \quad (5)$$

From Eq. (5), the cornering drag is proportional to the square of the front wheel steering angle, so it is independent of the steering direction and the response frequency is twice the steering frequency. These characteristics match the pitching motion characteristics shown in Fig. 2.

Next, the pitching moment M_{YJ} generated by the jacking force, which is the second term on the right side of Eq. (1), can be expressed as Eq. (6) using the roll center height, track width, center of gravity height, and cornering force.

$$M_{YJ} = 2 \frac{h}{mg} \left(\frac{2}{T} \right)^2 \left(-h_f F_{yf}^2 + h_r F_{yr}^2 \right) \quad (6)$$

Here, obtaining the rear wheel cornering force in the same way as in Eq. (3) and substituting it into Eq. (6) results in Eq. (7).

$$M_{YJ} = 2 \frac{mh}{g} \left(\frac{2}{T} \right)^2 \left(-h_f \frac{l_f}{l} + h_r \frac{l_r}{l} \right) Y_G^2 \quad (7)$$

From Eq. (7), the pitching moment generated by the jacking force is generated according to the square of the lateral acceleration. In addition, like Eq. (5), if the lateral acceleration gain G_Y relative to the front wheel steering angle is used, Eq. (7) can also be described as Eq. (8).

$$M_{YJ} = 2 \frac{mh}{g} \left(\frac{2}{T} \right)^2 \left(-h_f \frac{l_f}{l} + h_r \frac{l_r}{l} \right) (G_Y \delta)^2 \quad (8)$$

Since Eq. (8) is also proportional to the square of the front wheel steering angle, the pitching moment generated by the jacking force is also consistent with the pitching motion characteristics.

The pitching moment M_{YS} generated by the suspension,

which is the third term on the right side of Eq. (1), can be expressed as Eq. (9) using the pitch damping coefficient and pitch stiffness of the suspension.

$$M_{YS} = -C_\theta \dot{\theta} - K_\theta \theta \quad (9)$$

Therefore, the basic relationship between steering and pitching motion can be obtained as Eq. (10) by substituting the approximate equations (4), (7), and (9) into Eq. (1).

$$I_Y \ddot{\theta} = h \frac{l_f}{l} m Y_G \delta + 2 \frac{mh}{g} \left(\frac{2}{T} \right)^2 \left(-h_f \frac{l_f}{l} + h_r \frac{l_r}{l} \right) Y_G^2 - C_\theta \dot{\theta} - K_\theta \theta \quad (10)$$

From Eq. (10), an approximate equation was obtained that can concisely express the characteristics of the pitching motion produced by steering.

3.2. Derivation of Control Law

Next, it was thought that if the phase of the pitching behavior in response to the steering input could be adjusted by longitudinal force control, this would be effective to enhance the feeling in turn. Therefore, the approximate equation obtained in the previous section was used to examine a control law that advances the forward downward pitching behavior among the behaviors when increasing the steering angle such as turn-in as shown in Fig. 4.

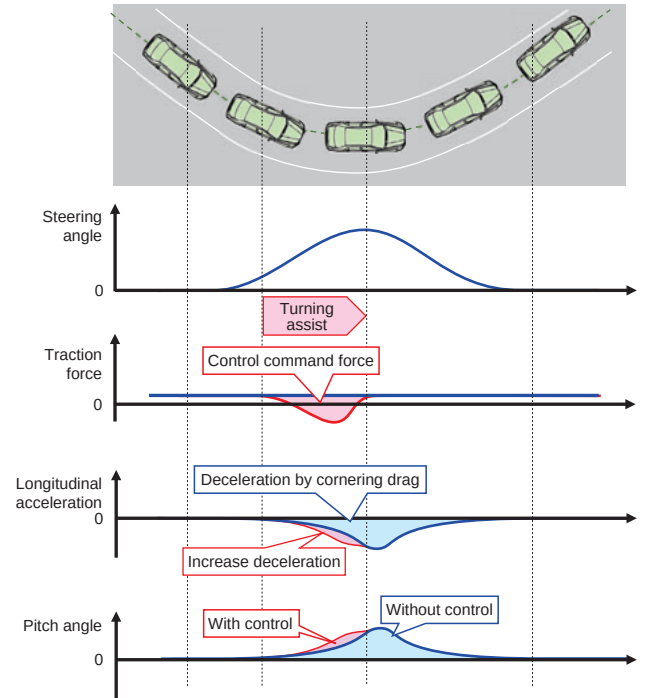


Fig. 4 Example of control law operation

The first term on the right side of Eq. (10) is the pitching moment proportional to the longitudinal force generated by cornering drag. It is thought that if the phase of the pitching moment can be advanced using this term, the pitch angle response characteristic shown in Fig. 2(b) can be retained, enhancing the feeling in turn while reducing the unnatural feeling produced by control intervention.

Addition of an item that advances the phase with the time constant τ_c to the first term on the right side of Eq. (10) in order to advance the pitching behavior results in Eq. (11).

$$I_Y \ddot{\theta} = h \frac{l_r}{l} m \left(Y_G \delta + \tau_c \frac{d}{dt} (Y_G \delta) \right) + 2 \frac{mh}{g} \left(\frac{2}{T} \right)^2 \left(-h_f \frac{l_r}{l} + h_r \frac{l_r}{l} \right) Y_G^2 - C_\theta \dot{\theta} - K_\theta \theta \quad (11)$$

However, for the pitching motion when longitudinal force control is performed, the pitching moment F_{xc} generated by the control command force is added to Eq. (10), resulting in Eq. (12).

$$I_Y \ddot{\theta} = h \frac{l_r}{l} m Y_G \delta + 2 \frac{mh}{g} \left(\frac{2}{T} \right)^2 \left(-h_f \frac{l_r}{l} + h_r \frac{l_r}{l} \right) Y_G^2 - C_\theta \dot{\theta} - K_\theta \theta - h F_{xc} \quad (12)$$

Furthermore, substituting Eq. (11) into Eq. (12) and summarizing obtained Eq. (13) as the control command force for advancing the pitching behavior.

$$F_{xc} = - \frac{l_r}{l} m \tau_c \frac{d}{dt} (Y_G \delta) \quad (13)$$

In Eq. (13), the product of the lateral acceleration and the front wheel steering angle is differentiated, so the longitudinal force that advances the pitch phase acts on the deceleration side when increasing the steering angle, and on the acceleration side when decreasing the steering angle. This control law is intended to advance the pitching behavior in turn-in, so Eq. (14) is used so that the control command force of Eq. (13) acts only on the deceleration side when increasing the steering angle.

$$F_{xc}' = \min \left(- \frac{l_r}{l} m \tau_c \frac{d}{dt} (Y_G \delta), 0 \right) \quad (14)$$

Here, by substituting Eq. (5), the control command force of Eq. (14) can also be described as Eq. (15).

$$F_{xc}' = \min \left(- \frac{l_r}{l} m \tau_c \frac{d}{dt} (G_Y \delta^2), 0 \right) \quad (15)$$

Like Eq. (5), the right side of Eq. (15) includes an element of the square of the front wheel steering angle, so the control command force is independent of the steering direction and the response frequency is twice the steering frequency.

From the above, a control law was established that adjusts the phase of the pitching behavior in turn-in by longitudinal force control using the time constant τ_c .

4. Simulation Results

The control effects of the control law were verified by simulation.

The vehicle model used in the simulation had ten degrees of freedom consisting of six sprung degrees of freedom and four unsprung degrees of freedom for each wheel (up and down). The model took into account jacking due to the roll center height, anti-dive angle, and anti-squat angle, and the tire characteristics were such that the cornering power was linear to the load.

The vehicle model used the specification values of a D-segment hybrid EV sedan. The control command force was applied to the vehicle body as longitudinal force at the wheel center, and the power plant response delay was considered as delay time.

As shown in Fig. 5(a), a J-turn at a vehicle speed of 50 km/h was used as the test mode, and the control operation and vehicle behavior in turn-in were verified.

In order to confirm the control effect, cases with and without control were compared. Four different time constant τ_c schemes were used for cases with control: reference scheme 1 that was the smallest value for which a significant difference was observed, and then 2.5, 5, and 10 times that value.

Figure 5 shows the simulation results.

The longitudinal force in Fig. 5(c) was output as the control command force when increasing the steering angle from straight running, and as the time constant τ_c increased, the control command force also increased.

At this time, the longitudinal acceleration in Fig. 5(d) rose faster and the peak also became larger as the time constant τ_c increased.

The pitch angle in Fig. 5(f) also exhibited changes similar to the longitudinal acceleration at this time, but it was confirmed that the roll angle in Fig. 5(e) was unaffected.

This confirmed that the longitudinal acceleration and the pitch angle can be controlled by the time constant τ_c .

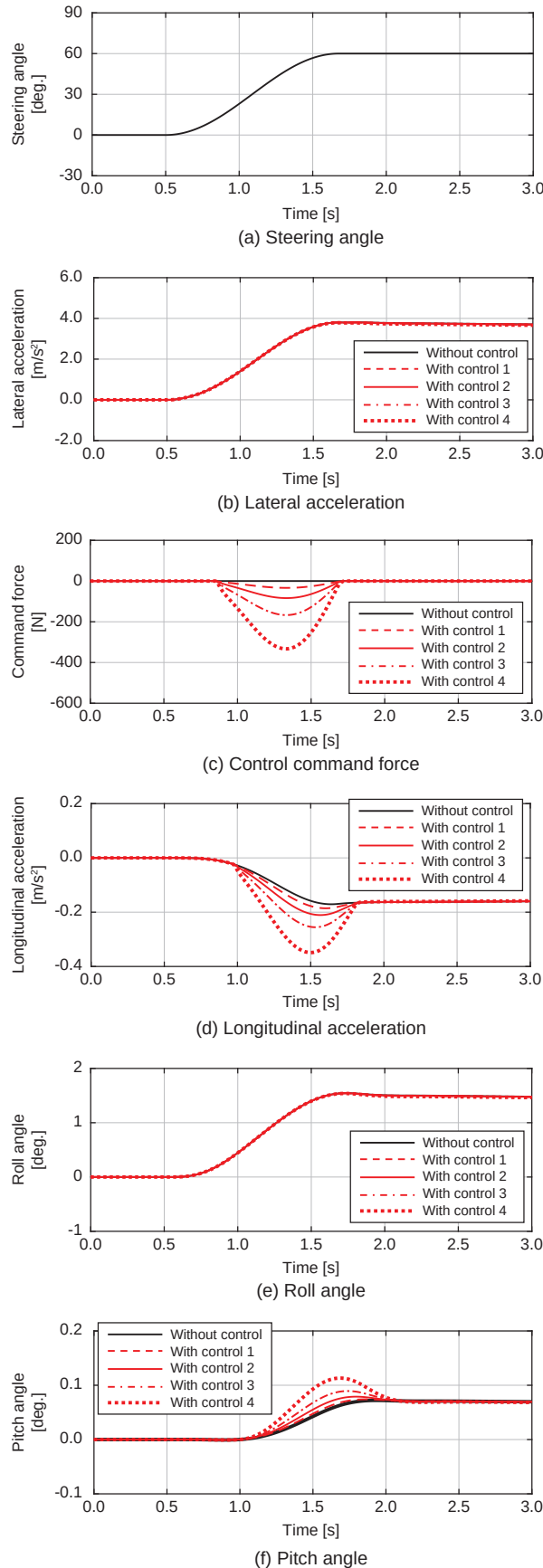


Fig. 5 Simulation results

5. Actual Vehicle Test Results

Next, verification was performed by actual vehicle tests.

The test vehicle used the D-segment hybrid EV sedan that was the basis for the simulation vehicle model. The control command force was given as the modified value of the driving force of the electric power plant system. As shown in Fig. 6(a), a J-turn at a vehicle speed of 50 km/h was used as the test mode, and the control operation and vehicle behavior in turn-in were verified.

A steering robot was used to steer the vehicle in order to standardize the steering input for each measurement, and the roll and pitch angles were measured using vehicle-to-ground laser displacement meters.

As in the simulation, cases with and without control were compared, and the cases with control used the same time constant τ_C schemes.

Figure 6 shows the measurement results of the actual vehicle tests.

The control command force in Fig. 6(c) output when increasing the steering angle from straight running changed in a similar manner to the simulation when the time constant τ_C was changed.

The longitudinal acceleration in Fig. 6(d) also changed in a similar manner, and it was further confirmed that the roll angle in Fig. 6(e) was unaffected as in the simulation.

From these results, it can be inferred that the pitch angle in Fig. 6(f) also changes in a similar manner, and schemes 3 and 4 with larger control command force changed in a similar manner to the simulation. In contrast, schemes 1 and 2 with smaller control command force deviated from the trends in the simulation due to the impact of measurement error.

Next, sensory evaluation was conducted by the expert driver assigned to this control development, and it was confirmed that as the time constant τ_C increased, the feeling in turn was enhanced compared to the case without control. However, when the time constant τ_C was increased further, the unnatural feeling increased, indicating that there is an appropriate value for the control strength.

In addition, to verify the control effect, sensory evaluation was also conducted by multiple test drivers not assigned to control development. Here, the value judged to be appropriate by the expert driver assigned to this development was used as the time constant τ_C setting for the case with control. As a result, comments were received that the feeling in turn with control was enhanced compared to without control.

From the above, although the effect of the devised control law to enhance feeling in turn could not be quantitatively demonstrated in terms of pitch angle, the effect was confirmed by the quantitative value of longitudinal acceleration and by sensory evaluation.

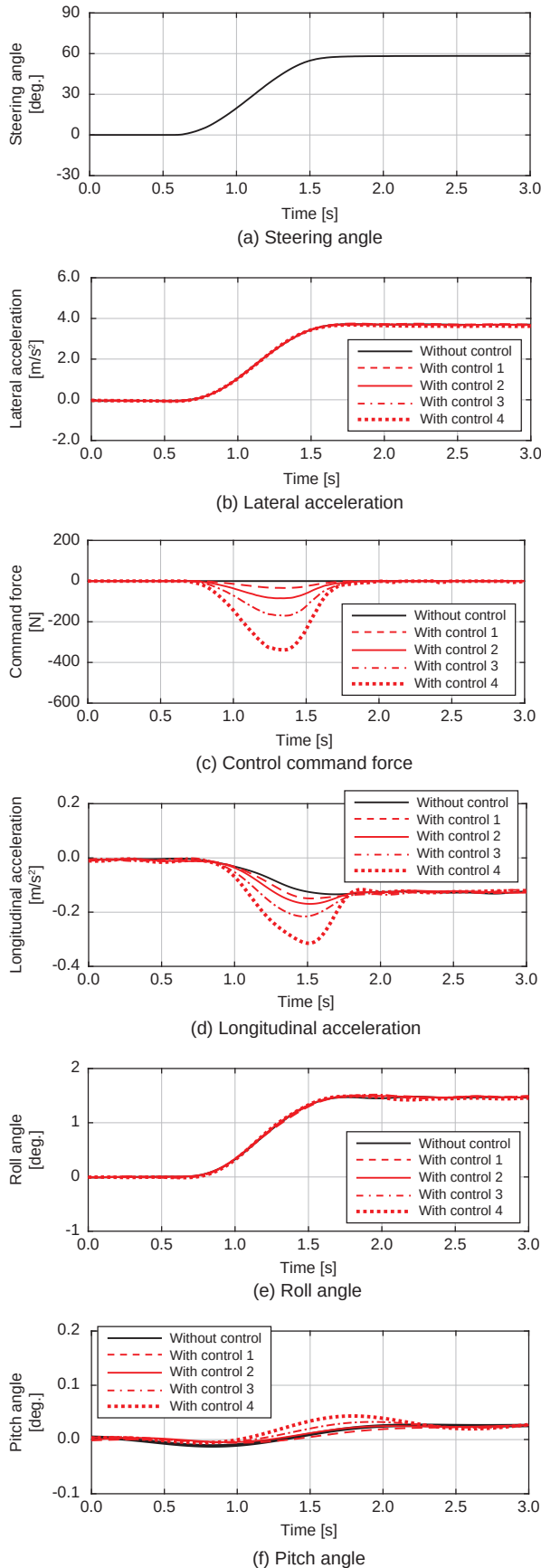


Fig. 6 Actual vehicle test results

6. Conclusion

In order to provide good feeling in turn with natural pitching behavior in the operation area used by general drivers in daily driving, a method was examined to enhance the feeling in turn and reduce the unnatural feeling produced by control intervention, focusing on pitching behavior in turning.

- (1) An approximate equation was derived that reproduces the aforementioned pitching motion characteristic with a minimum model, and a control law based on that approximate equation was examined.
- (2) A control law was devised that reduces the unnatural feeling in turn. This was done by incorporating the characteristics that the pitching behavior is independent of the steering direction and twice the steering frequency into the control law, and retaining the pitch angle response characteristics.
- (3) It was confirmed by simulation that the timing at which the pitch angle occurs can be effectively adjusted without impacting the roll angle.
- (4) Vehicle behavior similar to that in the simulation was also confirmed in actual vehicle tests.
- (5) Sensory evaluation by multiple drivers using an actual vehicle indicated that the control law is effective in enhancing the feeling in turn.

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List of Symbols

m	Vehicle mass
I_Y	Pitching moment of inertia around center of gravity
l	Wheelbase
l_f	Distance of front axle to center of gravity
l_r	Distance of rear axle to center of gravity
T	Track width
h	Center of gravity height
h_f	Front axle roll center height
h_r	Rear axle roll center height
C_θ	Suspension pitch damping coefficient
K_θ	Suspension pitch stiffness
F_{yf}	Front wheel cornering force
F_{yr}	Rear wheel cornering force
F_x	Longitudinal force
F_{xc}	Control command force
F_{xc}'	Control command force limited to deceleration side
M_{ys}	Pitching moment by suspension
M_{yj}	Pitching moment by jacking force
M_z	Yawing moment
Y_G	Lateral acceleration
G_Y	Lateral acceleration gain for front wheel steering angle
g	Gravity acceleration
$\ddot{\theta}$	Pitch angular acceleration
$\dot{\theta}$	Pitch angular velocity
θ	Pitch angle
δ	Front wheel steering angle

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