

Study of Simulation Technology for Limit Drivability

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ABSTRACT

Using conventional technology, it used to be difficult to calculate vehicle behavior in a limit handling situation by mechanical system analysis and predict that behavior with a high degree of accuracy. A method using tire modeling based on Magic Formula has been developed, which has been optimized for limit behavior, and accounts for lateral tire deflection. From a vehicle standpoint, a method using car modeling based on conventional vehicle model has been developed for improvement of the suspension rate and traction torque control. These measures have made it possible to perform mechanical system analysis calculation of vehicle handling behavior up to the limit. As a result, it has become possible to attain a high degree of accuracy in predicting vehicle limit behavior in turns, which is one of the dynamic characteristics for limit drivability.

1. Introduction

Various indexes are used to indicate vehicle driving stability, and a number of techniques for predicting vehicle driving stability have been researched, developed and applied. However, limit handling stability is still difficult to predict, and constructing highly accurate prediction technology has been a pressing issue. Reproducing vehicle behavior in limit conditions in the virtual space of a simulation would allow desktop evaluation and make it possible to reduce the test load using actual vehicles. Furthermore, it is thought that prediction technology for limit conditions could provide a new opportunity for investigating characteristics, and contribute to more efficient vehicle development. This paper reports that technology was developed to more accurately predict cornering performance in limit conditions by improving the vehicle model based on conventional simulation technology for vehicle dynamics, and constructing a tire model for calculation of cornering performance in limit conditions.

2. Basic Approach

Vehicle dynamic characteristics in limit conditions include various items, but this study focused only on cornering performance in limit conditions. There are two main patterns for evaluating cornering performance in limit conditions. One is evaluation of limit performance in the steady state. The testing method is prescribed by the ISO steady state cornering test (ISO4138), which also prescribes basic methods for evaluating limit performance. The other is evaluation of limit performance in the transient state. This evaluation method is typified by the J-turn mode test. Thus far, the establishment of evaluation techniques has been an issue. Figure 1 shows typical evaluation methods for both patterns. The J-turn mode is prescribed by the ISO transient response test (ISO7401), but this is mainly for evaluation of characteristics for linear systems of transient response. Therefore, this study used the ISO test as a reference and set a different testing method in order to evaluate limit performance in the transient state. The J-turn described here

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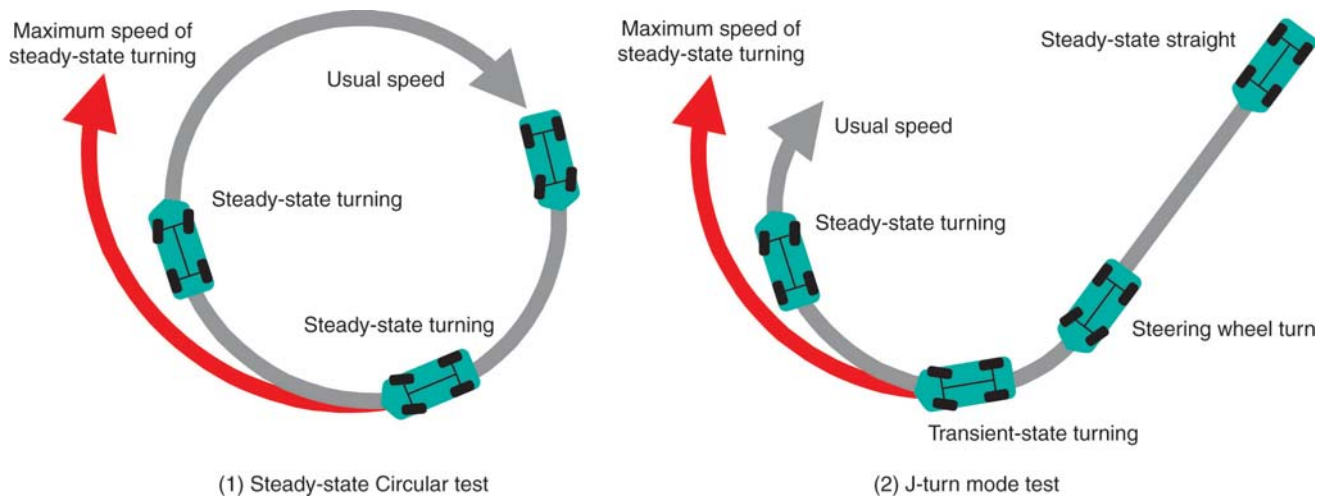


Fig. 1 Two patterns for evaluation of turning behavior

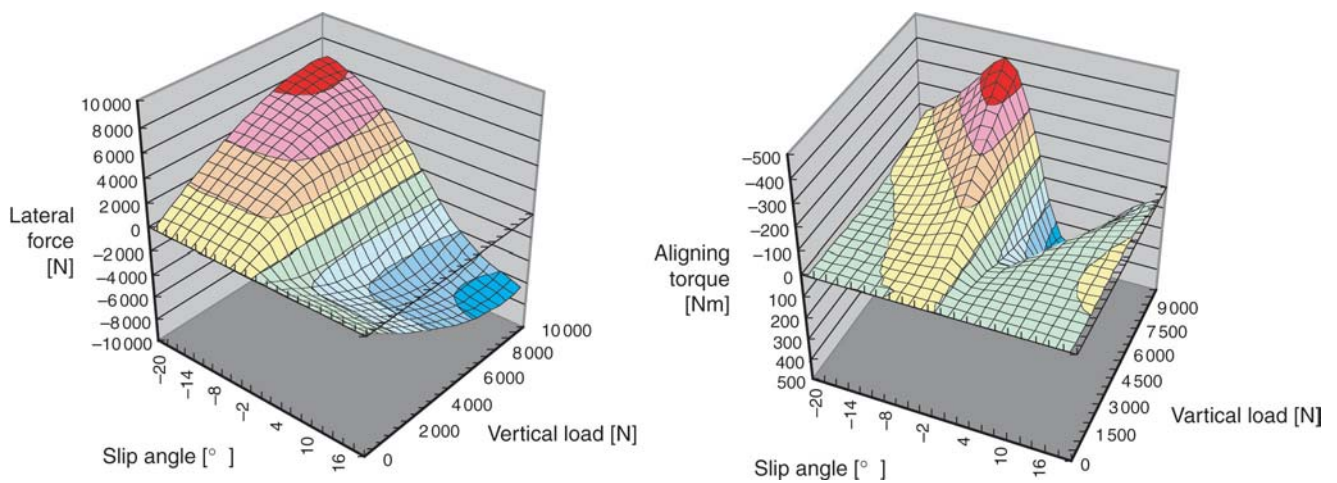


Fig. 2 Nonlinear characteristics of tire

indicates a driving pattern where the steering wheel is turned to a specific steering angle to transiently enter the turning state, then the vehicle cruises at a constant steering angle and speed until steady-state turning is reached. The vehicle behavior at the maximum speed ultimately reached is defined as the cornering performance at limit conditions, and the vehicle behavior at a sufficiently lower speed than the maximum speed is called the steady state cornering performance.

A number of tools for simulating and predicting vehicle behavior have been developed and applied thus far. However, none of these tools are capable of accurately expressing the strong nonlinear characteristics of the tires in limit conditions, or take into account the tire deflection characteristics, so application to investigations of cornering performance in limit conditions is difficult. In limit conditions, as shown in Fig. 2, the load, slip angle and other values become extremely large, and the generated force and torque exhibit strong nonlinear characteristics. In addition, Fig. 3 shows an image of tire deflection produced by lateral force on the tire, and the deflection amount in limit conditions is also a large value as shown here. Therefore, the results of calculations that ignore these factors will contain increasingly large errors, and the required accuracy cannot be obtained. Constructing a tire model that more accurately expresses tire cornering characteristics and deflection characteristics in limit conditions is a requirement for better predicting cornering performance in limit conditions.

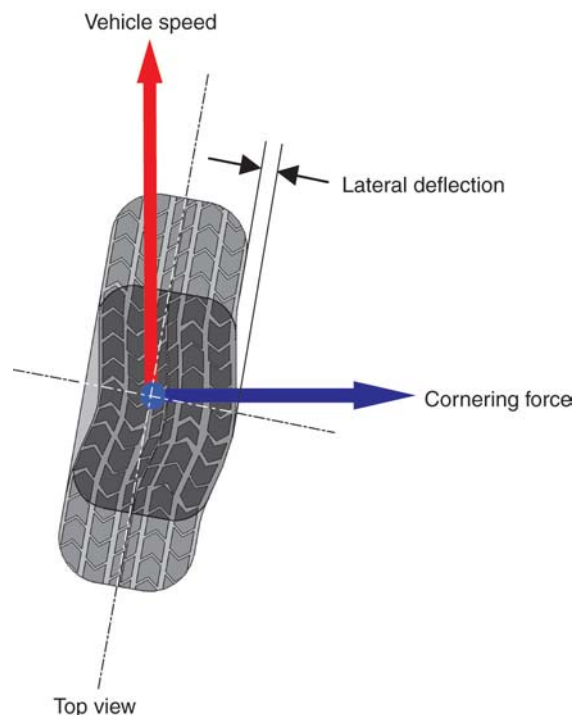


Fig. 3 Lateral deflection of tire

In addition, the state of areas other than the tire model is also quite different in limit conditions compared to normal conditions. Therefore, improvements must be made to the models to calculate the limit conditions. This includes improving characteristics settings in the large stroke range, stipulating the driving force and other conditions, etc.

Improving these models makes it possible to simulate vehicle behavior through mechanical analysis and better predict cornering performance in limit conditions.

3. Constructing a Tire Model

Construction of a tire model that can also be applied to better predict cornering performance in limit conditions can be broadly broken down into the following two elements.

- (1) Expressing the cornering characteristics of tires in limit conditions
- (2) Expressing the deflection of tires in limit conditions

3.1. Cornering Characteristics of Tires in Limit Conditions

Figure 4 shows the three main cornering characteristics of tires that are necessary to determine vehicle behavior. These three main characteristics are longitudinal force which is generated to the front and back of the tire, lateral force which is generated to the right and left of the tire, and self-aligning torque which is generated around the axis perpendicular to the tire contact surface. The absolute values of these three characteristics must be correctly understood and expressed by the model to more accurately express vehicle behavior in limit conditions.

There are many types of tire models with shapes suited to the application. Of these, three types of tire models were selected as candidates and judged for their appropriateness.

These were a dynamic model typified by the Fiala⁽¹⁾ and Gim⁽²⁾ theories, a mesh model using the finite element method, and a numerical model typified by Magic Formula.

The dynamic model calculates force dynamically by replacing the tire structure with a simple model. This allows significant investigations for determining the tire structure, but has the disadvantage of excessively large error with reality in limit conditions. This is thought to be because tires are made of complex, composite materials which exhibit complex changes that cannot be replaced with a simple structural model. Therefore, this model could not be applied to this simulation, which requires accuracy of absolute values.

The mesh model is capable of expressing tire characteristics that closely approximate reality. However, in order to obtain the required accuracy the model must have an extremely complex structure, and the complex calculations require an inordinate amount of time. This did not match the aims of this study, so this model also could not be applied.

Normally, the tire cornering characteristics change continuously relative to the four status levels of the load, slip rate, slip angle and camber angle acting on the tire. Therefore, if the tire model can be expressed by replacing these characteristics' values with the proper continuous functions having the status levels as the arguments, this numerical formula can be used as the tire model. A numerical model constructed based on actual measurement values offers the high accuracy of absolute values and also allows quick calculation, so this could be considered the most suitable tire model for this study.

Figure 5 shows the structure of the tire model used in this study. This is a Magic Formula, which is a typical tire numerical model.^{(3), (4)}



Fig. 4 Three-component forces for tire performance

Longitudinal force

$$F_x = D_{xa} \cos [C_{xa} \tan^{-1} \{B_{xa} (\alpha + Sh_{xa})\}]$$

$$F_{x0} = D_x \sin [C_x \tan^{-1} \{B_x (\kappa + Sh_x) - E_x (B_x (\kappa + Sh_x) - \tan^{-1} (B_x (\kappa + Sh_x)))\}] + S_{v_x}$$

$$B_{xa} = f(\kappa)$$

$$C_{xa} = \text{Constant}$$

$$D_{xa} = f(F_{x0}, \gamma)$$

$$Sh_{xa} = \text{Constant}$$

$$Sh_x = f(F_z)$$

$$S_{v_x} = f(F_z)$$

$$B_x = f(F_z)$$

$$C_x = \text{Constant}$$

$$D_x = f(F_z)$$

$$E_x = f(\kappa, F_z)$$

Lateral force

$$F_y = D_{yk} \cos [C_{yk} \tan^{-1} \{B_{yk} (\alpha + Sh_{yk})\}] + S_{v_{yk}}$$

$$F_{y0} = D_y \sin [C_y \tan^{-1} \{B_y (\alpha + Sh_y) - E_y (B_y (\alpha + Sh_y) - \tan^{-1} (B_y (\alpha + Sh_y)))\}] + S_{v_y}$$

$$B_{yk} = f(\alpha)$$

$$C_{yk} = \text{Constant}$$

$$D_{yk} = f(\alpha, F_{y0})$$

$$Sh_{yk} = \text{Constant}$$

$$S_{v_{yk}} = f(\alpha, \gamma, F_z)$$

$$S_{v_y} = f(\gamma, F_z)$$

$$B_y = f(\gamma, F_z)$$

$$C_y = \text{Constant}$$

$$D_y = f(\gamma, F_z)$$

$$E_y = f(\alpha, \gamma, F_z)$$

$$Sh_y = f(\gamma, F_z)$$

Aligning torque

$$M_z = -t F'_y + M_{zr} + s F_x$$

$$t = D_t \cos [C_t \tan^{-1} \{B_t \alpha_t - E_t (B_t \alpha_t - \tan^{-1} (B_t \alpha_t))\}] \cos(\alpha)$$

$$F'_y = F_y - S_{v_{yk}}$$

$$M_{zr} = D_r \cos [\tan^{-1} (B_r \alpha_r)] \cos(\alpha)$$

$$s = f(\gamma, F_z, F_y, R_0)$$

$$\alpha_t = f(\alpha, \gamma, \kappa, F_z)$$

$$B_t = f(\gamma, F_z)$$

$$C_t = \text{Constant}$$

$$D_t = f(\gamma, F_z, R_0)$$

$$E_t = f(\alpha, \gamma, F_z)$$

$$\alpha_r = f(\alpha, \gamma, \kappa, F_z)$$

$$B_r = \text{Constant}$$

$$D_r = f(\gamma, F_z, R_0)$$

Longitudinal Slip	: κ
Slip Angle	: α
Camber Angle	: γ
Normal Wheel Load	: F_z
Unloaded Tire Radius	: R_0

Fig. 5 Magic Formula model

The Magic Formula is a combination of trigonometric functions, and various curves can be expressed by setting the appropriate variables. The formula structure has a high degree of freedom for the slip angle α and slip rate κ , and can be expected to express nonlinear cornering characteristics up to limit conditions for general passenger car tires. However, the degree of freedom for the camber angle γ is relatively low, so it had been unclear thus far whether the cornering characteristics dependence on the camber angle can be accurately expressed up to limit conditions. The Magic Formula tire model conforms to the tire specific cornering characteristics as identified using a tire tester. Variables matching these characteristics are discovered using the optimization method, and used to construct the model. However, it is difficult for general tire testers to accurately

test the tire status in limit conditions, and it is also difficult to accurately measure the forces generated by the tire in limit conditions. Therefore, a Magic Formula that also covered limit conditions could not be constructed with the normal optimization method. This study succeeded in more accurately identifying the tire forces generated in limit conditions through detailed analysis of the six-component forces for tire using actual vehicles and by improving the tire tester. These characteristic changes were investigated in detail, and it was found that they could be adequately expressed by a Magic Formula. In addition, a tire model applicable even in limit conditions could be constructed by utilizing a technique that offsets and optimizes the weighting for the cornering characteristics in limit conditions based on these facts. Figure 6 compares a tire model constructed by

the conventional method with a tire model constructed to calculate cornering performance in limit conditions using the technique set in this study. These figures confirm that the accuracy is better in limit conditions than in steady-state conditions.

3.2. Deflection Characteristics of Tires in Limit Conditions

Tires experience large deflection in the lateral direction in limit conditions, but Magic Formula cannot accurately express this lateral deflection. Figure 7 shows the phenomenon where lateral deflection of the tire in limit conditions causes the available tread width to become narrower due to the center of contact becoming displaced

toward the inside of the vehicle. However, conventional simulations cannot express tire lateral deflection, so the effects of this narrowing of the available tread width cannot be reflected to the calculations.

This study allowed expression of these changes in the available tread width by inserting a spring element to the center of the hub that couples the tire model and the vehicle model. The Fig. 8 graph shows the deflection amount of the center of contact when various slip angles are applied. The deflection of the center of contact relative to the lateral force generated by the tire as determined from the slip angle and the vertical load is applied to the spring element in the center of the hub as the strain characteristic.

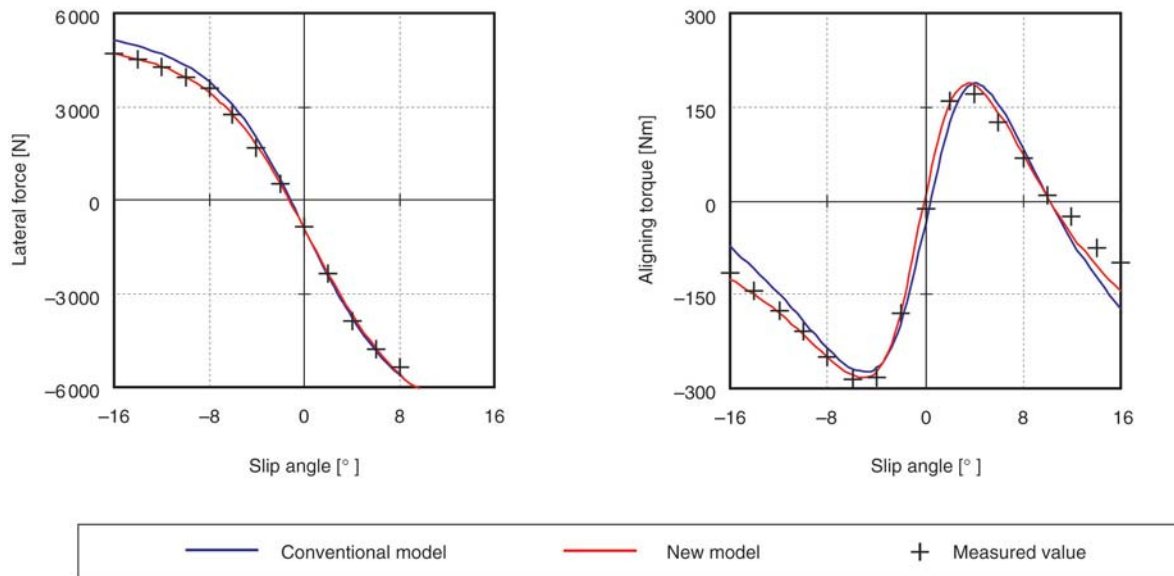


Fig. 6 Comparison between calculated value and measured value (Load 7,500 N, Camber angle 10°)

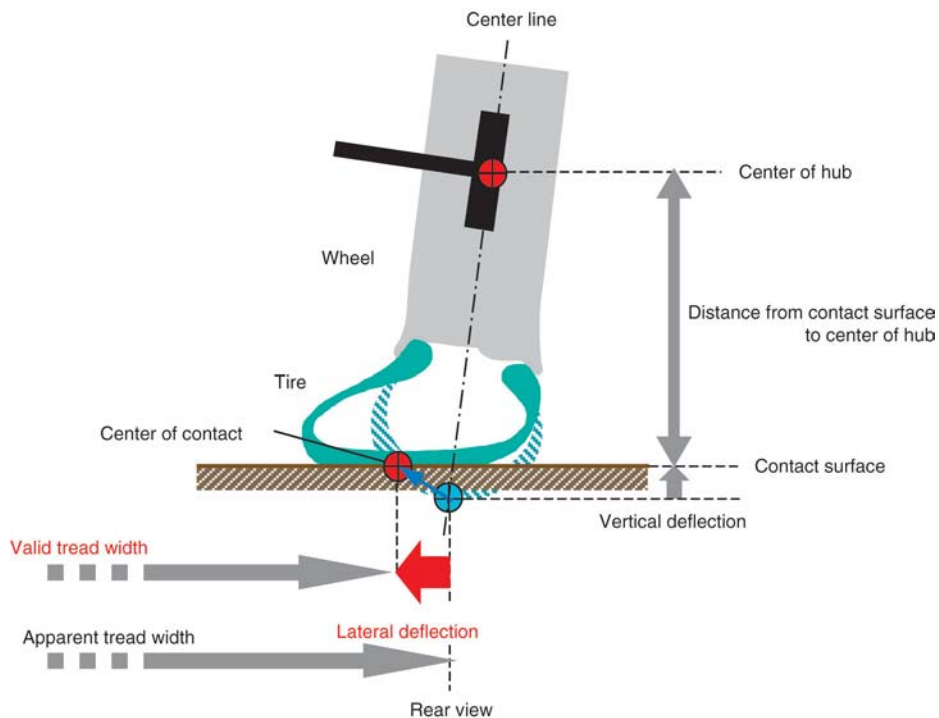


Fig. 7 Change of valid tread width

4. Vehicle Model Improvements

The main vehicle model items requiring improvement for better prediction of cornering performance in limit conditions are the following two elements.

- (1) Improvement of the suspension rate
- (2) Improvement of drive torque control

Note that in this study, all simulation models other than the tire model, such as the speed, steering and other stipulations generally called the driver model, are collectively referred to as the vehicle model.

4.1. Improvement of the Suspension Rate

In limit conditions the bump and rebound stroke reach ranges that are not used in normal conditions, so nonlinear characteristics equivalent to an actual vehicle must be set in the wide range from the full bump state to the full rebound state. Figure 9 shows an example comparison of the suspension rate used in the conventional simulation model and the suspension rate that takes into account limit conditions in this study. The former is not an issue for normal condition calculations, but the latter must be set for limit condition calculations.

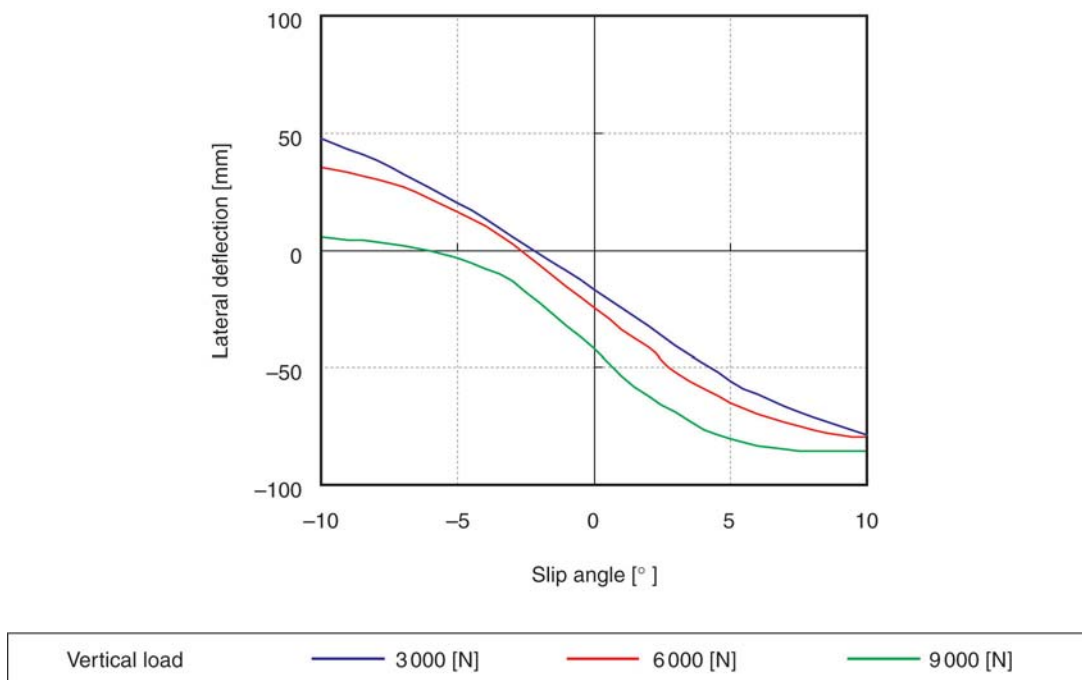


Fig. 8 Measurements of lateral deflection (Camber angle 5°)

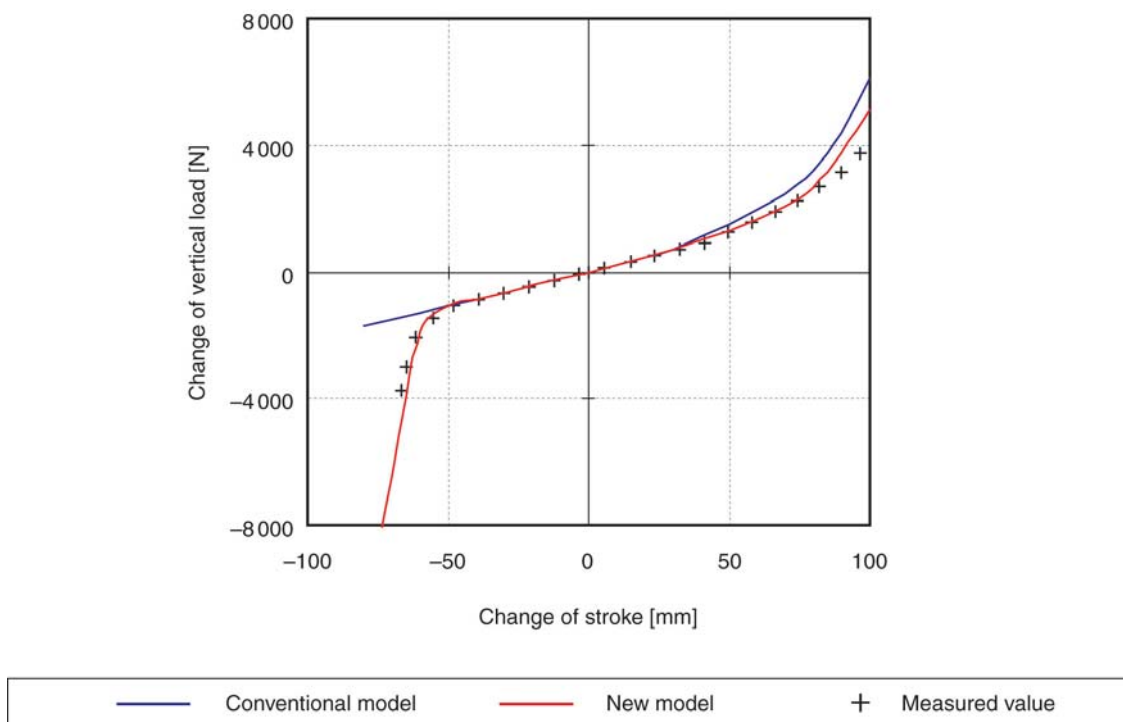


Fig. 9 Suspension rate

4.2. Improvement of Drive Torque Control

When the rapid turning state is entered from the high speed range, the longitudinal component of the side force of the tires relative to the vehicle acts as strong driving resistance. In tests using actual vehicles the speed is controlled by accelerator pedal operations to maintain a constant speed. However, the conventional simulation performs constant speed control by generating torque on the drive wheels. The driving resistance value is comparatively small when calculating normal conditions, so the drive torque value does not become extremely large and this is not a concern. However, the driving resistance value is large in limit conditions, so extremely large drive torque is generated suddenly. This creates the phenomenon where the effect of

the tire friction circle causes a drastic drop in the tire lateral force compared to actual measurements, and produces a large offset in the calculation results. Therefore, when calculating the cornering performance in limit conditions, the drive torque control was adjusted to prevent sudden drops in the lateral force. As a result the speed approached the actual vehicle test values, and the drive torque and lateral force produced when transiting from straight to the turning state also approached the actual vehicle values. Figure 10 compares the drive force and lateral force calculated by the conventional simulation model, calculated by the newly constructed simulation model, and produced when driving an actual vehicle.

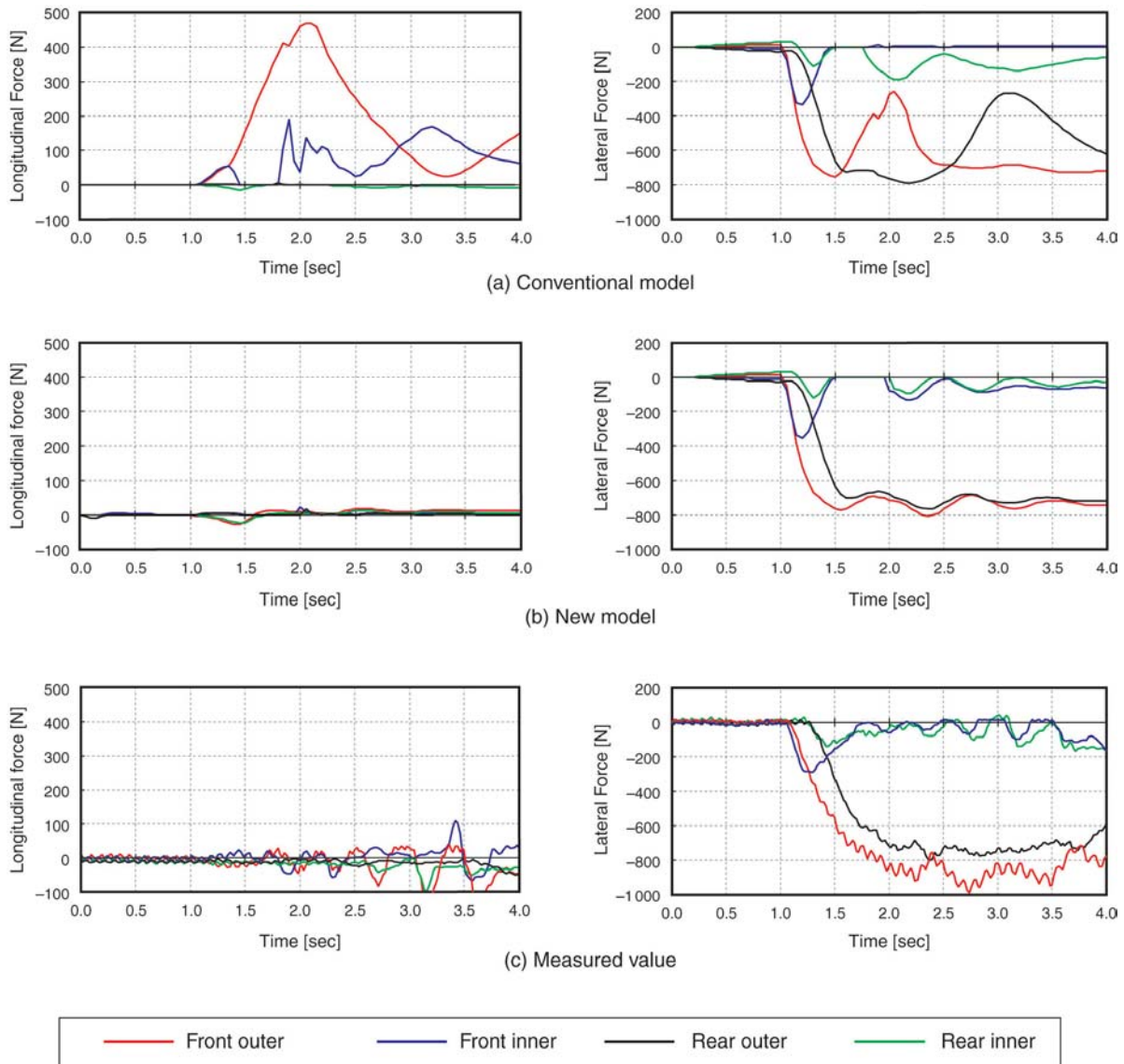


Fig. 10 Change of tire forces with torque control

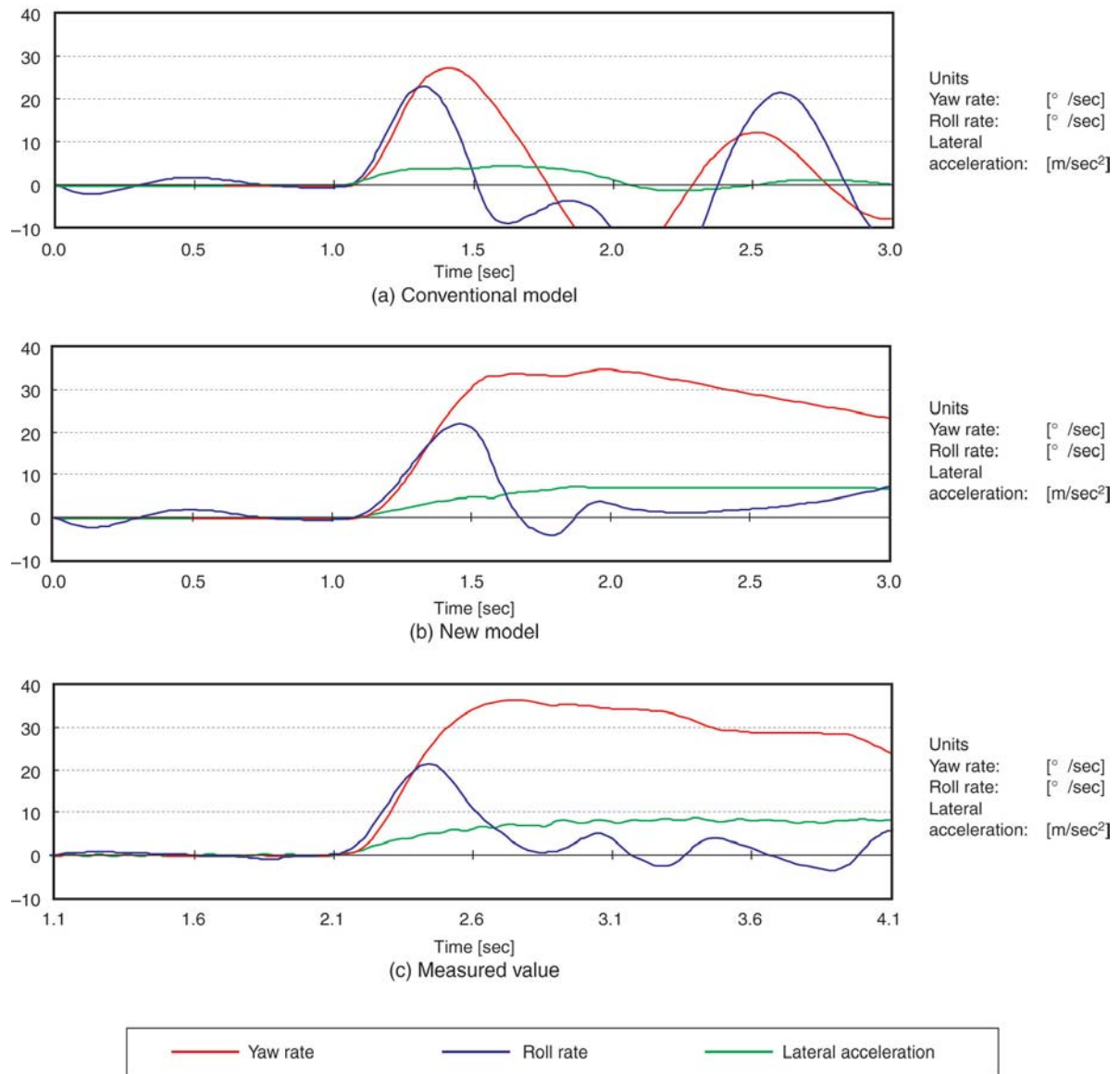


Fig. 11 Comparison between calculated value and measured value

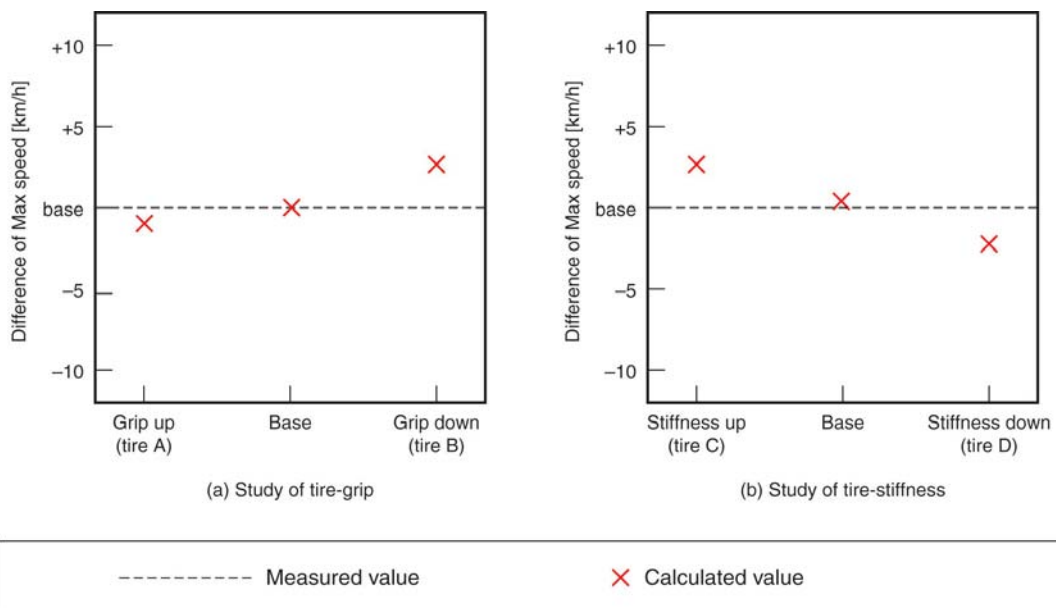


Fig. 12 Verification of simulation model

5. Calculation Results

Figure 11 shows the calculation results for J-turn mode driving obtained using the newly constructed tire and vehicle models. (a) shows the calculation results for the conventional simulation model, (b) shows the calculation results obtained by this study, and (c) shows the actual measurement values.

In limit conditions the vehicle behavior does not immediately shift to the steady state and the unstable state continues, so it is important to predict behavior during the several second interval following steering input. Compared with the actual measurement values, the simulated time series changes in the yaw rate, lateral acceleration, roll rate and other physical values during the approximately 2 seconds after steering input show a higher accuracy that is sufficient for predictive calculations in all cases.

In addition, Fig. 12 plots the relationships between the tire type and the maximum speed at which steady state turning becomes impossible for the two cases of different tire tread rubber (a) and different tire stiffness (b), using the constructed tire model as a reference. The calculation results match closely with the actual vehicle test results, thus confirming the validity of this simulation model.

6. Conclusion

This study aimed to construct technology for better predicting cornering performance in limit conditions with higher accuracy, and the following conclusions were obtained.

- (1) The nonlinear characteristics of tires in limit conditions can be expressed using a Magic Formula tire model.
- (2) Tire lateral deflection can be expressed by inserting a spring element to the center of the hub.
- (3) A suspension rate with high accuracy over the maximum stroke width from the full bump to the full rebound state must be set by the vehicle model in order to calculate limit conditions.
- (4) Extremely large drive torque generated to maintain a constant speed must be suppressed for limit condition calculations.
- (5) Cornering performance in limit conditions can be reproduced with a high degree of accuracy in a virtual space by adding items (1) to (4) above to conventional technology.

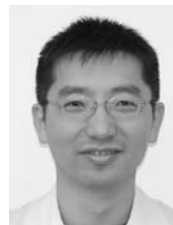
The results of this study show that vehicle dynamic characteristics settings over a wide range including cornering performance in limit conditions can be observed through desktop simulations. In addition, the results also showed great potential for reducing evaluation using actual vehicles and for investigating a wide range of vehicle characteristics, etc.

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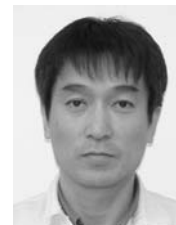
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