Review

Modeling, Analysis and Control Methods for Improving Vehicle Dynamic Behavior (Overview)

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車両運動性能向上のためのモデル化および解析・制御手法（概況）

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Abstract

So-called vehicle dynamics (or controllability and stability) refer to the "running, cornering and stopping" of automobiles, which are the most important and basic performance of automobiles. Therefore, many studies have been undertaken from several points of view all over the world. In this paper, our former studies, which focused on the analysis and modeling of vehicle and tire behavior, the vehicle dynamics control and state estimation, and the analysis of driver-vehicle system, are briefly summarized. Also, the purpose and background of these studies are mentioned. Moreover, a brief introduction to the three technical papers included in this special issue is presented.

Keywords Vehicle dynamics, Modeling, Simulation, Control system, State estimation, Tire model, Optimum control, Driver-vehicle system

要　旨

自動車の運動性能（または操縦性・安定性）とは，平易な言葉でいえば〝車が走る，曲がる，止まる〟性能や機能を意味し，車にとって最も基本的で重要な性能である。そのため自動車の運動性能に関しては，古くから世界各国で様々な観点から研究が行われてきた。本稿では，我々が現在までに実施してきた主な研究テーマである，自動車およびタイヤの運動力学的解析・モデル化技術，車両運動制御と状態推定技術，ドライバー自動車系の特性解析に関する研究の概要を紹介するとともに，それらの研究の目的や取り組みに対する考え方を述べる。また，本特集で取り上げる3報の研究の位置付けも解説する。

キーワード 車両運動性能，モデリング，シミュレーション，制御装置，状態推定，タイヤモデル，最適制御，人間－自動車系

特集

1. Introduction

Among the many points of view and stages in research and development in the vehicle dynamics field, we have been studying fundamental subjects focusing on the following concepts and purposes, mainly in the three following categories for improving vehicle dynamic behavior and safety. Here, it should be also noted that the "tire" is one of the key factors influencing our research activities, either directly or indirectly, because the tire plays an essential role in all aspects of vehicle behavior. This paper provides a brief summary and background of our studies. The layout of this paper is as follows.

(1) Analysis and modeling of vehicle and tire behavior

Considering the importance of the tire to vehicle maneuvering, we have been studying and modeling tire characteristics, especially from the viewpoint of developing accurate tire models for use in vehicle simulation calculations. In **Chapter 2**, we summarize the models we have developed to describe the tire steady state characteristics.

In the analysis of vehicle dynamic behavior, the road surface has been assumed to be flat and even in most cases, even though actual roads inevitably have some undulations and unevenness. Our trial for analyzing the braking performance of a vehicle on uneven roads is briefly explained in **Chapter 3**.

(2) Vehicle dynamics control and state estimation

In recent years, various kinds of control systems have been offered in vehicles on the market to improve the vehicle dynamic behavior and safety. The control algorithms of these systems and the state estimation techniques, which estimate the state variables of vehicle motion and tire characteristics etc., are the key technologies used in the development of all these control systems. **Chapter 4** discusses some of our former studies in this category.

(3) Analysis of driver-vehicle system

One of the most pressing and important problems facing automobile manufacturers is the reduction of the number of traffic accidents while increasing traffic safety. Given that almost accidents are caused by human-related factors, the study of driver-vehicle closed-loop systems is extremely important. Our recent study in this field is introduced in **Chapter 5**.

Finally, the purpose and outline of the three technical papers included in this special issue are briefly explained.

2. Tire modeling

In addition to the analysis and modeling of tire transient properties,[1, 2] we have also been developing a software system to model a tire steady state characteristics using the so-called Magic Formula[3-5] which has frequently been employed in vehicle dynamics simulation in recent years. The goal is to describe the tire force and moment properties very accurately over wide ranges of input variables including combined slip cases, this being very important to the analysis of vehicle dynamic behavior with multi-body dynamics simulation software like ADAMS or DADS, as well as by in-house development.

To establish the Magic Formula (abbreviated to MF) tire model, the optimum values for many MF parameters and coefficients have to be decided by using measured data for each tire. **Figure 1** shows the structure of our software system,[7] which can handle the tire side force, the longitudinal force, and the self aligning torque. The software was developed in a Matlab/Optimization toolbox environment to support the use of a wide range of tires and test facilities.[6, 7]

Examples of established MF models are shown in **Figs. 2** and **3**. These figures show that the models

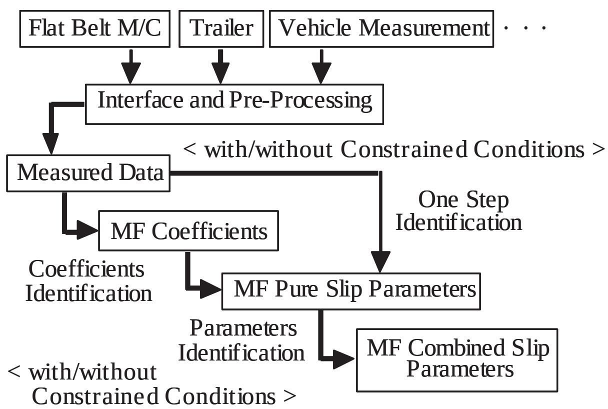


Fig. 1 Structure of tire model identification system.

identified by our system agree with the measured data very well. Figure 2 shows the so-called friction circle or friction ellipse, and Fig. 3 shows the braking force characteristics of a passenger vehicle tire (PV tire) and a commercial vehicle tire (CV tire) on ice road. From Fig. 3, we can see that there are rather large differences between the two kinds of tires, namely, the maximum braking force divided by the vertical load of the CV tire is smaller than that of the PV tire, and the decrease in the braking force after the peak of the CV tire is much larger than that of PV tire. These differences may be caused by the difference in the inflation pressure, which relates to the vertical load distribution per unit area in the contact patch, and therefore a difference in the generation of water between the tire and the icy road may be induced. In this case, the pressure was set to 220 kPa for the PV tire and 705 kPa for the CV tire.

3. Braking performance on uneven roads

Although vehicle behavior during steering and/or braking has been studied very widely for many years, most studies have assumed the road surface to be even and flat. The analysis of vehicle behavior on uneven roads is thought to be very important, however, when considering actual roads. On the other hand, it seems that many studies of brake systems and their performance have been undertaken, but that analyses of the influence of vehicle chassis elements on braking performance have rarely been reported. Then, analytical and experimental studies were performed, in which the braking performance of straight-running vehicles on uneven roads and the influence of chassis elements on that performance were investigated.[8)]

For the analysis, a model for simulating of vehicle behavior was developed based on the half car model, as shown in **Fig. 4**. The tire braking force characteristics that depend on the vertical load and the wheel slip ratio were described by the Magic Formula explained in a former chapter. In the simulation, vehicle responses such as the deceleration of the vehicle, the stopping distance after braking and the tire vertical load can be

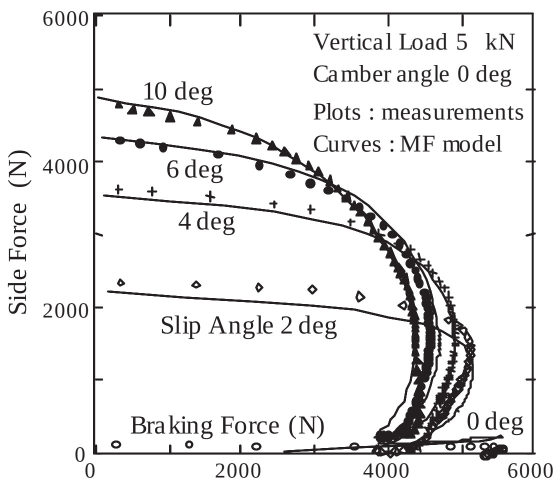
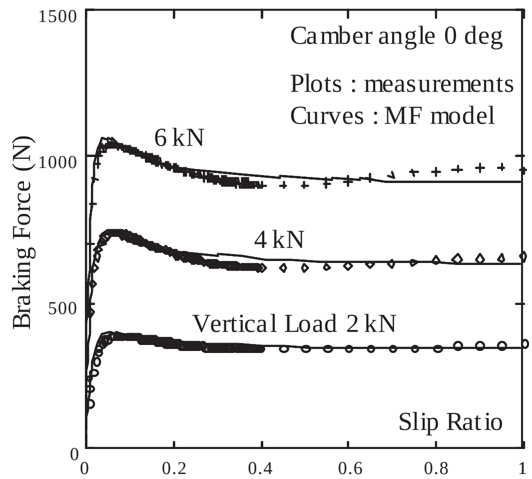
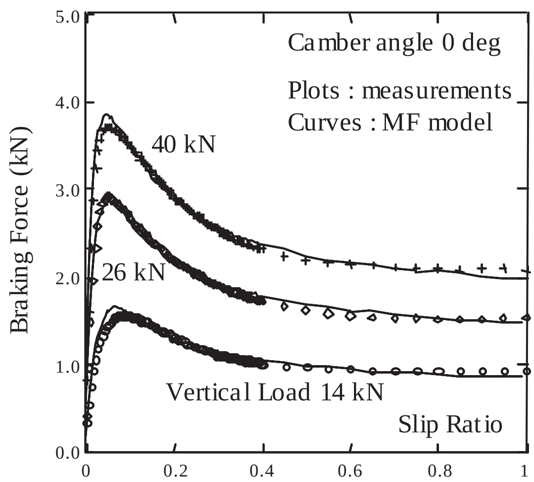


Fig. 2 Combined slip characteristics on dry road (Passenger vehicle tire : 195/65R15).



(a) Passenger vehicle tire : 195/65R15



(b) Commercial vehicle tire : 11R22.5

Fig. 3 Pure braking force characteristics on ice road.

calculated, provided the vehicle initial speed, the time history of the brake fluid pressure and the longitudinal road profile are given as inputs.

Figure 5 shows the calculated and measured values for the influence of the chassis elements' characteristics on the braking performance, in which the parameters of the chassis elements were changed from those of a standard vehicle (see **Table 1**) as shown below.

(A) Higher tire inflation pressure (k_{tf} = 215 kN/m)
(B) Higher tire inflation pressure + Larger damping of shock absorber (c_f = 1350 Nsec/m)
(C) Harder suspension bush (k_{xf} = 330 kN/m, c_{xf} = 800 Nsec/m)
(D) Higher tire inflation pressure + Larger damping of shock absorber + harder suspension bush

In Fig. 5, the difference in the stopping distance between each vehicle and the standard vehicle is indicated as a ratio (%) relative to the stopping distance of the standard vehicle both for calculated and measured results. Positive values indicate a shorter stopping distance than the standard. Although some differences can be seen in the figure, overall we can say that the tendency for the chassis elements to influence the braking performance as calculated agrees rather well with the experiments.

In addition, the influences of the longitudinal

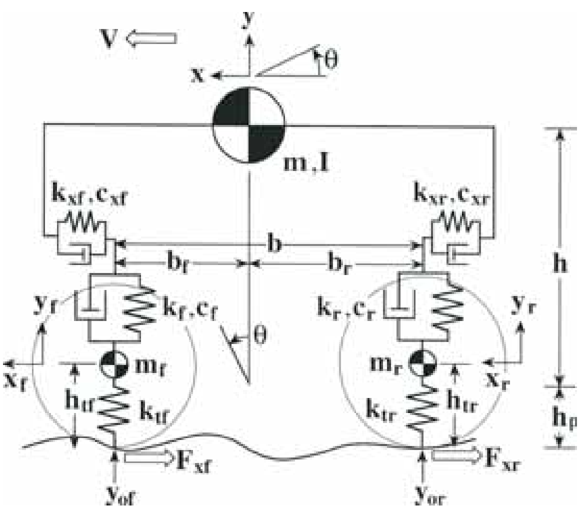


Fig. 4 Vehicle model and symbol notation.

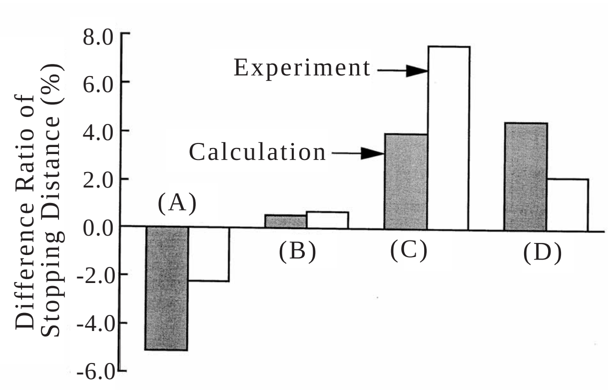


Fig. 5 Comparison of stopping distance between calculation and experiments.

Table 1 Parameter values of standard vehicle.

(unit)

m (kg)	I (kgm^2)	m_f (kg)	m_r (kg)	k_f (kN/m)	k_r (kN/m)	c_f (Nsec/m)	c_r (Nsec/m)
712	1500	45	42	27	28	1000	750
k_{xf} (kN/m)	k_{xr} (kN/m)	c_{xf}(Nsec/m)	c_{xr}(Nsec/m)	k_{tf} (kN/m)	k_{tr} (kN/m)	b (m)	b_f (m)
200	390	2400	800	190	190	2.68	1.22
b_r (m)	h (m)	h_p (m)	I_{tf} (kgm^2)	I_{tr} (kgm^2)	h_{tof} (m)	h_{tor} (m)	c_p (Nm/Mpa)
1.46	0.25	0.30	1.1	1.1	0.30	0.30	150
c_{pr}	R_{e1f}, R_{e1r}	R_{e2f}, R_{e2r}	R_{e3f}, R_{e4r}	R_{e4f}, R_{e4r}			
0	-1.818-14	3.919-10	-2.973E-6	0.3153			
a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
-22.615	1232.2	-0.007239	276.33	-0.002958	0.001176	-0.01911	0.75374

* a_1 to a_8 are Magic Formula coefficients when the unit kN is used for the vertical load and % for the slip ratio.

suspension characteristics and the road profile on the braking performance were investigated by simulation. We found that the braking performance is affected not only by the suspension stiffness but also by the damping of the unsprung mass in the longitudinal direction. The influence of the road profile was studied by assuming the roads to be sinusoidal undulations, and the wavelength and the amplitude were changed. The increase in the stopping distance on an uneven road relative to that on an even road is shown in **Fig. 6** as a ratio (%). It is said that the stopping distance increases considerably with an increase in the amplitude of undulation when the input frequency from the road undulation exceeds the vertical resonance frequency of the unsprung mass while braking, which is determined by the vehicle initial speed and the wavelength of the undulation.

4. Vehicle dynamics control and state estimation

Concerning vehicle dynamics control, our former study is summarized below. Following that study, the study presented in the third paper of this special issue was performed as a continuation and expansion. In the former study, the sliding mode control method was applied to the brake system.[9] At first, the preliminary method was developed and then confirmed by the experiments performed on various road surfaces. Although the system was stable, it proved insufficiently robust to changes in the road. So, an adaptive method was newly developed, in which a very simple tire model ("two-straight-line" model) was introduced and the controller gain was adjusted on-line. The results obtained with the new method are shown in **Fig. 7**. This shows a sufficient improvement in the robustness to changes in the road surfaces.

The state estimation technique is one of the key technologies for developing vehicle control systems. We have also been studying on-line estimation methods of estimating tire forces generated between the tire and road. Below, a summary of our recent studies[10, 11] is presented, in which a new method is

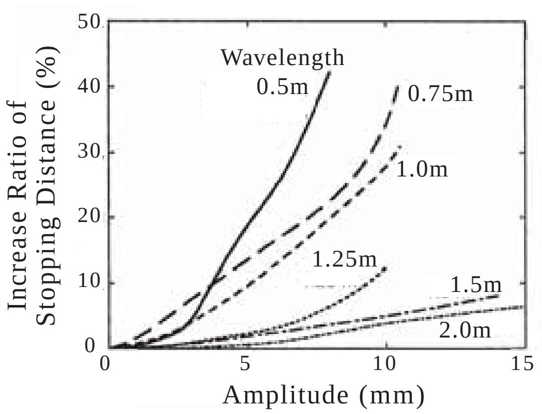
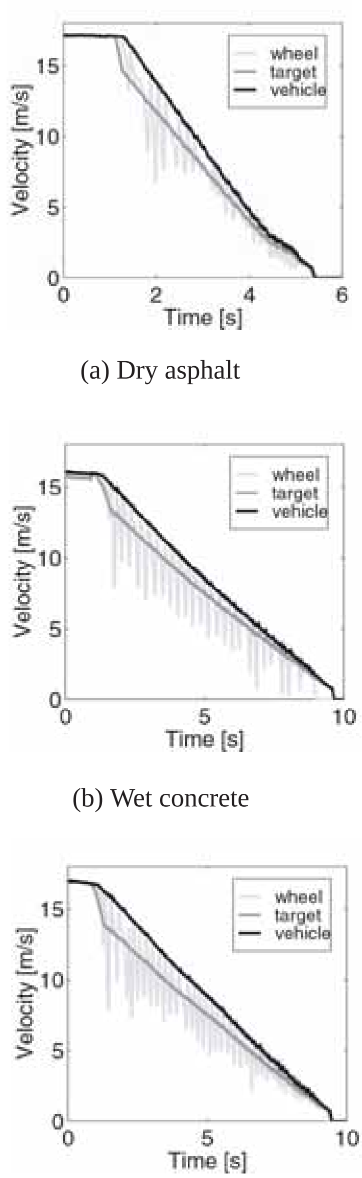


Fig. 6 Influence of wavelengths and amplitudes of road undulations on stopping distance.



(a) Dry asphalt

(b) Wet concrete

(c) Packed snow

Fig. 7 Experimental results of modified adaptive method on various roads.

proposed by using the self aligning torque (abbreviated to SAT) characteristics. The principle behind this method is based on the fact that the SAT reaches a maximum at a lower slip angle than the side force, as shown in **Fig. 8**. Because an SAT signal is required in the on-line estimation, the sensor signals from the electric power steering system were used. The grip margin of the tire was defined to assess the currently generated force relative to its maximum value, which was derived from the describing equations of the so-called Brush tire model known as the simple analytical tire model. The estimating algorithm was developed starting from the pure slip condition[10] and then expanded to the combined slip conditions. In the case of combined slip, even the description of the Brush model becomes very complicated, but the unique transformation of these equations was found.[11]

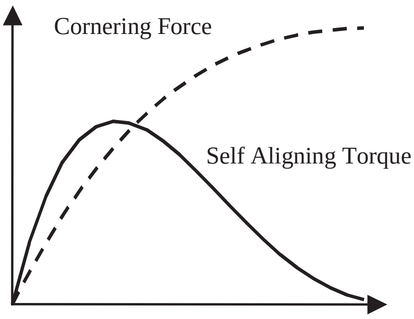


Fig. 8 Relationship between side force and self aligning torque with slip angle.

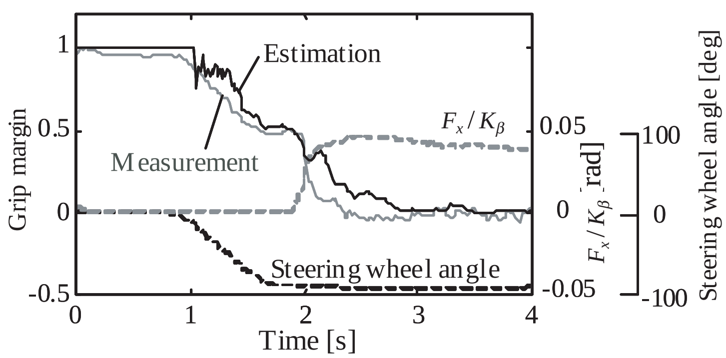


Fig. 9 Comparison of estimated and measured grip margin at combined slip condition.

Figure 9 shows a comparison of the estimated and measured grip margins at the combined slip condition (K_x/K_β in Fig. 9 is the normalized traction force), from which we can say that the estimated grip margin is very accurate.

5. Analysis of driver-vehicle system

In this category, we have been investigating and modeling ordinary drivers' behavior in normal and emergency situations to improve active safety, mainly by using driving simulators.[12, 13] Below, recent studies of combinations of drivers and a vehicle equipped with an active front steering system[14] are explained.

Although some studies have addressed the appropriate characteristics of the steering system in course-tracking maneuvers, very few studies have been done into those cases where the vehicle experienced disturbances. Then, an investigation to find the appropriate characteristics of a steering control system under disturbances while course tracking was performed using a fixed-type driving simulator. In the experiments, ten ordinary drivers were tested to investigate the effects of the steering gear ratio and the derivative steer, for which two parameters of the following equation of the actual steer angle were varied. The results shown below were obtained by averaging the test results obtained for ten drivers.

$$\delta_a = \frac{1}{K_v} \cdot \left(\delta_w + K_s \cdot \frac{d\delta_w}{dt} \right) \qquad \cdots\cdots\cdots (1)$$

Here,

δ_a : Actual steering angle
δ_w : Steering wheel angle
K_v : Steering gear ratio
K_s : Derivative steer gain

(1) Steering gear ratio

Relatively large yaw moment disturbances of 10 seconds duration were applied around the center of gravity of a vehicle traveling in a straight line at a fixed speed. The spin probability was examined by changing the steering gear ratio for a respective disturbance. **Figure 10** shows the spin evasive probability when the gear ratio was varied for three levels of disturbances. We can see from the figure that the spin evasive probability becomes larger for all disturbances when the gear ratio is smaller than the original ratio (K_v=21), but that at certain values of gear ratio, the probability reaches a maximum or saturates.

(2) Derivative steer

Three levels of lateral force disturbances of short durations (less than 1 second) were applied to the center of gravity of a vehicle traveling in a straight line at three constant speeds. **Figure 11** shows an example of the yaw rate time history when the driver corrects the steering upon experiencing a disturbance. Area (a) in the figure corresponds to the steering for reacting to the disturbance, and area (b) to the steering for converging the vehicle to straight-line travel. For each area, the RMS (root mean square) values of the yaw rate were calculated and then normalized by the RMS value of the vehicle without the derivative steer (original vehicle), as shown in **Fig. 12**. It can be seen that, in the reaction area (a), the RMS value falls monotonously with the increase in the derivative steer gain for all speeds, but that in the converging area (b), the optimal derivative steer gains exist for three speeds. From these results, we can conclude that the optimal values of the derivative steer gain depend on whether a driver is controlling or stabilizing the vehicle.

The above-mentioned results indicate that appropriate values exist for the gear ratio and the derivative steer gain for the driver-vehicle system under the influence of disturbances.

6. Contents of this special issue

Let us explain the relationship between the three technical papers in this special issue with the studies mentioned above. Two papers entitled "Modeling of Tire Overturning Moment Characteristics and the

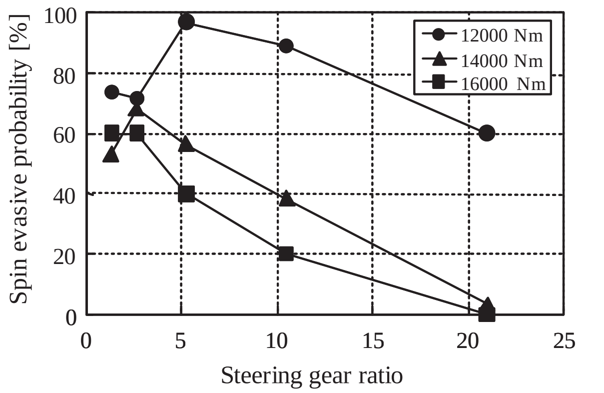


Fig. 10 Spin evasive probability to steering gear ratio and yaw moment disturbance.

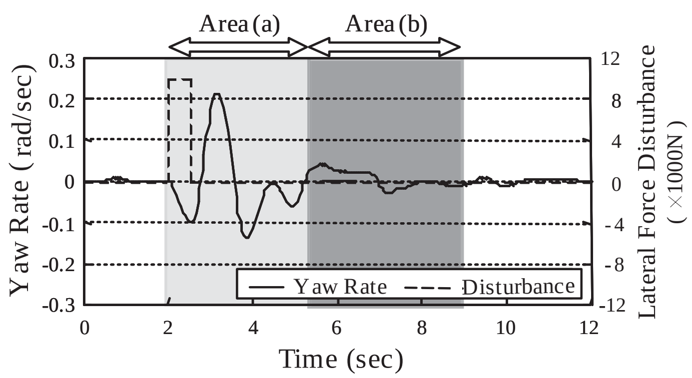
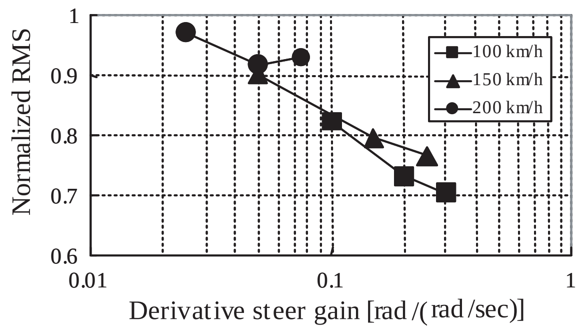
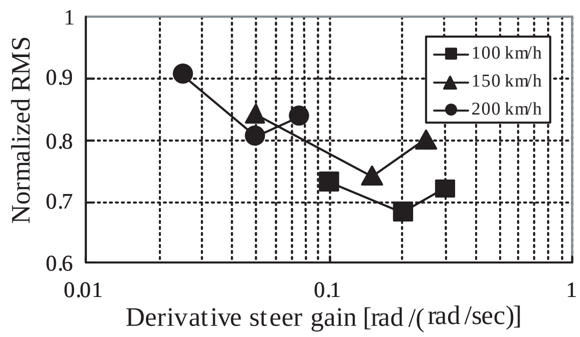


Fig. 11 Time history of yaw rate at corrective steering.



(a) Reaction area



(b) Converging area

Fig. 12 Normalized RMS values of yaw rate.

特集

Analysis of Their Influence on Vehicle Rollover Behavior" and "Development of Tire Side Force Model Based on "Magic Formula" with the Influence of Tire Surface Temperature" are included in Tire Modeling. Our studies of a tire model based on the Magic Formula mentioned in **Chapter 2** have almost reached their final stages with the conclusion of these two studies. The former study is intended to add the overturning moment characteristics to our software system, which could handle side forces, longitudinal forces, and self aligning torque. The latter study aims to consider a change in the side force depending on the tire surface temperature. In the third paper, entitled as "Optimum Vehicle Dynamics Control based on Tire Driving and Braking Forces", a new method of vehicle dynamics control is proposed by considering the optimum distribution of tire forces generated at each wheel. The background to, and a brief summary of, each of the three papers are presented below.

(1) Modeling of tire overturning moment characteristics and the analysis of their influence on vehicle rollover behavior

Although the characteristics of the longitudinal force, the side force and the self aligning torque have been studied quite exhaustively, very few studies related to the tire overturning moment (abbreviated to OTM) characteristics have been attempted. OTM generation is understood as a lateral shift of the acting center of the tire vertical load during vehicle cornering. Needless to say, the inclusion of OTM in the vehicle simulation achieves better calculated results. This paper presents a new OTM model that has been developed by introducing equations describing the "Residual Pneumatic Scrub" and a comparison of the calculated and measured results. In addition, the influence of OTM on vehicle rollover behavior is analyzed.

(2) Development of tire side force model based on "Magic Formula" with the influence of tire surface temperature

In general, the tire force and moment properties are measured using indoor test facilities, but the measuring conditions cannot be adjusted to exactly match the actual driving conditions of a certain vehicle/tire combination. On the other hand, it is known that the side force characteristics vary with changes in the tire surface temperature. So, the development of a model that considers the temperature change depending on the running conditions would be extremely advantageous, but such a model has not yet been proposed, as far as the author is aware. The concept and the new side force model are presented in this paper, in which a thermodynamic model of the tire is included to calculate its surface temperature. The thermal energy is produced by the work of the tire when the slip occurs. Also, an adjusting function for the side force depending on the temperature is proposed. Finally, the calculated results are compared with the measured results.

(3) Optimum vehicle dynamics control based on tire driving and braking forces

In recent years, various types of active control systems to ensure vehicle stability and controllability have been developed and introduced into automobiles in market. Among such systems, the so-called direct yaw moment control systems with active braking aim to stabilize vehicle maneuvering in a limited area,[15, 16] but it is rather difficult to control vehicle motion smoothly because the system starts to work only after the detection of the vehicle skidding. Therefore, a new control strategy is proposed to achieve the smooth and seamless control of vehicle stability and controllability, anytime and anywhere. Three key technologies are involved, namely, "Hierarchical algorithm", "Feedforward-wise force and moment control" and the "Non-linear optimum distribution method", which includes the tire model described by the Brush model. In this paper, those key technologies are explained and the proposed strategy is confirmed by simulation.

References

1) Takahashi, T., et al. : "Cornering on uneven roads", Supplement to Vehicle System Dynamics, **17**(1987), 469-480
2) Takahashi, T., et al. : "The Tyre Cornering Model on Uneven Roads for Vehicle Dynamics Studies", Proc. of 3rd Int. Symp. Advanced Vehicle Control (AVEC '96), Aachen, (1996), 941-953
3) Bakker, E., et al. : "Tyre Modelling for Use in Vehicle Dynamics Studies", SAE Tech. Pap. Ser., No. 870421, (1987)
4) Pacejka, H. B., et al. : "The Magic Formula Tyre

Model", Supplement to Vehicle System Dynamics, **21**(1991), 1-18
5) Pacejka, H. B., et al. : "Magic Formula Tyre Model with Transient Properties", Supplement to Vehicle System Dynamics, **27**(1997), 234-249
6) Mizuno, M., et al. : "Magic Formula Tire Model Using the Measured Data of a Vehicle Running on Actual Roads", Proc. of 4th Int. Symp. Advanced Vehicle Control (AVEC '98), Nagoya, (1998), 329-334
7) Takahashi, T., et al. : "The Modeling of Tire Force Characteristics of Passenger and Commercial Vehicles on Various Road Surfaces", Proc. of 5th Int. Symp. Advanced Vehicle Control (AVEC 2000), Michigan, (2000), 785-792
8) Takahashi, T., et al. : "Analysis of the Braking Performance of Straight-Running Vehicles on Uneven Roads", Proc. of 26th FISITA Congr., Praha, (1996)
9) Hattori, Y., et al. : "An Application of the Adaptive Method for the Sliding Mode Control of the Brake System", Proc. of 4th Int. Symp. Advanced Vehicle Control (AVEC '98), Nagoya, (1998), 611-616
10) Muragishi, Y., et al. : "Estimation of Grip State Based on Self Aligning Torque and Its Application to Enhance Vehicle Stability" (in Japanese), Proc. of JSAE Annu. Congr., Yokohama, JSAE Pap., No. 20035105(2003)
11) Ono, E., et al. : "Estimation of Lateral Tire Grip Margin Using Electric Power Steering System", Proc. of 18th IAVSD Symp. Dynamics of Vehicles on Road and Tracks, Atsugi, (2003),141-143
12) Doi, S., et al. : "Analysis of Active Safety Performances of Automobile Based on Driving Maneuvers in Emergent Situations" (in Japanese), R&D Review of Toyota CRDL, **33**-1, (1998), 3-12 <http://www.tytlabs.co.jp/japanese/review/rev331pdf/331_003doi.pdf>
13) Amano, Y., et al. : "A Model of Driver's Behavior in Ordinary and Emergent Situations" (in Japanese), R&D Review of Toyota CRDL, **33**-1(1998), 23-30 <http://www.tytlabs.co.jp/japanese/review/rev331pdf/331_023amano.pdf>
14) Kojo, T., et al. : "Development of Front Steering Control System", Proc. of 6th Int. Symp. Advanced Vehicle Control (AVEC '02), Hiroshima, (2002), 33-38
15) Koibuchi, K., et al. : "Vehicle Stability Control in Limit Cornering by Active Brake", SAE Tech. Pap. Ser. No. 960487, (1996)
16) van Zanten, A. T. : "Control Aspects of the BOSCH-VDC", Proc. of 3rd Int. Symp. Advanced Vehicle Control (AVEC '96), Aachen, (1996), 573-608

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