

Flat Belt Test System for Suspension and Tire Measurement

Tomonori SAKAI* Kaoru KUSAKA* Yuji SATO*

ABSTRACT

A new chassis testing system equipped with flat belt roadways for both left and right vehicle wheels has been developed and put into operation. This system is designed to be capable of comprehensive performance evaluation of vehicle suspension and tires.

Testing of suspension characteristics using actual vehicles requires many work-hours of testing on the proving ground in order to assure measurement accuracy and to reduce deviation from environmental factors. The use of the present system, however, enables enhanced development efficiency by replacing proving grounds test evaluations with testing of the system in a fixed environment and by shortening measurement time.

This test system can be transformed into three measurement modes: the first mode can measure suspension characteristics of the front or rear wheels of a vehicle; the second mode can measure suspension assembly characteristics by testing just a suspension system with tires; and the third mode can measure the characteristics of tires alone.

In actual vehicle testing, the vehicle behavior is measured under the influence of forces generated in both front and rear axles, which are dynamically coupled with each other through the vehicle's motion. It becomes difficult, therefore, to separately analyze the influences of the front and rear axle tire forces on vehicle dynamics. The present test system can measure the component forces and moments of each tire of front or rear axles separately with a vehicle body constrained to the ground, and can provide analytical information to improve vehicle dynamics performance.

1. Introduction

Vehicle developers and manufacturers have been increasingly required to develop more attractive products that achieve a balance between high environmental performance and the qualities of safety, comfort, and driving pleasure. Vehicle performance derives from combinations of a variety of different parts and components, and among various components, tires are one of the few parts that have significant influence across the range of vehicle handling and stability, ride comfort, noise and vibration, and fuel consumption, which are considered elements of chassis performance, and tires have recently been displaying a conspicuous shift toward lower rolling resistance coefficients (hereafter, lower RRC) in conjunction with the call for enhanced fuel economy.

In general, the shift toward lower tire RRC is accompanied by reduction in grip performance. In order to pursue higher chassis performance with such lower RRC tires, therefore, it is of great importance that a quantitative grasp of tire characteristics be obtained and that, on that knowledge, an optimal suspension be designed from the initial stages of the development.

Recently, the vehicle development period has been becoming shorter year by year in order to respond more quickly to customer needs, which are changing with the times. In place of running tests using prototype vehicles, therefore, development methods making use of computer simulation are progressively being introduced. Consequently, there is increasing demand for quantification of the characteristics of vehicle parts and components, including tires and suspensions, which are needed for these methods.

If sole reliance is placed on actual vehicle tests for the measurements that such quantification needs, then many work-hours have to be expended to assure the desired data accuracy in the presence of such disturbance factors as temperature, condition, and slight undulations of the road surface. For example, making quantitative comparisons of slight variations, such as differences in parts specifications, calls for the acquisition of vast quantities of data as well as statistical processing of that data in order to obtain sufficient accuracy as considered necessary for examination. Carrying out quantification for all of the various different parts becomes a serious issue in terms of development efficiency.

In that respect, although test bench measurement is

* Automobile R&D Center

limited by the measurable conditions available to it, it is able to keep variations resulting from disturbance factors and changes in the environment to a minimum, and it is capable of highly accurate and reproducible measurement. This approach is also well suited to quantification of the specifications and characteristics of parts and components for which measurement accuracy offers particular advantages, and when combined with simulation techniques, this approach enables investigation of optimal designs for a variety of different performance parameters.

At every stage of vehicle development, the influence on chassis performance of various parts and components of the chassis should be researched quantitatively in order for development to proceed. What this calls for, therefore, is not just the characteristics of the chassis as attached to the vehicle, but also quantitative characteristics analysis based on analysis of the characteristics of the suspension assembly alone, of the tires alone, and so on. For example, the suspension has stabilizer bars that link the left and right wheels together, and there are configurations that are structurally linked, as typified by the coupled beam suspension. In addition, quantitative analysis of the suspension assembly characteristics with the shock-absorbing function of the suspension included calls for reproduction of undulated road profiles. One example of a method for bench analysis of such characteristics used to date is to perform measurements of a tire mounted against a rotating drum. A drum has curvature, however, so that the contact patch shape of the tire would differ from the shape on the road, so there would be cases in which actual driving characteristics could not be represented.

With the aim of resolving the various issues described above, a suspension and tire test system has been developed. The system enables comprehensive measurement and analysis of chassis performance by the capability to measure the left and right tires of the suspension simultaneously on two flat belts and also by the excitation function of the flat belts. This paper presents an overview of this test system together with an example of measurement results.

2. Overview of the Test System

The present test system has three measurement modes

suited to each purpose:

- (1) Vehicle test mode (VT mode);
- (2) Suspension carrier mode (SC mode); and
- (3) Tire stand mode (TS mode).

Figure 1 shows a schematic diagram of the system in VT mode configuration.

When in VT mode, two flat belt units are positioned underneath the vehicle to enable drive-on testing. This is how the basic configuration was designed, so that the floor surface and the upper belt surface would be at the same height. Each flat belt unit is also configured with wobbling and vertical excitation functions so that freely selectable slip angles and vertical input can be applied to the front and rear axes.

The flat belt units are equipped with steel belts that are passed around two cylindrical drums. One of the drums drives the belt, and the other drum performs lateral belt tracking. Air bearings, which have better maintainability, are used in the structure that holds vertical load F_z for the level part of the flat belt. In order to simulate a coefficient of friction (μ) equivalent to an actual road, measurement is conducted with a sheet to which abrasive are bonded affixed to the steel belt surface.

The configuration and specifications for each mode are summarized in the following.

2.1. VT Mode

In VT mode, the front axle or rear axle of the vehicle is positioned over the flat belts, the vehicle body is fixed on a surface plate, and the slip angle and vertical force are applied from the flat belts. The test system specifications are shown in Table 1. Figure 2 shows a photograph of the system with an actual vehicle loaded on it.

In this mode, the system is equipped with six-component wheel force and moment sensors to measure tire forces and with alignment equipment to measure tire position and orientation. This configuration measures forces generated on the tires, including influences from body stiffness and suspension characteristics.

In actual vehicle testing, there is mutual influence between the force on the front axle and the force on the rear axle, and the slip angles of the individual tires and the vertical load on them vary with the vehicle behavior. This makes separate analysis of the front and rear axles, or of the

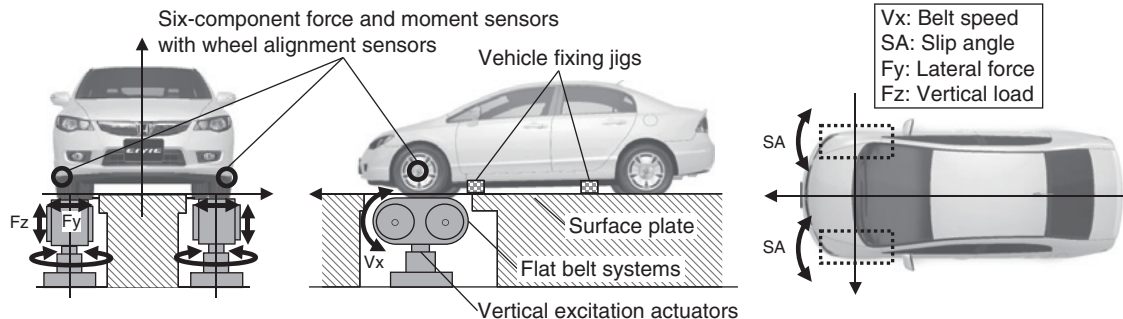


Fig. 1 Configuration of VT mode

Table 1 System specification of VT mode

Vx	0 to 180 km/h
SA	-20 to +20 deg (up to 3 Hz)
Fz	0 to 15000 N (up to 25 Hz)
Fy	-10000 to 10000N

left and right wheels, difficult. When vehicle characteristics do not exhibit the desired performance, therefore, it can be more difficult to determine quantitatively where in the tires, suspension, or body the technical issues are located.

In this mode, the vehicle's front axle or its rear axle can be subjected to individual measurement on the test bench. This enables detailed analysis of the tire forces, such as the influence of body deformation on alignment and the tire forces, including compliance steer functions of the suspension.

In addition, the suspension functions to assure the comfort of vehicle occupants by mitigating shock force from road surfaces, and also functions to keep the tires in contact with road surfaces and maintain vehicle handling and stability performances. Making simultaneous measurements of these areas of performance calls not only for flat roads, but also for input that is equivalent to input from undulating roads. The present test system is equipped with vertical excitation function to enable verification of whether or not the suspension is functioning according to



Fig. 2 Photograph of VT mode

Table 2 System specification of SC mode

Vx	0 to 180 km/h
SA	-20 to 20 deg (up to 3 Hz)
RA	-15 to 15 deg
Fz	0 to 15000 N (up to 25 Hz)
Fy	-10000 to 10000N

design under a variety of different conditions, including vehicle stability and cornering limit performance, on undulating roads as well as under conditions equivalent to flat roads. Furthermore, performance objectives can be replaced with more quantitative indicators by making comparisons between benchmark vehicles and the vehicle under development.

The device specifications also take into account scalability to allow attachment of a steering robot and/or braking robot for testing that simulates a human driver's steering and/or braking operations. This enables clarification of how mounting point stiffness on the suspension, steering gearbox, and steering hanger influences vehicle handling and stability as well as steering torque.

2.2. SC Mode

In SC mode, the suspension system and tires are attached to a fixing jig. Measurement can then be made of forces that include the influence of the suspension assembly in a condition that is not influenced by the stiffness of the body. Test system specifications for SC mode are shown in Table 2. Figure 3 shows a schematic diagram of the system in that configuration, and Fig. 4 shows a photograph of that actual measurement mode.

This mode is similar to the VT mode in that six-component force and moment sensors and alignment equipment are attached to the measured wheels. Not only can this configuration measure the forces generated on each tire, but the other six-component force and moment sensor installed under the fixing jig can also measure the total value of forces generated on the suspension system and tires as a whole.

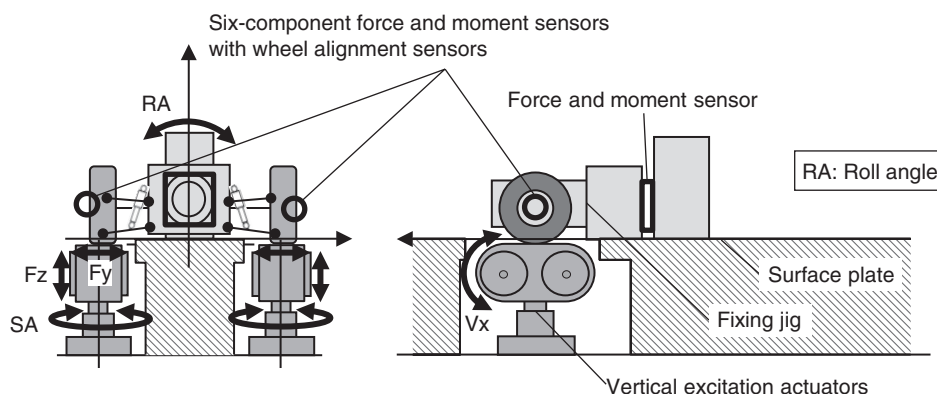


Fig. 3 Configuration of SC mode

In VT mode, measurements of factors that are due to suspension characteristics, such as changes of geometry, response lags, and inputs to steering components, are made in a state that includes body characteristics. In SC mode, however, measurements can be made so as to exclude input from the body. As a result, detailed analysis can be made as to whether the kinematic geometry of the suspension, and its component parts, such as springs, dampers, and every kind of rubber bushing, are functioning as the designers intend, as well as what is contributing to response lag, and other such questions.

It is also the case that, in VT mode, highly accurate sensors and measuring equipment could not readily be installed due to the layout of parts and components on actual vehicles. In SC mode, however, there are not as many constraints on layout. It is anticipated, for example, that highly accurate sensors can be installed to measure input to the steering assembly that is generated by a difference in the tire forces on the left and right wheels, therefore also enabling analysis of the contribution made by steering assembly components to steering force.

2.3. TS Mode

Test system specifications for TS mode are shown in Table 3. Figure 5 shows a schematic diagram of the system in that configuration, and Fig. 6 shows a photograph of it.

Analysis of suspension characteristics calls for

Table 3 System specification of TS mode

Vx	0 to 180 km/h
SA	-20 to 20 deg (up to 3 Hz)
CA	-15 to 15 deg
Fz	0 to 15000 N
Fy	-10000 to 10000N
My	-2800 to 2800 Nm
Fx	-6600 to 6600 N
Slip rate	-100 to 100%

comparison of the measurement results obtained from the suspension assembly with tires alone. Measurement of tires alone used to be carried out using flat belt test systems owned by tire manufacturers and independent measurement organizations. Their conceptual approaches to tire measurement differed from each other, however, and there were also differences due to the use of different test systems, so that comparisons could not be made of data under identical conditions. Consequently, measurement of the characteristics of tires alone using the same test system as for VT mode and SC mode will enable highly accurate quantification of the extent to which the suspension brings out the performance of the tire and of how the tire performance is transmitted to the vehicle.

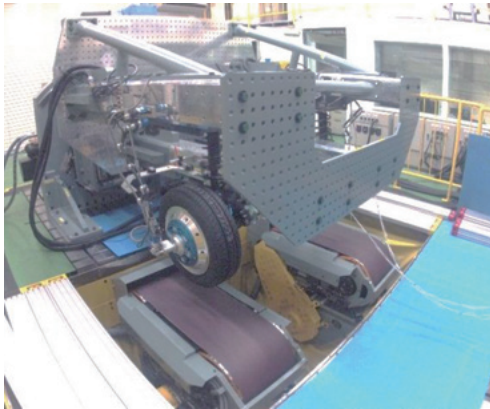


Fig. 4 Photograph of SC mode



Fig. 6 Photograph of TS mode

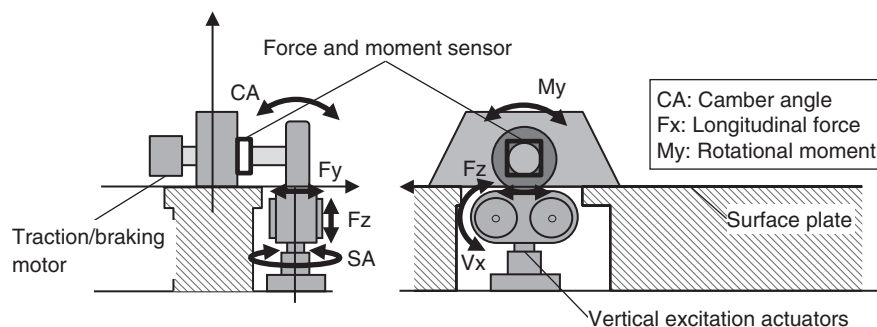


Fig. 5 Configuration of TS mode

In TS mode, the device that applies vertical displacement and camber angle to the tire is combined with the flat belt that applies rolling speed and slip angle, enabling measurement of the characteristics of a tire alone under conditions simulating those in which the tire is used. The system was designed to allow slip angles up to 20 deg and camber angle up to 16 deg with a view to measuring the characteristics of the tire alone under driving conditions that involve a large steering angle such as would result in a vehicle spinning or rolling over.

When measuring braking and acceleration characteristics, the rolling speed of the test tire is controlled by a driving and braking motor, and slip states from -100% (driving) to +100% (braking) are reproduced by causing a speed difference between tire speed and belt speed.

3. Measurement Results

Examples of measurement results obtained from the present system in each mode will be shown below.

3.1. VT Mode

Figure 7 shows a comparison of results from measurement with the front wheels positioned on the flat belts and the tire slip angle applied by wobble in the belt units, and measurement with the same front wheels with vertical excitation simulating an undulating road in addition to the slip angle. Table 4 shows the test conditions.

The horizontal axis in Fig. 7 represents the tire slip angle and the vertical axis represents the cornering force (CF). This shows the resultant CF on the left and right wheels when F_z is increased by causing a vertical stroke of 20 mm and of 40 mm with the vertical stroke set to 0 mm for the suspension with an empty vehicle. The lateral forces when the flat belts are steered to the right and to the left are averaged and treated as the CF. The CF characteristics of the tire alone are known to reach a saturation state at angles from 6 deg to 10 deg, and a saturation state is similarly reached at 10 deg or more

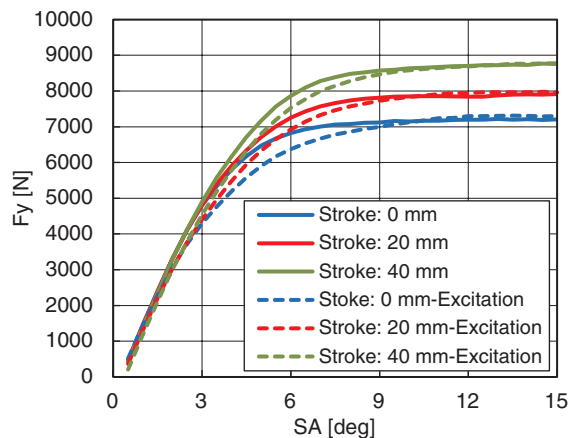


Fig. 7 Cornering force change to slip angle in VT mode with or without vertical excitation

Table 4 Cornering force test conditions in VT mode

Test vehicle	2010 model year JAZZ
Tire	175/65R15 84T
Vx	30 km/h
SA	0 to 12 deg
SA change speed	3 deg/sec
Air pressure	220 kPa
Suspension stroke	0, 20 and 40 mm
Vertical excitation	5 Hz, +/-5 mm

when the vehicle characteristics are included, and this method is expected to be capable of quantification of the suspension with tires as a whole handled in the same way as measurement of the tire alone.

When vertical excitation is applied, the reaction force in the suspension that keeps the tire in contact with the road surface becomes unable to keep up with the excitation, and the force F_z on the tire fluctuates. The coefficient of friction of the tire is dependent on load, so that CF generated with respect to a fluctuating load tends to diminish. The measurement examples here were made in a state that included the suspension characteristics, and the results confirmed that excitation caused a significant reduction in the CF even in the conditions that are observed in ordinary driving.

3.2. SC Mode

Figure 8 shows the results from measurement made

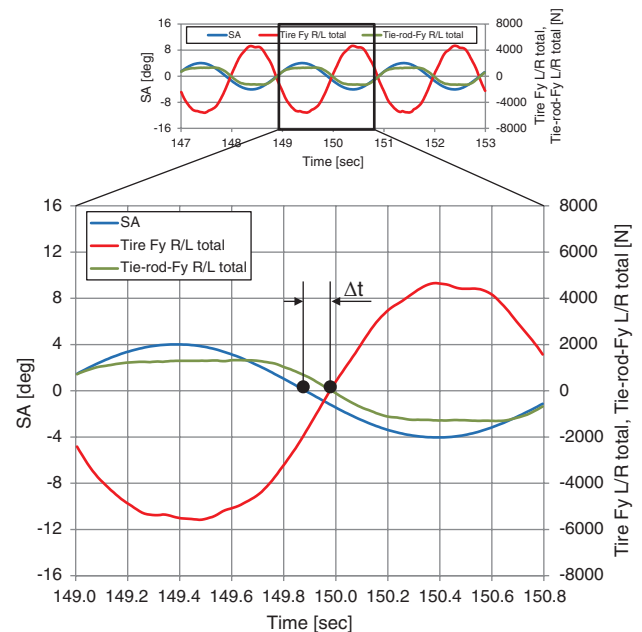


Fig. 8 Time history of cornering force and tie-rod end force

Table 5 Cornering force test conditions in SC mode

Test suspension	2010 model year JAZZ
Tire	175/65R15 84T
Vx	30 km/h
Fz	7000 N
SA change	-4 to 4 deg, 0.5 Hz
Air pressure	220 kPa

with the front suspension assembly fitted to a jig and slip angle input. The test conditions are shown in Table 5.

In the Fig. 8, the horizontal axis is the time and the vertical axis represents the resultant CF on the left and right wheels, the slip angle applied to the suspension assembly, and the resultant force on the steering tie rods at the left and right wheels.

The system was able to confirm the CF response lag Δt , which had been submerged in load variations caused by the undulating road surface and therefore had not been readily susceptible to analysis in actual vehicle testing, the state in which forces on the tie rods reach saturation, and so on.

This approach also enables analysis of the CF on each wheel, which could not be analyzed in actual vehicle testing, and comparison of it with the force on the suspension assembly as a whole can be expected to enable analysis of how each part of the suspension is functioning.

3.3. TS Mode

Figure 9 shows the results from measurement of CF with the tire alone, which is a representative characteristics of the tire, placed against the flat belt and with input of the slip angle. The test conditions are shown in Table 6. With the axes the same as in Fig. 7, the measurement results when Fz of 2 kN, 4 kN, and 6 kN is applied are shown and, as in section 3.1, the average of the left and right SA is treated as the CF.

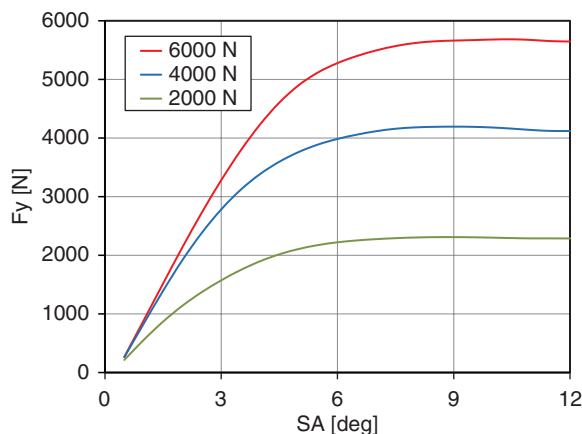


Fig. 9 Cornering force change to slip angle

Table 6 Cornering force test conditions in TS mode

Tire	205/60R16 92H
Vx	60 km/h
Fz	2000, 4000, 6000 N
SA	-12 to 12 deg, 6 deg/sec (triangle)
Air pressure	220 kPa

Table 7 Cornering stiffness test conditions in TS mode

Tire	205/60R16 92H
Vx	10 km/h, 100 km/h
Fz	200 to 7600 kN
SA	1 deg (const.)
Air pressure	220 kPa

Figure 10 shows CF measurements under varying speed and load with changes in the tire temperature. The test conditions are shown in Table 7. The horizontal axis represents Fz and the vertical axis represents CF and tire surface temperature. The CF per unit SA with the slip angle in the vicinity of 0 deg is termed cornering power (CP). This is an important tire characteristic that governs basic performance of vehicle dynamics.

Significantly different CP characteristics are obtained when measurement speed and tire surface temperature change. This makes it a matter of importance, therefore, to create measurement methods for appropriate quantification of tire characteristics based on a grasp of tire speed and temperature under actual driving conditions that change from moment to moment. This applies, for example, to lane changing when driving at high speeds, driving on winding roads at medium speeds, and emergency avoidance maneuvers.

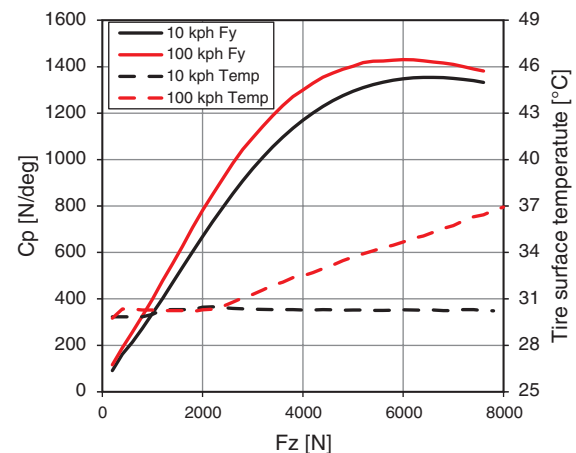


Fig. 10 Cornering stiffness change to vertical load

4. Conclusion

The features of a test system that performs comprehensive performance evaluation of the suspension and tires have been described.

The three test system modes were introduced by examples of how they can be used in development. VT mode was shown through the example of changing CF performance due to vertical excitation simulating an undulating road. SC mode was shown through the example of the relationship between CF and forces on the tie rods. TS mode was shown through the example of tire characteristics that change with a variety of factors.

The use of these test modes enables analysis of tire forces that previously were not readily susceptible to analysis in actual driving as well as highly accurate analysis of individual systems. This can be expected to enable enhanced accuracy of desktop examination using simulation and enhanced accuracy of verification of suspension component parts even at initial stages of development when a completed vehicle cannot be tested. By making the performance of prototype vehicles approach objectives more closely than before from the initial stages, this approach can be anticipated to enable the development of mass-production vehicles with a high level of maturity even with a short period of development.

The verification functions of this test system can also be applied in later development, for example to analyze phenomena that present issues, thus enabling the preparation of appropriate countermeasures. This test device can therefore be expected to perform effectively in the development of chassis performance.

References

- (1) Milliken, W. F., Milliken, D. L.: Chapter 8 Force-Moment Analysis, Race Car Vehicle Dynamics, SAE International, p. 293-343 (1995)
- (2) The Yokohama Rubber Co. Ltd.: Chapter 4 Tire dynamics of road, Pneumatic Tire Technology, Sankaido, p. 109-150 (1995)
- (3) Bridgestone Co.: Chapter 4 Tire characteristic, Section 3 Vehicle Dynamics, Pneumatic Tire Technology, Sankaido, p. 124-158 (2006)
- (4) Uno, T.: Section 2 Chassis and Tire dynamics, Vehicle dynamics and Chassis mechanism, Grand Prix Book Publishing Co. Ltd., p. 16-75 (2001)
- (5) Abe, M.: Chapter 2 Tire dynamic, Automotive Vehicle Dynamics, Publication Administration of Tokyo Denki University, p. 5-45 (2009)
- (6) Pacejka, H. B.: Chapter 1 Tyre Characteristics and Vehicle Handling and Stability, Tire and Vehicle Dynamics - Second Edition, Elsevier, p. 5-60 (2006)
- (7) Gillespie, T. D.: Chapter 6 Steady-state cornering, Fundamentals of Vehicle Dynamics, SAE, p. 195-235 (1996)
- (8) Reimpell, J., Stoll, H.: Chapter 2 Tyre and wheels, The Automotive Chassis: Engineering Principles, SAE International, p. 72-96 (1996)

■ Author ■



Tomonori SAKAI



Kaoru KUSAKA



Yuji SATO