1



# Abstract

One of the most fundamental approaches to increasing automobile safety involves improving the basic performance of the automobile itself, that is, its "running, cornering, and stopping." This article describes how we derived the control system requirements that are necessary to avoid spin, which is essential to vehicle performance, by analyzing vehicle stability, and also explains a hierarchical control system configuration for satisfying the control system requirements for improving the active safety performance of vehicles. It also clarifies the positions of the researches featured herein within a control system configuration.

Keywords Vehicle dynamics control, Active safety, Vehicle dynamics integrated management

要

安全性向上の最も基本的な要件は、「走る、曲 がる、止まる」の基本性能の向上と考えられる。 ここでは、基本性能としてのスピン抑制性能を確 保するために必要な制御系の要件を車両運動の安

## 旨

定性解析から導く。さらにこの要件を満たし,予 防安全性能を向上させる階層型制御系構成につい て解説する。そして,制御系構成における本特集 の研究の位置づけを示す。

キーワード 車両運動制御,予防安全,車両運動総合マネジメント

集

## 1. Introduction

To improve the active safety performance of a vehicle, there is a need for a control technology that can sense the environment in which the vehicle is operating, estimate the vehicle's behavior, and control the vehicle based on the estimated values. This article introduces studies that have estimated and attempted to control vehicle behavior in an attempt to improve active safety.

Figure 1 shows the concept of the hierarchical Vehicle Dynamics Integral Management (VDIM) we are proposing. In a present-day vehicle, which is controlled by a driver, the driver maneuvers the vehicle based on feedback on the external environment and vehicle behavior. In this case, an important factor is the stability of the driver-vehiclecontrol system. Meanwhile, it is expected that a system that is capable of automatically evading emergencies will eventually emerge, as environment sensing technologies evolve. The highest level of the hierarchy shown in Fig. 1 represents a trajectory plan for the driver's maneuvering and automatic operation. Vehicle dynamics control calculates the necessary forces (longitudinal and lateral) and moment (yaw moment) to be applied to the vehicle in order to achieve the target behavior according to the driver's maneuvering and the desired trajectory. The forces and moment are distributed as the forces on the tire of each wheel, according to the grip margin of the tire. Wheel control is the model





following control that is applied to attain the target forces on the tires through the actions of the brakes and steering actuators. This article is intended to explain the major element technologies in the control system shown in Fig. 1.

### 2. Analysis of vehicle dynamics stability

A fundamental approach to improving automobile safety involves improving the basic performance of automobiles, that is, their "running, cornering, and stopping." This article describes how we derived the control system requirements that are necessary to avoid spin, which is essential to vehicle performance, by analyzing vehicle stability.

First, let us numerically analyze vehicle behavior<sup>1)</sup> when the vehicle is running at a constant speed based on the two-degrees-of-freedom model shown in **Fig. 2**, as represented by the following equation, which contains non-linear cornering characteristics.

$$mv\left(\frac{d}{dt}\beta + r\right) = F_f + F_r \dots (1)$$

$$I_z \frac{d}{dt}r = \left(l_f F_f + l_r F_r\right)\cos\beta \dots (2)$$

where  $\beta$  is the sideslip angle, *r* is the yaw velocity,  $F_f$  is the cornering force of the front tires,  $F_r$  is the cornering force of the rear tires,  $l_f$  is the distance from the front axle to the center of gravity (c.g.),  $l_r$  is the distance from the rear axle to the c.g., *m* is the mass of the vehicle, and  $I_z$  is the yaw moment of inertia.

**Figure 3** shows the state trajectories of a vehicle in the two seconds after the initial states (+). These trajectories were obtained by assuming the vehicle speed to be 20 m/s. When the front steer angle  $\delta_f = 0$ [rad], the stable equilibrium point is at the origin.



Fig. 2 Equivalent cornering characteristics.

隹

This means that the vehicle is moving in a straight line. The trajectory starts in a stable area and converges to a stable equilibrium point and a small disturbance-caused vehicle body slip angle (if any) will not prevent the vehicle from returning to the straight-line travel. Meanwhile, a trajectory starting in an unstable area causes the vehicle body slip angle to diverge, resulting in the vehicle entering a spin. In addition, there is an unstable equilibrium point (saddle point) on the separatrix<sup>2</sup>) between the stable area and the unstable area. Applying a large steering angle exceeding the critical point would cause the stable and unstable equilibrium points to collide with each other, resulting in the disappearance of both points. This equilibrium point disappearance is one bifurcation symptom, called





saddle-node bifurcation.<sup>2)</sup> As the existence of an unstable equilibrium point can cause spin, stabilizing the unstable equilibrium point can prevent spin.

Meanwhile, the characteristic equation for a system that is linearized around an equilibrium point is:



 $c_f^*$  and  $c_r^*$  represent the slip angle gradients, respectively, of the front- and rear-wheel cornering forces. Because q<0 at the saddle point, Eq. (5) can be transformed into the following for the unstable equilibrium point (saddle point) shown in Fig. 3:

$$c_r^* < \frac{mv^2 l_f c_f^*}{mv^2 l_r + (l_f + l_r)^2 c_f^*}$$
 .....(6)

That is, the unstable equilibrium point can be attributed to a decrease in the gradient of the rearwheel cornering force, or to the saturation characteristic of the rear-wheel cornering force.

# 3. Vehicle dynamics control for improving active safety

If the road  $\mu$  of each wheel is known precisely, the vehicle dynamics control shown in Fig. 1 can be treated as a simple rigid-vehicle body dynamics control by confining the inputs, such as the target value for the vehicle dynamics state, into a bound based on the road  $\mu$ . If the estimated road  $\mu$ performance is not satisfactory, however, it is likely that the constraints on the vehicle dynamics state amount may adversely affect the critical vehicle behavior performance. For this reason, it is important to design a control system for compensating the stability for those inputs that exceed the bound. As stated earlier, the unstable state of the vehicle can be ascribed to the saturation characteristics of the rear-wheel cornering force. So, measures have been proposed for achieving robust stability by setting up a sector whose upper and lower perturbation bounds match, respectively, the upper and lower bounds of the gradient of the rear-

集

wheel cornering force characteristic, as shown in **Fig. 4**, and by modeling the rear-wheel cornering force in the form of the following equation that contains perturbations.<sup>1, 3)</sup>

 $F_r = -c_m (1 + W_r \Delta(t)) \alpha_r \cdots (7)$ where  $c_m$  is a nominal value to be used as a design standard for the rear-wheel cornering force gradient,  $W_r$  is the weight for standardizing the rear-wheel cornering force perturbation ratio,  $\Delta(t)$  is a standardized perturbation ratio ( $-1 \le \Delta(t) \le 1$ ), and  $\alpha_r$  is the rear-wheel slip angle.

It is possible to apply this control system design to vehicle integrated control in which the vehicle body force and moment are maneuverable amounts. This control design uses the vehicle body lateral force and yaw moment as maneuverable amounts in order to prevent the vehicle from entering a spin when it is at a critical spin start point. When the vehicle is at the critical spin start point, the vehicle body force, one of the maneuverable amounts, will be approaching the physical limit that can be attained. For this reason, the control structure shown in **Fig. 5** 



Fig. 4 Bounds for perturbations of rear cornering force.



Fig. 5 Control structure of vehicle dynamics control.

was configured by taking maneuverable amount perturbations into account where  $C_{FF}$  is the feedforward controller for calculating the vehicle body force and moment needed to achieve the target state amount  $x_0$ ,  $C_{FB}$  is the state feedback controller,  $\Delta_1(t)$  is the vehicle body lateral force perturbation ratio  $(-1 \le \Delta_1(t) \le 1)$ , and  $\Delta_2(t)$  is the rear-wheel cornering force perturbation ratio  $(-1 \le \Delta_2(t) \le 1)$ . As shown in **Fig. 6**, the vehicle body lateral force perturbations are modeled by setting up upper and lower bounds in such a way that the saturation characteristics are enclosed within the sector. The control target model shown in Fig. 5 can be represented as:

For the feedback controller  $C_{FB}$  in Fig. 5, a state feedback gain is obtained that accepts arbitrary  $\Delta_1(t)$  $(-1 \le \Delta_1(t))$  and  $\Delta_2(t)$   $(\Delta_2(t) \le 1)$  on the assumption that the steering angle  $\delta_{sw} = 0$ . This design problem can be formulated as a problem in which the state feedback gain  $C_{FB}$  is obtained with the  $H_{\infty}$  norm



Fig. 6 Modeling of lateral force with saturation characteristics.

from w' to z', as shown in **Fig. 7** below 1. In Fig. 7, W is a constant scaling parameter corresponding to the structure of the perturbations.

This problem can be derived by obtaining values of X, M, and W that satisfy the following:

$\exists X = X^T > 0$	)	• • • • • •	(10)
$\exists M = C_{FB}X$	• • • • • • • • • • • • • • •	• • • • • •	(11)
$\exists W \equiv \begin{bmatrix} W_1 & 0 \\ 0 & W \end{bmatrix}$	$\binom{1}{V_2} > 0 \dots$	• • • • • •	(12)
$\begin{bmatrix} H + H^T \\ CX + DM \\ WB_1^T \end{bmatrix}$	$\begin{array}{c} XC^{T} + M^{T}D^{T} \\ -W \\ 0 \end{array}$	$B_1W$ 0 W	< 0(13)
hana			

where

$H = AX + B_2M$	(14)
-----------------	------

These LMI (Linear Matrix Inequality) values can be obtained using the Matlab LMI toolbox.<sup>5)</sup>

## 4. Contents of this special issue

The design explained in the previous section is for the vehicle dynamics control in the hierarchical VDIM shown in Fig. 1. The longitudinal and lateral forces and yaw moment output here are optimally distributed as the force generated on the tire of each wheel, using a force and moment distribution algorithm at a lower hierarchical level. The distribution algorithm minimizes the maximum grip margin of each wheel. Algorithms for estimating and distributing the grip margin will be introduced in an individual research report, entitled "Estimation of tire friction circle and vehicle dynamics integrated control for four-wheel distributed steering and fourwheel distributed traction/braking systems."

Wheel control for estimating the grip margin and attaining the target value for the force generated on the tire of each wheel inevitably requires that the force be sensed accurately. The tire drive/brake



Fig. 7 Augmented system for designing feedback gain.

force can be estimated relatively easily from the engine torque and brake cylinder pressure. However, it is difficult to estimate the lateral force on each individual wheel. This is one of the major technical problems to be solved. Another individual research report, entitled "Detection of tire lateral force based on a resolver mechanism," introduces a lateral force sensing technology that uses a rotation angle sensor called a "resolver." This technology senses the amount of axle displacement caused by the lateral forces in terms of the differential phase shift of the resolver.

The highest hierarchical level must assume two cases. In the first case, the driver maneuvers the vehicle by feeding back forward-vision information. In the other case, the vehicle runs autonomously according to the sensed environment. Yet another individual research report, entitled "Study of the performance of a driver-vehicle system for changing the steering characteristics of a vehicle," introduces research that applies driver-vehicle system analysis technology that is based on a stationary driving simulator to the verification of the effects of steering control. This research has proved that steering control in accordance with the state of the road friction can be used with general drivers, for whom verification during driving experiments is difficult, that is, the stability of the driver-vehicle-control system is improved. The report only discusses the application of the current analysis technology to steering control, but the element technologies presented in it might be useful for the hierarchical VDIM we have proposed.

As environment sensing technologies evolve, it is expected that a system that is capable of automatically evading emergency situations will appear. Again, another individual research report, entitled "Optimum vehicle trajectory control for obstacle avoidance problem," introduces research into optimum evasion control with an eye on future automatic operation. This report proposes a trajectory control algorithm that has been designed to minimize the distance needed to avoid a collision in an emergency (single lane-change). It simultaneously solves the problems related to trajectory control and vehicle dynamics control on the assumption that the road  $\mu$  is given.

集

This special feature is intended to introduce our studies on the major element technologies we use in the hierarchical VDIM system shown in Fig. 1. The technological levels of the subjects included in the special feature range widely, from initial research to a high-quality commercial level. Meanwhile, there are some technical issues, such as accurate sideslip estimation, that are essential to this system configuration but which have yet to be addressed. We hope that future technical developments will solve these issues.

### References

- Ono, E., et al.: "Bifurcation in Vehicle Dynamics and Robust Front Wheel Steering Control", IEEE Trans. on Control Syst. Technol., 6-3(1998), 412-420
- 2) Hale, J. K., et al. : "Dynamics and Bifurcations",, (1991), Springer-Verlag
- Ono, E. et al. : "Robust Stabilization of the Vehicle Dynamics by Gain-Scheduled H ∞ Control", Trans. of SICE, 35-3(1999), 393-400
- 4) Desoer, C. A., et al. : "Feedback Systems", Input-Output Properties, (1975), Academic Press
- 5) Gahinet, P., et al. : "LMI Control Toolbox for Use with MATLAB", User's Guide version 1.0, (1995) (Report received on Sep. 22, 2005)



### Eiichi Ono

Research fields : Vehicle Dynamics Control Academic degree : Dr. Eng. Academic society : Soc. Instrum. Control Eng., Soc. Automot. Eng. Jpn. Awards : SICE Award for Outstanding Paper, 1995 SICE Chubu Chapter Award for Outstanding Research, 1999 SICE Chubu Chapter Award for Outstanding Technology, 2002 IFAC Congress Applications Paper Prize, 2002 Papar Award of AVEC, 2002 Papar Award of AVEC, 2004

R&D Review of Toyota CRDL Vol. 40 No. 4