

Estimation and Control of Vehicle Dynamics for Active Safety

Review

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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

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-vehicle-control 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

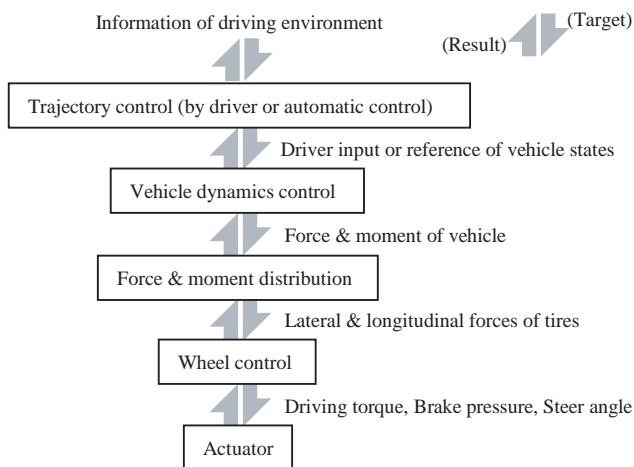


Fig. 1 Structure of hierarchical VDIM (Vehicle Dynamics Integrated Management).

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 behavior¹⁾ 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.

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

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

where β 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.

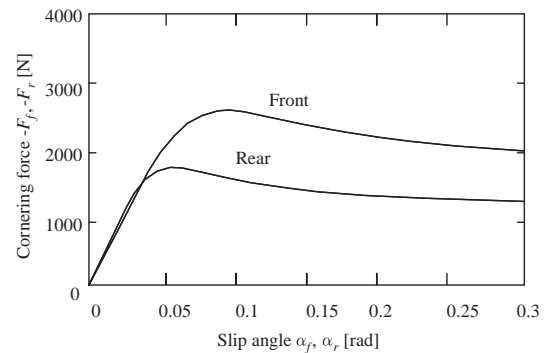


Fig. 2 Equivalent cornering characteristics.

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 separatrix²⁾ 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.²⁾ 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:

$$s^2 + p \cdot s + q = 0 \dots\dots\dots (3)$$

where

$$p = \frac{c_f^* + c_r^*}{mv} + \frac{l_f^2 c_f^* + l_r^2 c_r^*}{I_z v} \dots\dots\dots (4)$$

$$q = \frac{(l_f + l_r)^2 c_f^* c_r^*}{m I_z v^2} - \frac{l_f c_f^* - l_r c_r^*}{I_z} \dots\dots\dots (5)$$

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:

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

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

3. Vehicle dynamics control for improving active safety

If the road μ 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 μ . If the estimated road μ 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-

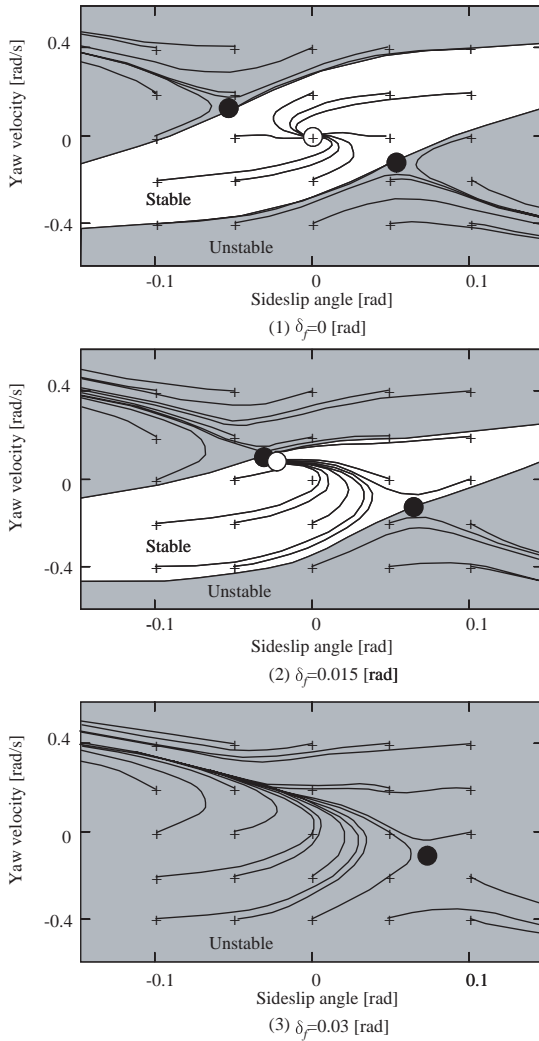


Fig. 3 State trajectories of the vehicle.
○: Stable equilibrium point and ● Unstable equilibrium point

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:

$$\exists X = X^T > 0 \dots\dots\dots (10)$$

$$\exists M = C_{FB} X \dots\dots\dots (11)$$

$$\exists W = \begin{bmatrix} W_1 & 0 \\ 0 & W_2 \end{bmatrix} > 0 \dots\dots\dots (12)$$

$$\begin{bmatrix} H + H^T & XC^T + M^T D^T & B_1 W \\ CX + DM & -W & 0 \\ WB_1^T & 0 & W \end{bmatrix} < 0 \dots\dots\dots (13)$$

where

$$H = AX + B_2 M \dots\dots\dots (14)$$

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

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 four-wheel 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

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 μ is given.

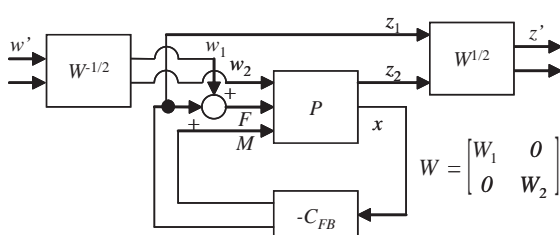


Fig. 7 Augmented system for designing feedback gain.

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.

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Papar Award of AVEC, 2004