

Enhancements in Vehicle Stability and Steerability with Slip Control

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ABSTRACT

To enhance both vehicle stability and steerability, vehicle dynamic parameters such as vehicle side slip angle, road friction coefficient, and tire side forces were precisely estimated in real time; and, utilizing four wheel slip control, a logic for optimizing vehicle dynamics was formulated. Tests on ice- and snow-covered roads demonstrated the effectiveness of the control, and confirmed the validity of the logic.

1. Introduction

Honda's Vehicle Stability Assist (VSA), which was introduced to the market in 1998 ⁽¹⁾, was developed based on front wheel brake control with the purpose of enhancing stability in FF (front-engine-front drive) vehicles. Since then the system has been further refined. However, in order to further enhance steerability and to apply VSA to vehicles other than FF vehicles, technology needs to be developed that can control slip at all 4 wheels. The goal of this research project was to enhance the performance of the VSA. Therefore, we looked at the issues involved and how to achieve this goal, and later we verified the developments made with actual vehicles. The vehicle dynamic controls applied are slip control, utilizing 4-wheel hydraulic brake actuators, and engine torque control. The test vehicle used was a FR (front engine – rear drive) vehicle, and the test course was a snow and ice covered track, where the control is particularly effective.

2. Research Goals

VSA is based on front wheel slip control, and is a stability control system that applies the appropriate braking to the outside front wheel when the vehicle's yaw rate exceeds the nominal yaw rate to restrain excessive moment. In this research project, the team worked to take VSA a step further, to achieve enhanced handling particularly during avoidance maneuvers, as shown in Fig. 1, by securing not only stability but also securing tire cornering force on various road surfaces to the greatest degree possible.

That is, the basic goal of this research is to achieve both of the following:

- (1) Enhanced stability (rear tire cornering force)
- (2) Enhanced steerability (steering effectiveness)

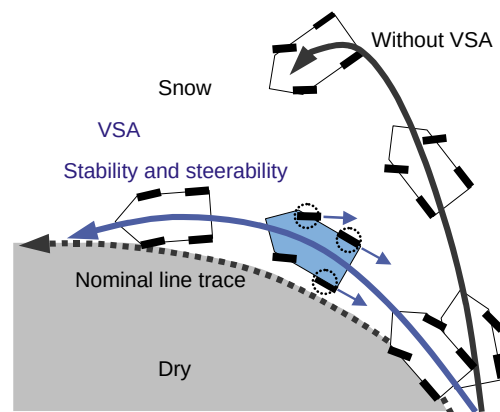


Fig. 1 Image of improved VSA

3. Research Issues

When a vehicle is cornering, the tire side forces on all 4 wheels determine the lateral acceleration and yaw moment. These side forces increase proportionally to tire side slip angle, but at a certain angle they become saturated. This grip limit differs according to road surface, as shown in Fig. 2. On icy or snowy roads the limit is reached between 1° and 5°, after which the vehicle becomes unstable. The process from cornering force critical conditions to instability, and the relationship between vehicle operation force and tire side slip angle are shown in Fig. 3. As you will come to see, in order to accurately understand vehicle dynamics, it is necessary to obtain the tire force from the graph of lateral force and side slip angle characteristics using the tire side slip angle that is converted from the estimated vehicle side slip angle. Also, it is necessary to estimate road surface friction coefficients in order to respond to various road

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surfaces. Furthermore, over-steer (OS) and under-steer (US) are judged from the estimated 4-wheel side forces, the vehicle's yaw moment and side slip angle are corrected with the optimal 4-wheel slip control, so that both stability and steerability can be achieved. From the above, the research issues can be summarized as the following three items.

- (1) Develop vehicle side slip angle and tire side slip angle estimation logic (β estimation logic)
- (2) Develop logic for estimating the friction coefficient for the friction between the tire and the road surface (μ estimation logic)
- (3) Develop optimal 4-wheel slip control logic (λ control logic)

Hereafter, the vehicle side slip angle is referred to as β , the friction coefficient between the tires and the road surface as μ , and tire slip rate as λ .

4. Basic Estimation Logic for Tire Slip Angle α and Vehicle Side Slip Angle β

Target estimation accuracy for tire side slip angle α is

$\pm 0.5^\circ$, making it possible to distinguish the 1° to 2° where side forces are saturated on ice. The basic technology's system configuration is shown in Fig. 4. The sensors include those for steering angle, longitudinal acceleration, lateral acceleration, yaw rate, and wheel velocity. Fig. 5 shows the basic logic configuration. The total logic is comprised of the following four types of logic – α and β estimation logic, μ estimation logic, tire characteristics data map logic, and β control logic (4-wheel λ control). The method for estimating vehicle side slip angle β is a logic that can estimate forces on each tire by combining the conventional two tire vehicle model (above spring) and non-linear tire model (below spring). Furthermore, in order to avoid integration noise, the total of the estimated side forces for all 4 wheels is fed back, rather than the lateral acceleration sensor values, and those estimated side forces are read from the tire data map. Tire data is expressed as three characteristics,

- (1) Side slip angle / side force
- (2) Slip rate / side force
- (3) Slip rate / braking and traction force

and is applied according to the estimated μ .

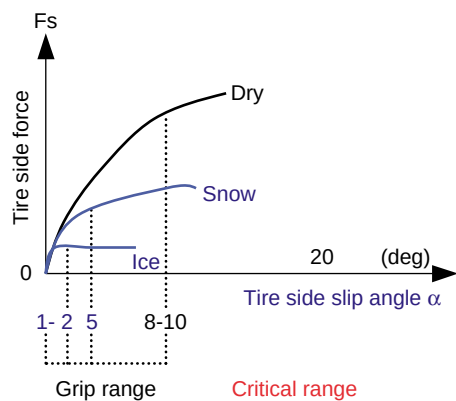


Fig. 2 Tire side force characteristics

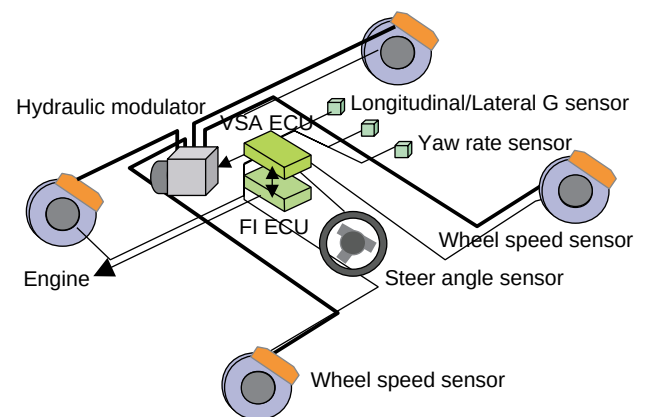


Fig. 4 System configuration

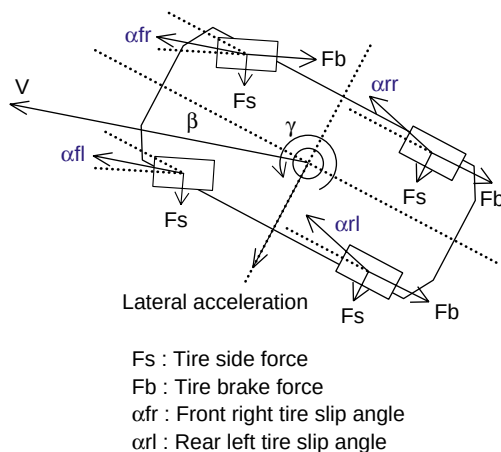
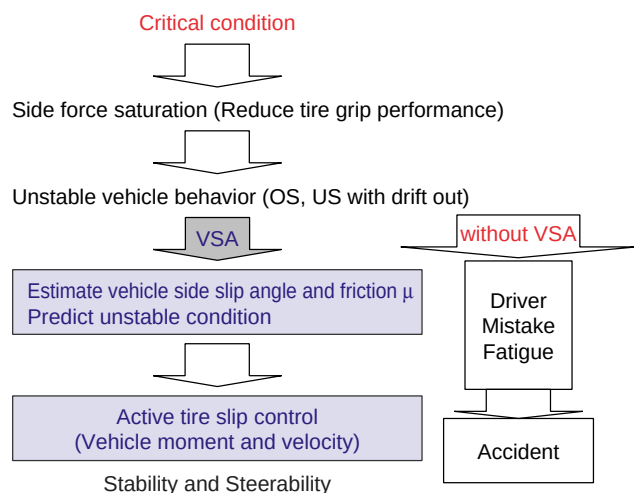


Fig. 3 Vehicle dynamics and stabilizing flow



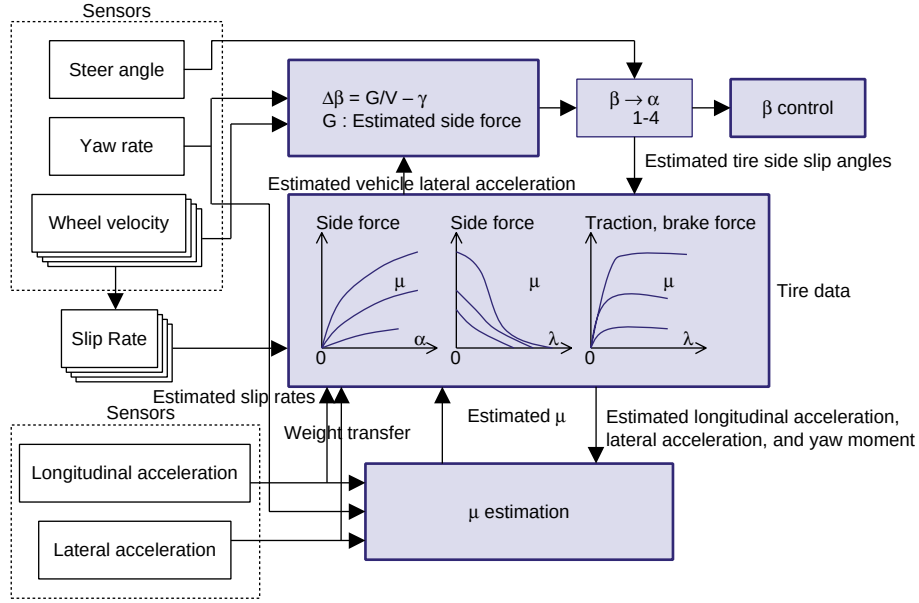


Fig. 5 Basic estimation logic

5. Tire and Road Surface μ Estimation Logic

The μ estimation logic is the most important issue in this research. The situation that should be estimated is as follows: there is a change from constant speed straight line driving to cornering that is close to limit conditions, or when there is a sudden jump in μ , and in addition, tire slip control is implemented through such means as ABS, and it is necessary to stably maintain estimation accuracy across a wide range. In order to achieve this, the logic shown in Fig. 6 was created, based on the following flow.

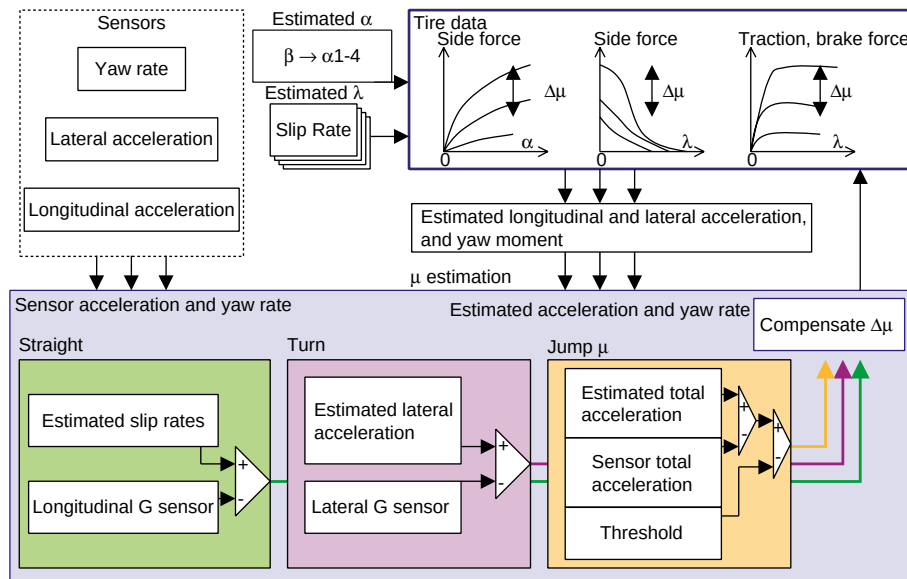
- (1) Separate μ estimation for each mode – straight line driving, cornering, jump μ
- (2) Calculation of longitudinal and lateral acceleration and

yaw moment from the estimated tire side slip angle α and the tire data map

- (3) Calculation of the μ correction value from a comparison of the estimated value (longitudinal and lateral acceleration, yaw moment) and each sensor's value
- (4) Application of the tire characteristics data map gain, based on the μ correction value.

In addition, although it is not clear in the diagram, tire data map application according to longitudinal and lateral load transfer is also included.

The target accuracy for μ estimation is set at 0.05, as calculated and converted from the side slip angle target accuracy of 0.5° .


 Fig. 6 μ estimation logic

6. Vehicle Side Slip Angle β and Road Surface μ Estimation Vehicle Data

The results of actual vehicle tests using the two types of logic outlined above are shown below. Fig. 7 shows the β estimation results during slalom course driving (40km/h) on an icy road. It was confirmed that the estimation results obtained were almost identical to those of the vehicle side slip angle sensor. Fig. 8 shows the μ estimation results when performing a slalom maneuver between dry asphalt and a low μ (wet basalt) surfaces at 40 km/h. It was confirmed that μ correction is carried out in real time when entering the low μ area. Wheel velocity data shows control dynamics.

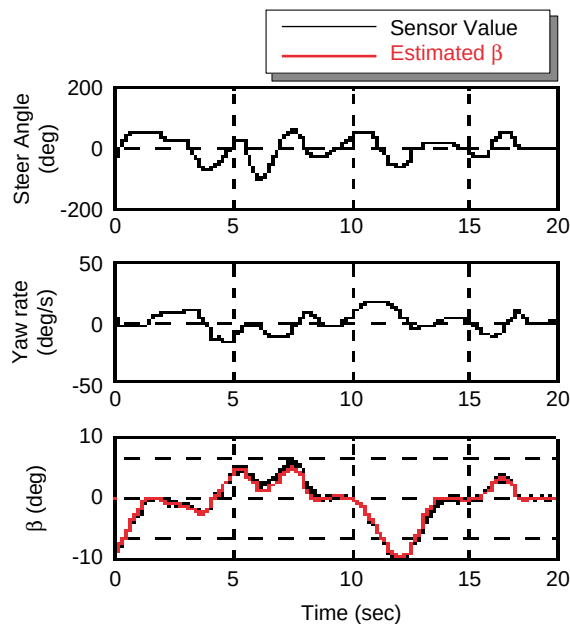


Fig. 7 β estimation test data

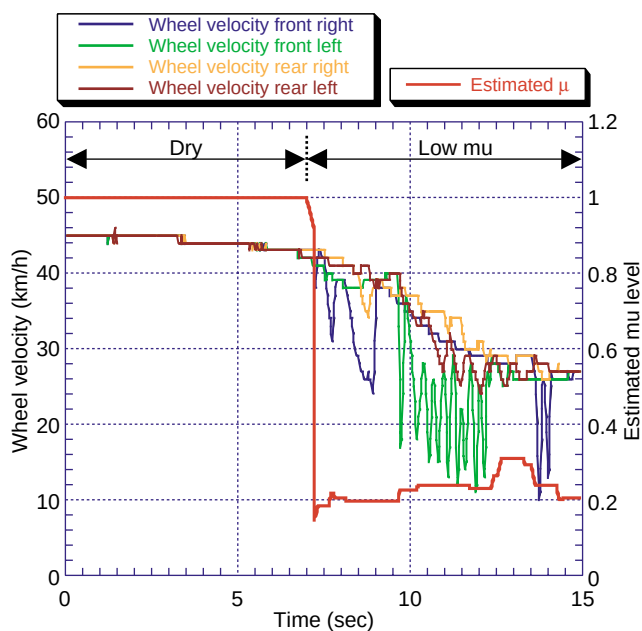


Fig. 8 μ estimation test data

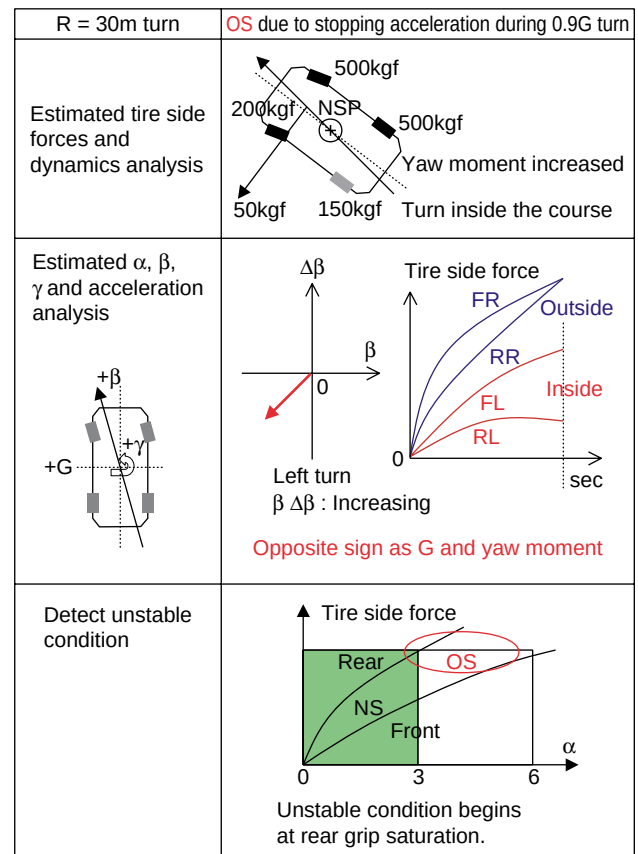


Fig. 9 Stability analysis

7. Tire Side Force Estimation and Stability Judgments

Fig. 9 shows the results of analysis of OS using estimated tire side slip angle α , vehicle side slip angle β , yaw rate, lateral acceleration, and tire side forces. According to these results, we found that rear tire side forces are saturated from the onset of OS. Calculating the absolute value of α (rear wheel side slip angle) and the differential value $\Delta\alpha$, then comparing them with each limit (judgment value), makes it possible to make an early prediction of critical conditions.

For reference, here is a brief discussion of US. In comparison with OS, which is excess moment due to a drop in rear tire grip, almost all US is a deviation from the target trace line due to excess speed. Quantifying the amount of deviation is difficult with only the current sensors and logic. This is because there is no method for accurately knowing what the target driving line should be.

Also, with conventional US control, the control amount is set by a comparison between the nominal yaw rate at the velocity estimated from the steering angle, and the sensor's yaw rate. However, even if yaw moment control is achieved with this method, it is not possible to return to the target driving trace line. Therefore, this research project is limited to OS control, explaining the control to achieve stability and steerability, and comparing it to conventional yaw rate control. As for US control, it is not thought that current performance can be enhanced with simple vehicle unit control, and thus it is left as a future issue.

8. Optimum Control of Vehicle Dynamics

The optimum control, this project's third issue, is discussed here.

The process for analyzing OS and spin during cornering on icy and snowy roads can be divided into four stages as shown in Fig. 10.

- (1) Rear tire side slip angle αr exceeds limit value.
- (2) Rear tire side forces are saturated.
- (3) Vehicle side slip angle and yaw moment increase.
- (4) Grip is lost and consequentially so is steerability, rendering turning impossible.

As can be understood from this process, if OS can be predicted in step (1), then by repeating both counter-moment control and deceleration control in steps (2) and

(3), vehicle stability can be maintained, steering is effective, and it is possible to recover the motion state. This is outlined in Fig. 11.

That is, stability uses front outside wheel brake control, and steerability uses the brake control of the two rear wheels to return to the grip range. This control flow is shown in Fig. 12.

The innovation of this research lies in the fact that, in addition to stability control, steerability control is also achieved simultaneously. That is, while leaving the lower limit side forces required to maintain rear tire stability, optimum control (referred to as β control hereafter) is used to obtain maximum deceleration. Tire side slip angle α and road surface μ estimation logic are indispensable in achieving this control.

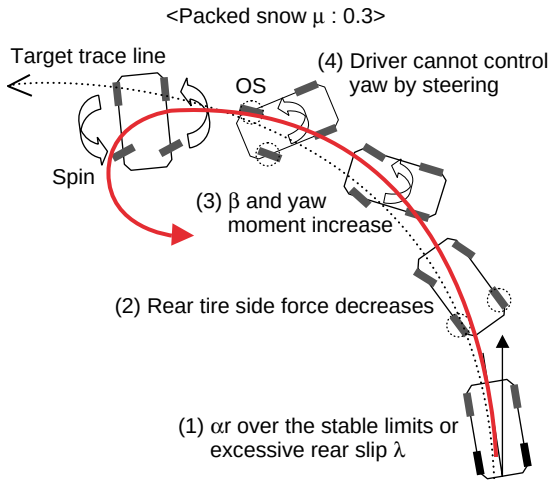


Fig. 10 Over steer dynamics analysis

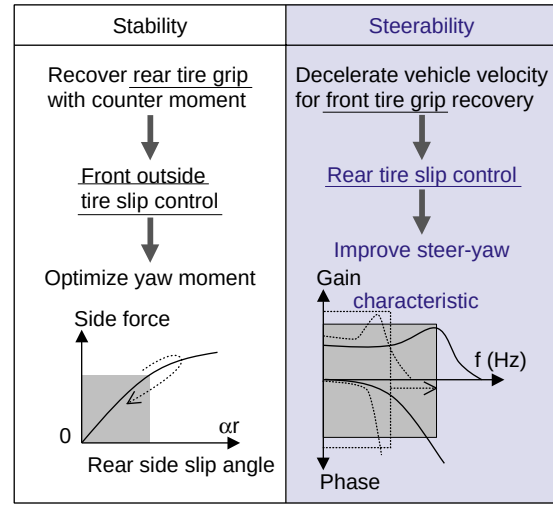


Fig. 11 Optimum control concept

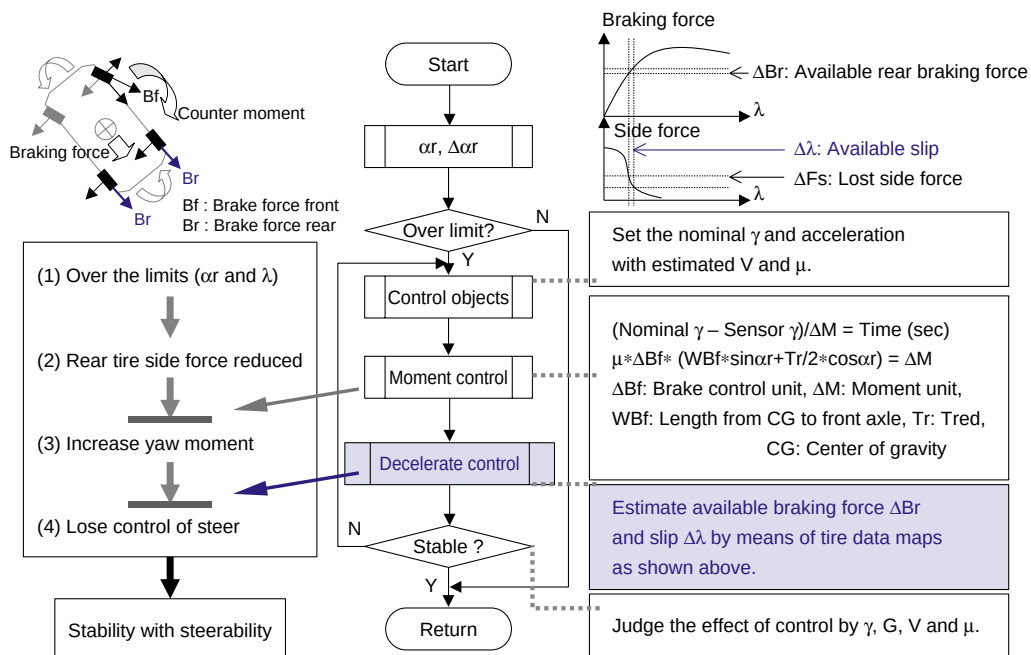


Fig. 12 Basic control logic

9. Vehicle Control Test Data

Driving tests were implemented in three modes, slalom, J-turn, and winding, on both compact snow (μ = approx. 0.4) and ice (μ = approx. 0.15). Due to limits on the length of this paper, only the data for the slalom and the J-turn on compact snow are included here (Fig. 13, Fig. 15: β control, and Fig. 14, Fig. 16: conventional yaw rate control). The graphs show time series data for steering angle (red: left turning is +), estimated vehicle side slip angle β (blue), and yaw rate (green: left turning is +).

When comparing β control to conventional yaw control, it is clear both β control stability and steerability are

enhanced. With β control, yaw rate and side slip angle restraint performance is good, and steering angle movement (driver input) is stable. The driver can feel a secure cornering force. This effect matches the first targeted effect of enhanced stability. In comparison, conventional yaw rate control quickly subdues excess yaw movement itself, but the ability to maintain a stable position (side slip angle) is missing. That is, grip force when turning fluctuates and steering correction is large and frequent.

In other driving modes as well, β control has better stable line trace performance. In particular, β control effectiveness is greatest with a low μ and at high vehicle speeds, that is, the closer to the limit, the bigger the effects of β control.

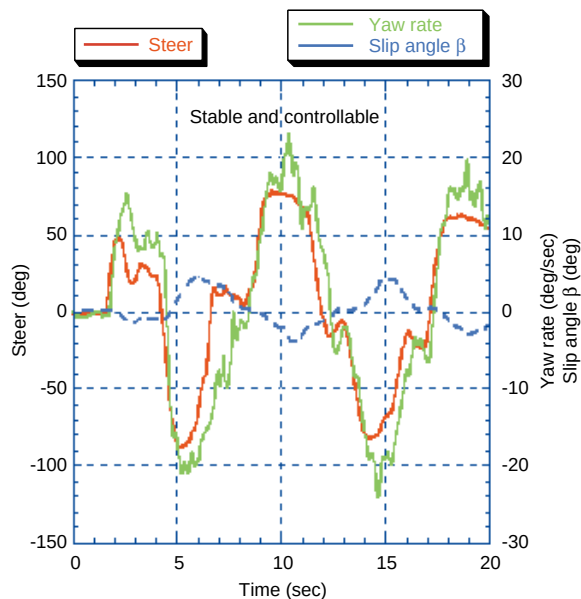


Fig. 13 Slalom test on snow (β control)

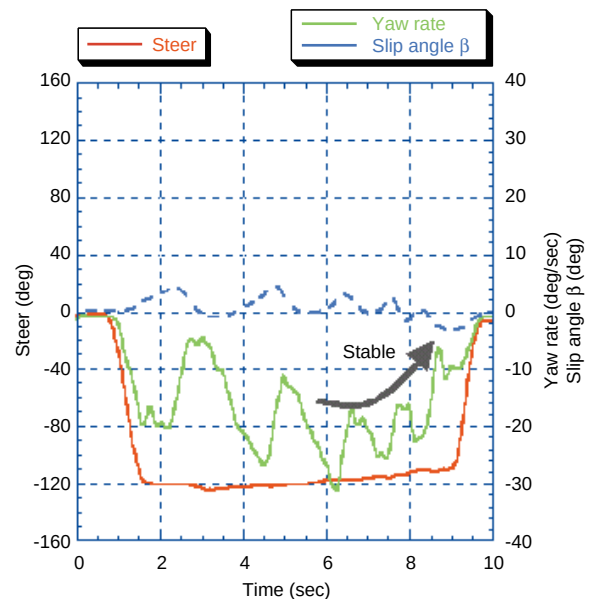


Fig. 15 J turn test on snow (β control)

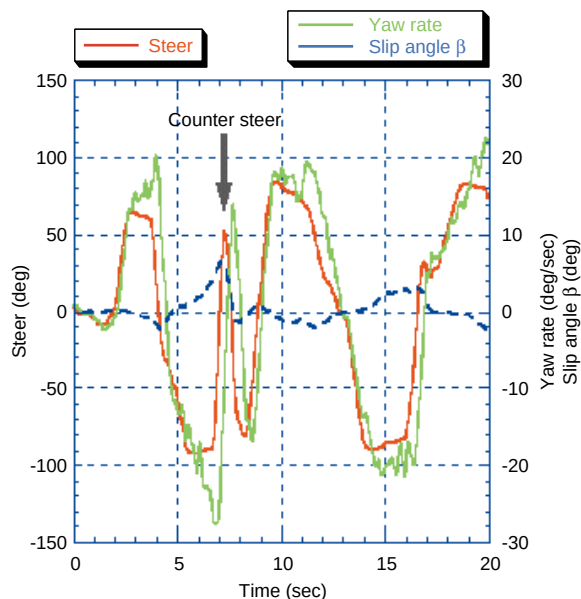


Fig. 14 Slalom test on snow (Yaw rate control)

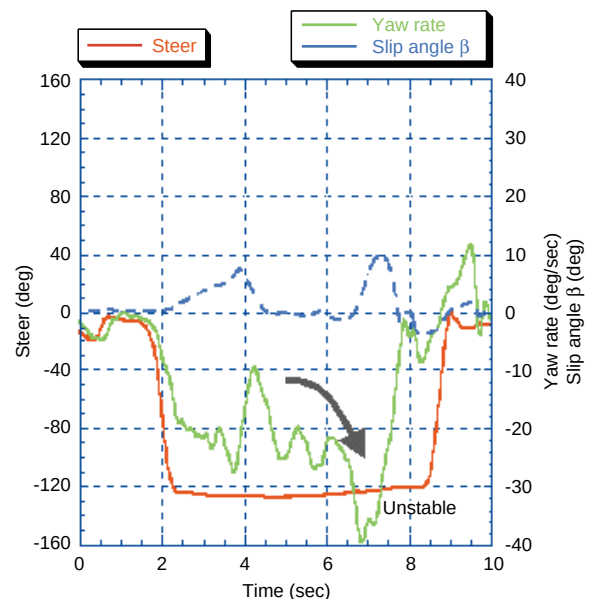


Fig. 16 J turn test on snow (Yaw rate control)

10. Control Effects and Evaluation Method

The results of testing on ice and snow covered roads are examined. First, the evaluation method will be discussed.

When evaluating non-linear dynamics, $\beta - \Delta\beta$ phase flat Lissajous should be considered, but as shown in Fig. 17, we must divide the dynamics into two types – steering angle and yaw rate, and steering angle and side slip angle – and examine them closely. The reason for this is that vehicle dynamics control makes it possible to achieve both stability and steeringability by supporting good input/output characteristics in relation with the driver. That is, it is

necessary to study whether or not vehicle yaw rate and side slip angle response process for driver steering input is stable and feeding back the amounts and directions which correspond to the predictions. Also, if these results are good, then the characteristics should be good in terms of $\beta - \Delta\beta$ phase, too.

(1) Steeringability Evaluation

As long as the steering angle / yaw rate flat trace stays, as a whole, in a narrow band range, time phase delay is small and over-steer and steer lag are reduced (steeringability). Furthermore, if the trace path passes close to the point of origin, control is certain, correction by

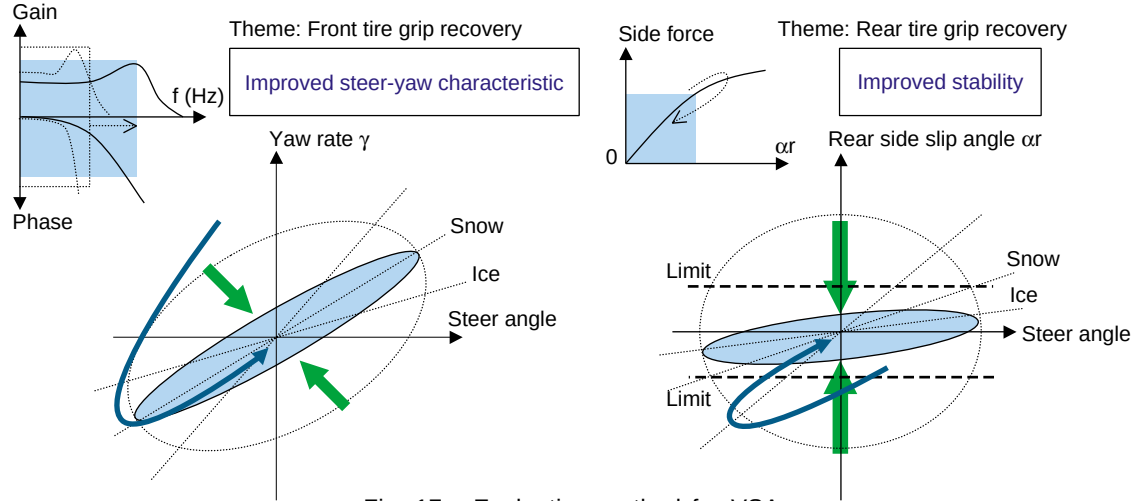


Fig. 17 Evaluation method for VSA

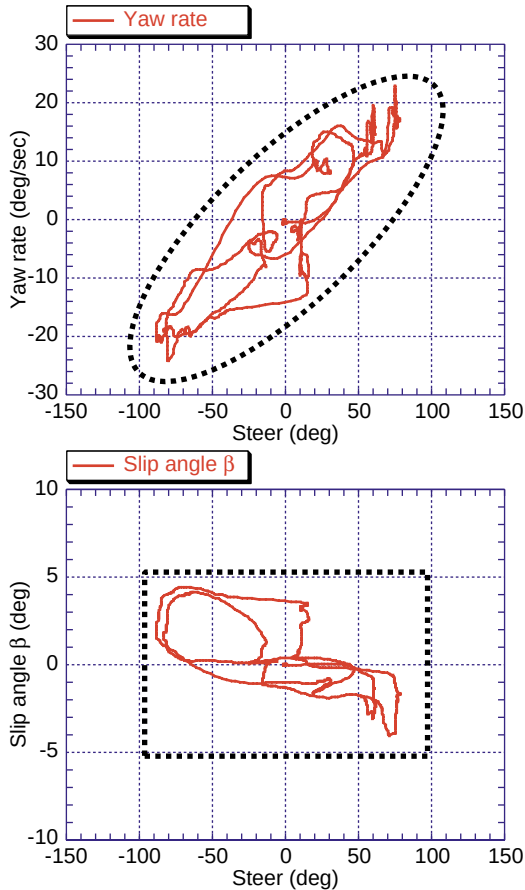


Fig. 18 Slalom evaluation on snow (β control)

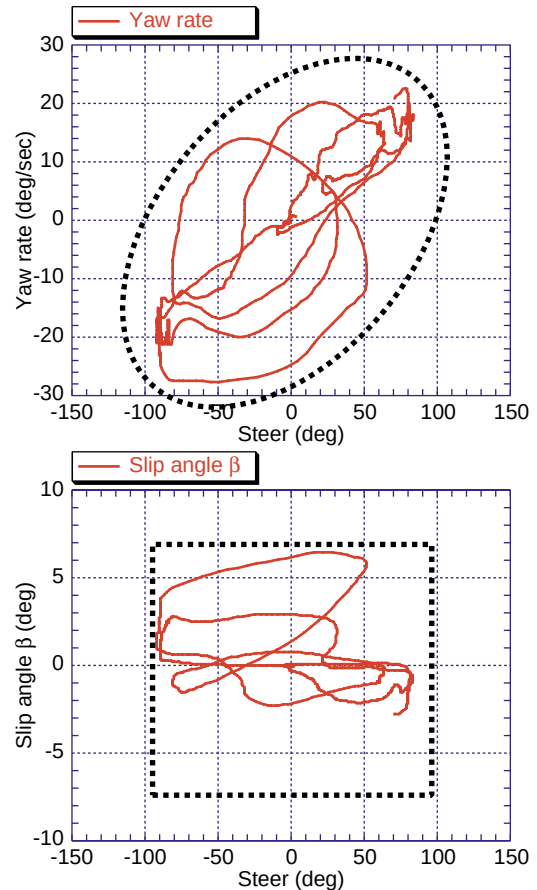


Fig. 19 Slalom evaluation on snow (Yaw rate control)

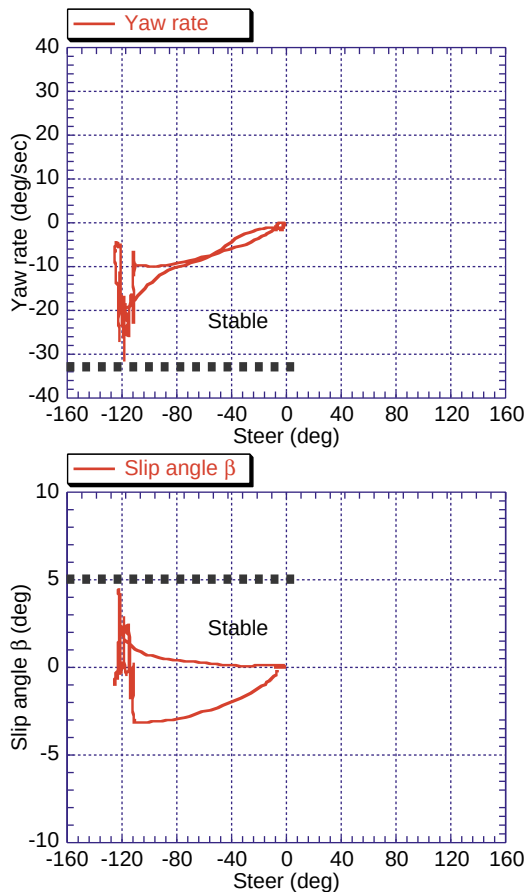
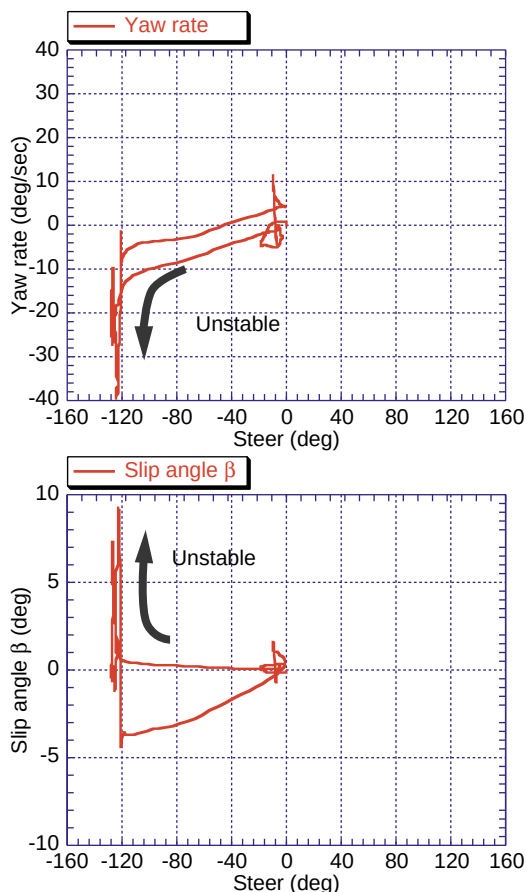
Fig. 20 J turn evaluation on snow (β control)

Fig. 21 J turn evaluation on snow (Yaw rate control)

the driver is small, and stability can be maintained.

(2) Stability Evaluation

As long as the steering angle / side slip angle flat trace is kept below the rear side slip angle α limit value, yaw rate movement is stabilized (stability). Furthermore, if the trace path passes close to the point of origin, control is certain, and there is little counter-steer by the driver. It is possible to reduce divergence in slalom driving.

Next, the test data for the compact snow slalom and J-turn test modes are discussed. (Fig. 18, Fig. 20: β control; Fig. 19, Fig. 21: conventional yaw rate control.)

β control has the following qualities over yaw rate control.

- (1) Concerning steering and yaw characteristics, time phase lag is small, and control is reliable, so steerability is high.
- (2) Concerning steering and side slip angle characteristics, excessive side slip angle is reduced and stability is high.

11. Conclusions

The goal of this research project was to achieve both of the following:

- (1) Enhance stability
- (2) Enhance steerability

Based on the vehicle control effects shown in the section above, "handling that is stable and is faithful to the steering" is achieved. Thus, basically, the validity of the optimum 4-wheel slip control logic has been proven.

The following three concrete results have been achieved:

- (A) Creation of a basic logic for accurately estimating stable side slip angle (vehicle, tires)
- (B) Creation of a basic logic for a practical, real-time, tire / road surface μ estimation logic
- (C) Creation of a basic method for optimum slip control in order to obtain both stability and steerability.

We will continue development in the fields of stability and steerability technology as we work toward practical applications of this technology.

References

- (1) Yutaka Horiuchi, et al: VSA (Vehicle Stability Assist), Automobile Technology, May Vol. 47, No. 7 (1998), p. 36 – 43.

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