Technology Introduction

Research on SA-PS Integrated Control Technology

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1 Introduction

As driving automation technology enters widespread use in the future, about 30% of new automobiles are expected to be self-driving vehicles of Level 3 or higher in 2040 [1]. Accordingly, the needs for safety, security and riding comfort during automated driving will probably be higher and more diversified. To respond to these needs, KYB is making use of its strengths in shock absorbers (hereinafter "SA") and power steering (hereinafter "PS") to conduct research on an integrated SA-PS control technology to freely control the behavior of a vehicle. For improved safety and security of automated driving, it is indispensable for self-driving vehicles to run properly without wandering. A technology that allows these vehicles to correctly follow the target trajectory by suppressing the effect of uneven road surfaces is needed.

In this research, we applied the SA information associated with the vertical vibration of vehicles to the control of electronic power steering (hereinafter "EPS") as part of the development of an SA-PS integrated control technology. For this technology application, we addressed the development of two types of vehicle control: trajectory tracking control and anti-yaw control, as shown in Fig. 1.

Trajectory tracking control, which is now one of the basic technologies of the SA-PS integrated control technology, is an EPS control technique to allow the vehicle to accurately follow the target trajectory by making use of the information collected during automated driving. The anti-roll control uses the information from SAs subjected to vertical vibration to control the EPS, thereby suppressing the yawing associated with the vertical vibration.

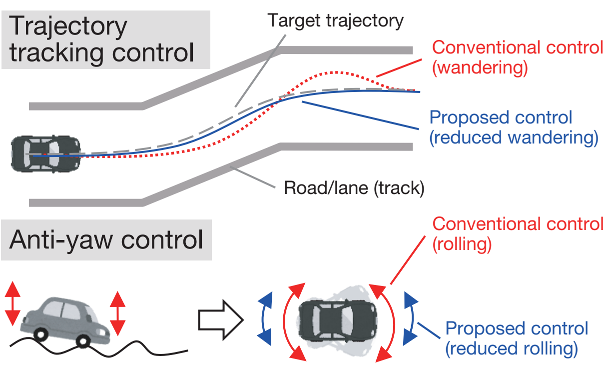

Fig. 1 Overview of SA-PS integrated control technology

2 Overview of Control System

This research used an experimental vehicle fabricated for the research and development of an SA-PS control system. This vehicle is designed to be able to automatically follow the path data within a test-driving course (a digital lane set on a map dataset) that was created in advance. This means that the experimental vehicle can only be run on the test-driving course. For the purpose of this paper, the experimental vehicle is classified as an automated steering vehicle since only steering control has been automated.

In the test, the brake and accelerator of the vehicle were applied manually, and the vehicle speed was maintained by the cruise control function provided as standard.

2.1 Control Components of Experimental Vehicle

Fig. 2 shows an overview of the equipment of the experimental vehicle. The experimental vehicle was fabricated based on a commercially available vehicle with additional sensors to measure the stroke (displacement) of the suspensions (hereinafter "stroke sensors"), acceleration sensors, and a GPS sensor capable of precisely locating

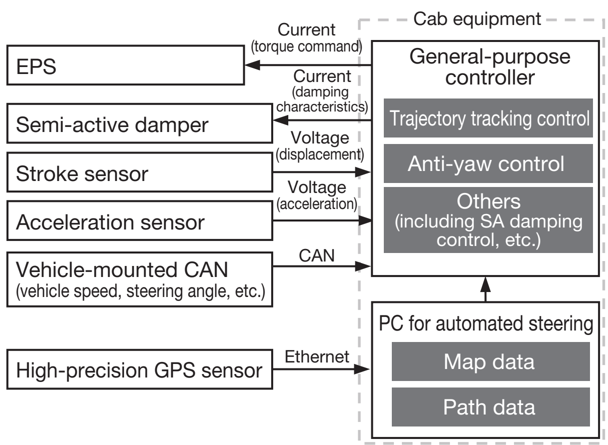

Fig. 2 Overview of equipment of experimental vehicle

the vehicle's position. Furthermore, a general-purpose controller and a personal computer (PC) system for automated steering were installed in the cab for the purpose of vehicle control.

As steering has been automated, the experimental vehicle uses an EPS prototype fabricated by KYB, which is connected to the general-purpose controller to achieve automatic control. The vehicle also has electronically controlled semi-active dampers made by KYB, which are also connected to the general-purpose controller to achieve automatic control.

2.2 System Configuration

Fig. 3 shows an overview of the control system configuration. Since the two types of control systems introduced in this paper mainly work for the EPS, Fig. 3 illustrates the connection to the EPS.

The PC for automated steering is installed with Autoware® Note 1) driving automation software. It also includes path data of the test-driving course that was designed and measured in advance. The PC for automated steering uses this path data and GPS positioning information to send information about the target paths nearby necessary for path following to the general-purpose controller.

The general-purpose controller has a control model created with MATLAB®/Simulink®. The controller performs even calculation of control commands (torque commands) given to the EPS necessary for path following.

Autoware® can originally calculate the steering angle necessary for path following from the path information and its own positional information. In this research, this function has been transferred to the general-purpose controller for improvement.

Note 1) Autoware®: An open-source software program for driving automation systems based on Linux and ROS, made public for the research and development of driving automation as part of the joint results of a project participated in by Nagoya University, Nagasaki University and National Institute of Advanced Industrial Science and Technology (AIST).

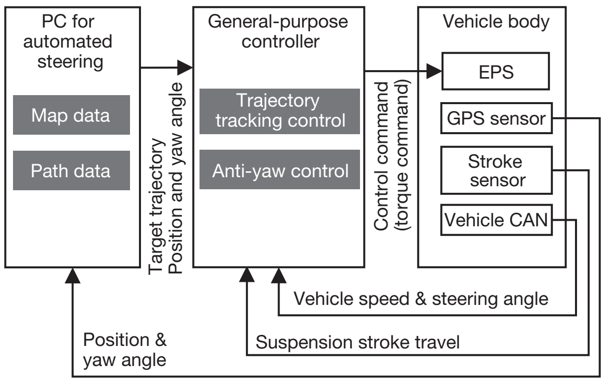

Fig. 3 Overview of system configuration

3 Design of Trajectory Tracking Control

One of the requirements for ensuring accurate tracking of a target trajectory is to suppress the delay in response to the yaw rate.

The delay in response to the yaw rate occurs in relation to various mechanical or physical characteristics of the vehicle during the transfer of the steering force to the vehicle body until the vehicle starts yawing. To eliminate the delay in response, the steering wheel should be operated to advance the phase according to the transfer characteristics, suppressing the delay in transfer of the force from the steering wheel to the vehicle.

One of the methods of eliminating the delay in response is model based predictive control. This method is often used in control systems in chemical plants or other facilities that involve relatively slow processes [2]. However, the method requires relatively complex procedures for calculation of constraints and optimization, posing the problem of time-consuming processing. Recently, the problem has been almost resolved by the use of processors or algorithms, but there still exists a high technical hurdle.

With the aim of implementing the control by as simple a method as possible, we developed in this research a trajectory tracking control system shown in Fig. 4. This control begins with prediction of the vehicle response: predicting the vehicle position and attitude during tracking of the target trajectory. It then goes on to yaw rate control that references to a future target value as far as the predicted response is delayed, thereby suppressing the delay.

After that is steering angle control. This control uses the inverse function of the EPS transfer function and introduces a 2-degree-of-freedom control that cancels the EPS transfer characteristics, suppressing the delay in response. Since an accurate differential value is needed to deal with the inverse function, the steering angle control accepts input of up to the second derivative of the target steering angle.

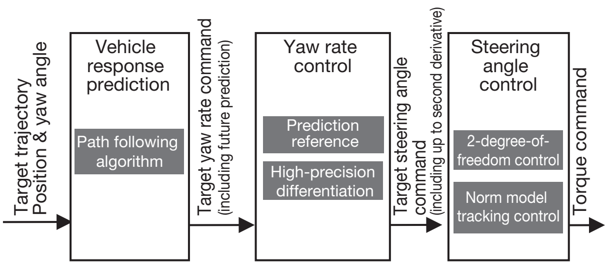

Fig. 4 Overview of trajectory tracking control

3.1 Path Following and Target Trajectory

For the purpose of this research, the path is defined as a route established on a map in advance, similar to a railroad track, and the target trajectory is defined as a route along which the vehicle should actually run while path following. The target trajectory greatly varies by the design concept or algorithm of driving automation. Particularly for running on a curved path or changing lanes, how the target trajectory is depicted against the established path affects the riding comfort and safety of the vehicle.

This research uses a tracking algorithm called the Pure Pursuit method [3], which is also used in Autoware®. A trajectory produced by the path following with this algorithm is defined as the target trajectory.

Fig. 5 shows an overview of the path following algorithm. The Pure Pursuit algorithm calculates the target yaw rate from a position that is some distance ahead of the vehicle on the path, called a lookahead distance, and its deviation from the path and then determines the steering angle based on the vehicle characteristics.

For performance evaluation, this path following algorithm was used to calculate in advance the vehicle's track against the path data of the test road. The resultant track was used as the target trajectory.

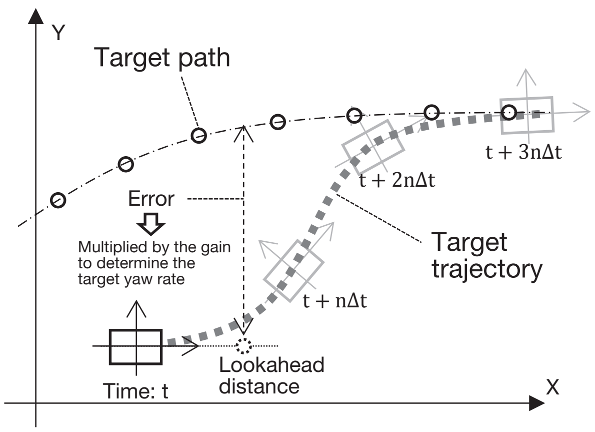

Fig. 5 Path following algorithm and target trajectory

3.2 Prediction of Vehicle Response

The location and attitude of the vehicle at any given future point in time can be predicted by calculating the response of the vehicle according to the tracking algorithm if the relationship between the current position of the vehicle and the path is known, although the accuracy is limited to some degree. With the aims of a reduced volume of calculation and simplified implementation of the system in this research, a 2-degree-of-freedom planar vehicle model was used to predict the vehicle response. Path following was performed according to the Pure Pursuit algorithm described in section 3.1. The changes in location and attitude of the vehicle per unit of time based on a discrete model were sequentially calculated to predict the yaw rate at future points in time up to one second ahead. Finally, the target yaw rate was determined.

3.3 Yaw Rate Control-Prediction Reference and Control

The vehicle's delay in response to the yaw rate can be predicted based on the vehicle characteristics as well as the vehicle's actual responses data. As in the reference to a target value based on the prediction as shown in Fig. 6, an estimated target value at a future point of time equivalent to the predicted delay in response is used to hopefully suppress the delay.

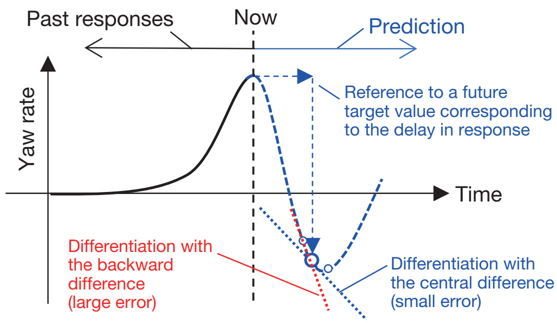

Fig. 6 Reference to predicted target value

Furthermore, the use of past and future values before and after the target value, respectively, makes it possible to obtain the approximation of up to the second derivative required to control the steering angle with a higher accuracy than with the central difference approximation.

The target yaw rate is controlled by a combination of the feedforward control that determines the steering angle with the vehicle speed gain with the vehicle stability factor [4] based on the vehicle characteristics taken into account and the feedback control that relies on the difference between the target yaw rate and the actual yaw rate.

3.4 2-degree-of-freedom Control Using Steering Angle Control-Prediction and Norm Model Tracking Control

As a method of suppressing the delay in response, 2-degree-of-freedom control is available. This method controls the target object by applying the inverse function, namely, the inverse characteristics, of the object's transfer characteristics to cancel the original transfer characteristics. However, the strict use of inverse functions requires highly accurate derivatives. Moreover, it is difficult to apply inverse functions to the EPS because of its complex characteristics.

In this research, we applied a combination of the 2-degree-of-freedom control and the norm model tracking control shown in Fig. 7 to control the steering angle.

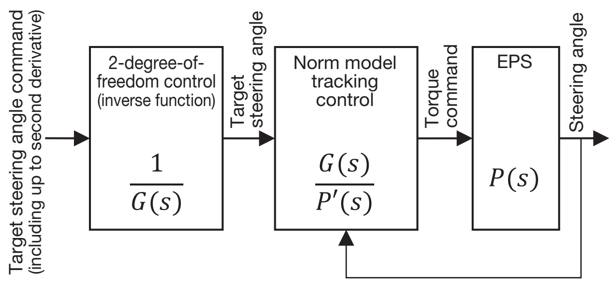

Fig. 7 Overview of EPS steering angle response delay control

When the EPS transfer function is $P(s)$, the norm model tracking control is first used to approximate the EPS response characteristics to a given transfer function $G(s)$ (norm model). In this process, the EPS transfer function is linearized to obtain the approximate transfer function $P'(s)$.

For the 2-degree-of-freedom control, the accurate derivative determined in section 3.3 is used to calculate the inverse function. Now the equation (1) below holds on the whole. The steering angle is controlled so that the input X ≒ the output Y.

$$\frac{\mathrm{Y}}{\mathrm{X}}=\frac{1}{G(s)}\frac{G(s)}{P'(s)}P(s)\fallingdotseq 1 \qquad (1)$$

Since the use of the inverse function $1/P'(s)$ alone would deteriorate the performance if the EPS characteristics $P(s)$ change, we use the norm model control for approximation to the norm model $G(s)$ with the feedback control. This is intended to improve the robustness against disturbance.

The results of simulation of the steering angle control we developed are shown in Fig. 8. The word "Conventional" in the legend indicates the steering angle control installed on KYB's EPS prototype. "Proposed" shows the steering angle control attained in this research. For the trapezoidal waveform response (90 degrees at 4 sec.), which is one of the normal range response tests, the proposed control shows earlier response and earlier conversion with less overshoot than the conventional control. According to the step response diagram, the proposed control produces earlier response and earlier conversion than the conventional control as well, but with a little bit larger overshoot. This may be attributable to the model following error of the norm model control and/or the effect of the differentiation accuracy of the inverse function.

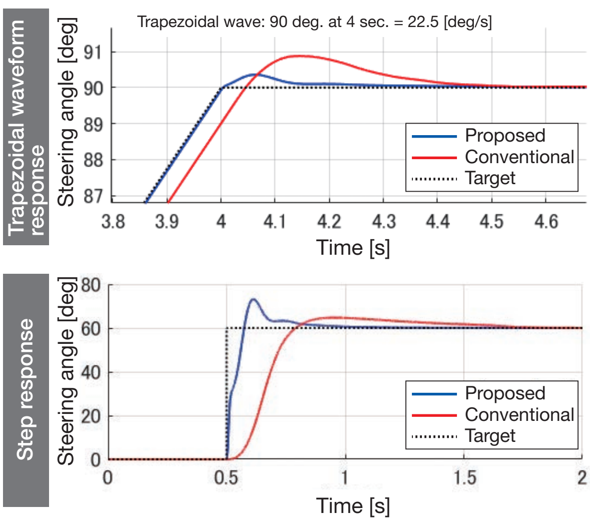

Fig. 8 EPS response to steering angle control

4 Design of Anti-yaw Control

When the vehicle vibrates up and down while running on an uneven road surface, the camber angle changes to generate a camber thrust [5] due to the suspension geometry. In this case, the vehicle body may laterally swing to have a yaw rate.

In this research, such a yaw rate occurring during running on an uneven road surface is defined as rolling. We developed an anti-yaw control function to suppress the rolling by estimating the vehicle yawing based on the information collected from the stroke sensors mounted on the SAs and correcting the steering angle with the EPS.

4.1 Prediction of Vehicle Yawing from Strokes

The yaw rate of the vehicle attributable to running on an uneven road surface could be measured with a sensor such as an inertial measurement unit (IMU). Measurements obtained by such a sensor represent remaining vibration of the vehicle body after the occurrence. This implies that it is difficult to use these measurements to quickly suppress the yawing.

Another solution is to determine the stroke motion of the suspensions of the four-wheel car at the moment when the tires ride on an uneven road surface, thereby predicting the rolling. Based on the prediction, the steering can be controlled in advance to prevent the yawing just before the vibration is transferred from the vehicle axles to the body.

Fig. 9 shows the design of an anti-yaw control that we developed. This control design can achieve higher prediction accuracy by combining different prediction logics depending on the type of uneven road surface: for example, a road surface that causes both the front and rear wheels to yaw together or a road surface that causes the front and rear wheels to roll independently.

In particular, differentiating the difference in yaw between the front and rear wheels now enables prediction of the yawing caused by the torsion of the vehicle body when the wheels on one side of the vehicle ride on a step height.

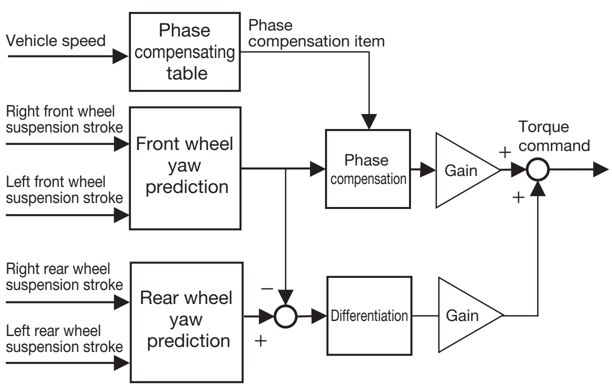

Fig. 9 Overview of anti-yaw control

4.2 Vehicle Response on Test Road Surface and its Prediction

We selected two different types of test road surfaces for verification and evaluation of the rolling of vehicles on uneven road surfaces. An overview of these test road surfaces is shown in Fig. 10. The cyclic wheels-on-both-sides vibrating road indicates a road surface on which the right and left tires of the vehicle running thereon alternately vibrate up and down. The single vibrating road has a step height of approximately 10 cm on which only the wheels on one side of the vehicle are riding.

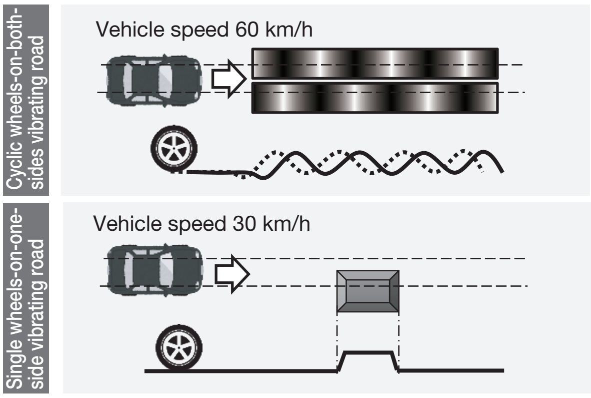

Fig. 10 Test road surface for yawing evaluation

In order to determine the occurrence of the yaw rate due to the uneven road surface and the accuracy of rolling prediction, the test vehicle with the anti-yawing control disabled was run on the uneven road surface straight ahead. The actual yaw rate response during the test along with the predicted yaw rate are shown in Fig. 11. The figure shows good results for the prediction of the yaw rate response based on the stroke motion with relatively high accuracy.

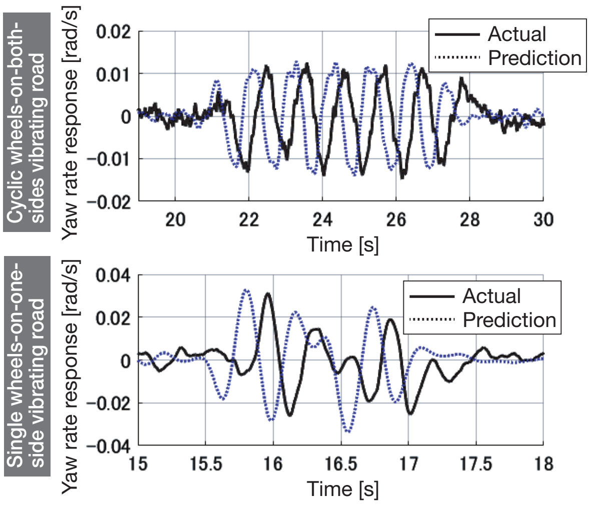

Fig. 11 Yaw rate response and prediction for vehicle running on test road surface

4.3 Prediction-based Yaw Suppression

Fig. 12 shows how the anti-yaw control command is input to the EPS. Predicted yawing is converted into a torque command by multiplying a gain, which is then added to the EPS torque command. Adding this converted value to the torque command whose response speed is very high can produce a sufficient allowance to cover the period of time from yawing prediction to suppression.

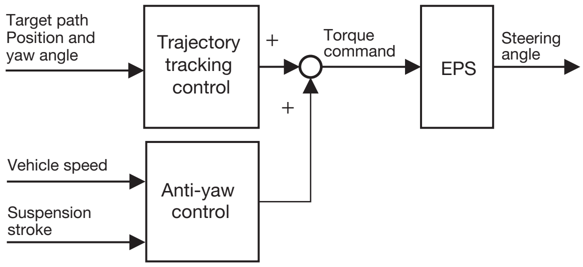

Fig. 12 Addition of anti-yaw control command

5 Evaluation of Trajectory Tracking Performance

In order to evaluate the tracking performance of the trajectory tracking control proposed in this research, a test was carried out on test courses. The test results were compared to those of the conventional feedforward control that determines the steering angle based on the target yaw rate command multiplied by the vehicle speed gain as described in section 3.3.

5.1 Performance Evaluation Conditions

As described in section 3.1, the Pure Pursuit path following algorithm was applied to obtain a track of the vehicle following the path data established on a map in an ideal way with no lateral slip. The track was used as the target trajectory.

The trajectory tracking error was defined as the distance between the center of gravity of the vehicle and the intersection of the target trajectory and the lateral line normal to the center of gravity of the vehicle, and then used for evaluation. For performance evaluation, the maximum trajectory tracking error was compared between the conventional and proposed controls to determine the error ratio to the conventional level.

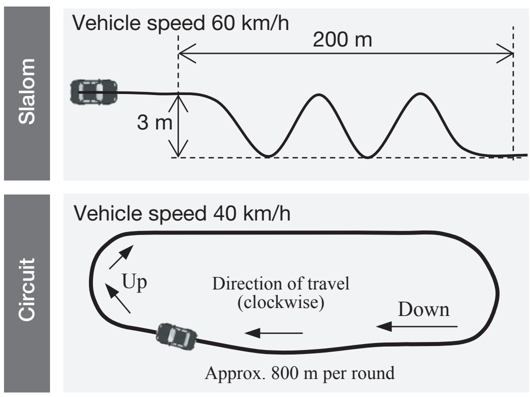

Fig. 13 Trajectory tracking performance test roads

In the test, the vehicle was run on a flat road surface slaloming at a vehicle speed of 60 km/h and on an up-and-down circuit road at a vehicle speed of 40 km/h as shown in Fig. 13, in order to measure the trajectory tracking error. The vehicle speed was maintained with automated steering during measurement.

5.2 Results of Performance Evaluation

Fig. 14 shows the results of the driving test. For each of the test roads, the tracking error from the target trajectory over the total travel is plotted. The proposed control only generates a trajectory tracking error of 35% of the conventional level at maximum for the slalom. For the circuit road, the error is substantially reduced in the curved sections. Though the vehicle was run at low speed, the proposed control is found to have the effect of error reduction even on the course with many disturbances, including up and down.

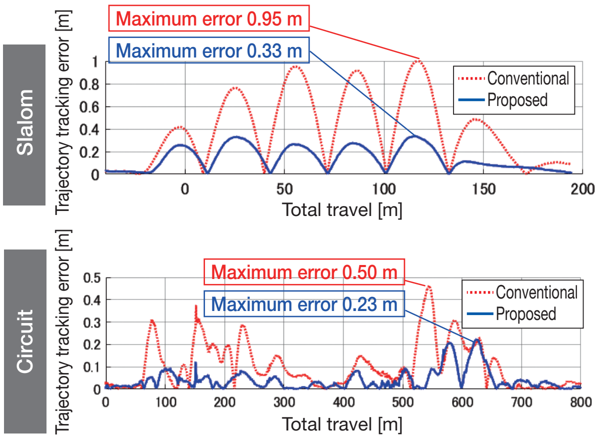

Fig. 14 Results of trajectory tracking performance evaluation

6 Evaluation of Anti-yaw Performance

In order to evaluate the proposed anti-yaw control for suppression of the yawing of the vehicle running on an uneven road surface, a test was carried out on test courses. The test results were compared to a case with no anti-yaw control.

6.1 Performance Evaluation Conditions

The anti-roll performance was evaluated with the PP value (the difference between maximum and minimum values) for the yaw rate measured with the on-vehicle IMU sensor. The ratio of the PP value of the proposed control to the PP value of the conventional one was calculated for comparison purposes.

The same test conditions related to the road surface and vehicle speed as those described in section 4.2 were applied. The test vehicle was run on the cyclic wheels-on-both-sides vibrating road at 60 km/h and run on the single wheels-on-one-side vibrating road straight ahead at 30 km/h. The actual yaw rate was measured.

6.2 Results of Performance Evaluation

The results of the performance evaluation test are shown in Fig. 15. The rolling has been reduced to 46% of the conventional level at maximum. In addition, the yaw rate is further reduced in positions near the intermediate point of the cyclic wheels-on-both-sides vibrating road.

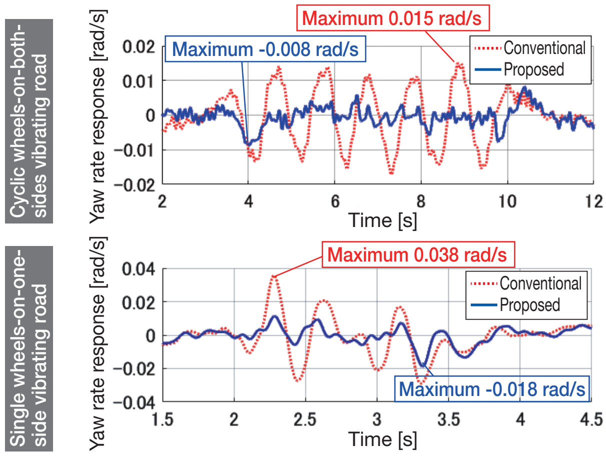

Fig. 15 Results of anti-roll performance evaluation

To determine the effect of the anti-yaw control, drivers from Experiment Dept., KYB, test-drove the vehicle to conduct sensory evaluation. As a result, positive comments were collected, including "the feel of rolling is better than before," "I felt zippy about the car rolling," and "the vertical shock feeling has been improved." Furthermore, it was also clarified that the reduced rolling affected the sensory evaluation about the vibration in the vertical and rolling directions.

On the other hand, comments like "with reduced yawing, I am annoyed by the vertical vibration" and "I cannot get well with any change in yawing (if the vertical vibration is terrible)" were collected. We eventually identified a challenge that it would be necessary to design and adjust the control and sensory effect with consideration given to a trade-off between yawing and vertical vibration.

7 In Closing

As an SA-PS integrated control technology for achieving improved safety, security and riding comfort during automated driving, we developed trajectory tracking control that allows vehicles to correctly follow the target trajectory, and anti-yaw control that can suppress the yawing of vehicles running on an uneven road surface. With these technologies, the tracking error for the target trajectory has been reduced to 35% of the conventional level at maximum and the yawing has been reduced to 46% of the conventional level at maximum. The anti-yaw control sensory evaluation has revealed that the control can deliver a certain effect of improvement but has given rise to a challenge that a trade-off between yawing and vertical vibration needs to be addressed.

By focusing on not only the yawing associated with the vertical vibration but also the vertical vibration involved in steering operation, we will promote the improvement of the SA-PS integrated control technology.

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