VEHICLE DYNAMICS

1 Introduction

In 2021, the world continued to be affected by the COVID-19 pandemic, which has been raging worldwide since the beginning of 2020. The problem of supplying parts such as semiconductors caused by that pandemic a large-scale adjustment in automobile production. The recent circumstances surrounding the automotive industry are extremely harsh, and automakers are pursuing development along major trends such as electrification and automated driving to make it through this once-in-a-century period of profound transformation.

The field of vehicle dynamic performance involves not only an open loop to improve that performance, but also active research on the evaluation of dynamic performance as a human-vehicle system, as well as on quantitative analysis methods for driver sensory evaluation. These efforts place the emphasis on ease of handling for drivers. Technological progress in automated driving is also remarkable. The Public-Private ITS Initiatives & Roadmap aims to realize the world's safest and smoothest road traffic society, and sets the goal of commercialize automated driving (level 4) on expressways by 2025. Currently, the installation of technology conforming to level 3 automated driving makes it possible for the system to take over driving under certain conditions, such as traffic jams on highways. Research on integrated control and cooperative control using multiple control devices is being conducted to secure stability and improve comfort in both automated driving and driver driving.

In terms of environmental issues, a number of European countries are banning sales of internal combustion engine vehicles that emit carbon dioxide, such as gasoline and diesel vehicles. Bans on sales of new gasoline and diesel vehicles are planned by 2030 in the U.K, and 2040 in France. Japan has also announced a policy of reducing greenhouse gas emissions to virtually zero by 2050, and the Biden administration of the United States has announced the goal of increasing the proportion of new car sales that do not emit exhaust gas, such as electric vehicles, to 50% of the total sales by 2030, aiming to achieve carbon neutrality by 2050. In that context, automotive OEMs are accelerating the introduction of electric vehicles to the market, and the shift to motors as the drive source is leading to many new technological innovations. Comprehensive technological development is progressing throughout the industry, including motion control aimed at improving marketability, battery/inverter control development aimed at improving power consumption, and the further promotion of vehicle weight reduction.

2 Tires

Vehicle motion is a physical phenomenon that first occurs because of the existence of force acting between the tires and road surface. Therefore, one of the most important aspects of the field of vehicle dynamics is understanding tire characteristics.

Analyzing vehicle motion using known tires or a model of tires identified in advance is a common practice. However, it is extremely difficult to estimate the force generated by tires because the road surface conditions change from moment to moment in actual driving environments, and especially ordinary roads. Therefore, efforts were made to estimate the m-S characteristics of friction characteristics on actual roads for the purpose of optimizing dynamic motion performance in more advanced vehicle motion control and level 4 automated driving. Validation performed by varying the tires, their load, and road surface conditions has demonstrated that the distribution of coefficients of the magic formula (MF) parameters presents certain characteristics depending on road surface conditions. Such technology is expected to serve as the basis for building a road surface condition database. In addition, the results of the m-S characteristics were used to conduct a study to estimate the lateral force, and an algorithm for calculating the lateral force and self-aligning torque (SAT) was derived by extending the brush model.

It is well known that the characteristics of the wheel combined with the tire have a great influence on the steering stability. One initiative focused on the relationship between the rigidity of the wheel joint and the fastening force to analyze their contribution to steering stability. A higher fastening torque between the wheel and hub increases the camber rigidity of the wheel disc increases, making the lateral rigidity of the contact point larger. In the vehicles used in this study, the rigidity of the rear wheels was greatly improved, resulting in an enhanced yaw rate resonance frequency relative to the steering frequency.

Tires also play a major role in off-road driving performance on sandy terrain, and research is being conducted to clarify the interaction between sand and tires using actual vehicles. A sensor that can measure the driving force on the tire contact surface in an off-road environment was developed. It demonstrated that the driving force and road surface resistance of the tire contact surface increase with the slip ratio, that traction force has a convex peak with respect to the slip ratio, and that a lower tire pressure decreases road surface resistance and increases traction.

3 Braking and Driving

Research on the braking and driving characteristics of automobiles has expanded from anti-lock brake system (ABS) and electrical stability control (ESC) systems, which improve the stability when the vehicle is driven at its performance limits, to direct yaw moment control (DYC), which improves cornering performance during normal driving. More recently, these functions have been combined with front and rear, as well as left and right wheel driving torque controls to develop technology to control not only the plane but also the sprung posture. [!] With the introduction of electric vehicles in full swing, precise vehicle dynamic control using motors has become a reality. Braking drive control has not only been used for its conventional purpose of improving maneuverability, but also become the subject of active research to improve the subjective evaluations of drivers.

Extensive research already conducted on DYC has contributed to improving the dynamic performance of commercial vehicles. However, DYC control methods were only studied for individual events, and there were few that could be applied to the entire steering response. Therefore, an attempt was made to derive a control law that could improve the vehicle's transient response characteristics using DYC. The addition of feed-forward control and feedback control that modify the steering speed and of yaw moment control proportional to the yaw rate demonstrated that it is possible to obtain almost the same steering response characteristics as in a vehicle with a reduced yaw moment of inertia, as well as to improve robustness and disturbance toughness. The effect of friction torque of differential gear was also analyzed, and the reduction of steady yaw gain at small steering angles, the effect on steering transient response, and the effect on damped natural frequency have been demonstrated. These are the essence of handling DYC control, and are viewed as the basis for various control studies in the future.

A control law that combines driving force with the anti-dive and anti-squat characteristics of the suspension to advance the roll phase with respect to the yaw rate while also coupling with the pitch was formulated in the context of control technology for the sprung posture based on braking and accelerating. The effectiveness of that control was verified with an actual vehicle equipped with for in-wheel motors (IWM), and improved operability was confirmed.

4 Directional Stability and Steering Responsiveness

In this field, a wide variety of research results have been produced, such as analysis of the effects of specifications, evolution of cooperative control, derivation of system design guidelines for steer by wire (SBW), and proposals for new control construction methods.

In the field of vehicle dynamics control, the main trend is to coordinate planar motion and sprung posture to realize vehicle behavior with a sense of unity. One example is a report of controlling the electrical power steering (EPS) and semi-active damper in a coordinated manner, and using the steering torque information in the control to follow the pitch behavior starting minute roll range at the start of steering, thereby improving stability and the driving feel. Setting the internal state of the damper as a control variable improved the accuracy of SAT estimation is improved and led to identifying a control law that suppresses the tendency of fast steering force input to diverge. A theoretical analysis of the coupling of plane motion and roll motion led to proposing a roll control technique that achieves the desired roll motion in response to transient driver steering input. In addition, from the viewpoint of improving passenger comfort, efforts are being made to effectively suppress occupant roll behavior using two combined inputs, steering and acceleration/deceleration. Another approach to improving comfort in the era of automated driving, involves an attempt to control the vehicle dynamics by choosing the optimum driving trajectory instead of simply following the road in the same manner as human driver. A trajectory planning method that optimizes vehicle dynamics within a drivable area has been proposed, and it has been demonstrated that the acceleration and jerk that occur in the vehicle can be reduced while shortening travel time. It is hoped that automated driving as good as experienced drivers at not making passengers feel uneasy will be realized.

Proposals have also been made regarding innovative changes in the mechanism of control development. An integrated motion control method has been devised to optimally control vehicle actuators by determining target behavior to minimize tire slip loss while considering interference components such as suspension reaction force and inertial force. This is expected to develop into technology that performs integrated control of the drive motors introduced with electrification.

The adoption of SBW in commercial vehicles is becoming more common. In terms of vehicle dynamics, being able to change the steering gear ratio is a major benefit, and there is a strong possibility that both low-speed handling and high-speed stability can be achieved. However, there are many problems to solve, including excessively sensitive vehicle behavior and the provision of appropriate steering force feedback, and many solutions have been proposed.

Steering control capable of turning the wheels up to the maximum steering angle in all vehicle speed ranges without requiring drivers to change the way they grip the steering wheel is being developed. A natural driving feel and reduced axial force have been realized by setting a gear ratio accounting for driver operability in accordance with vehicle speed, building filtering technology that guarantees occupant comfort, and making adjustments to the steering amount at low speeds. In addition, a steering reaction force control that can achieve a steering feeling equivalent to EPS was developed specifically for SBW systems that does not require shifting the grip the steering wheel. Steering capable of generating steering reaction force in various situations ranging from normal use to the tire grip limit, blocking unnecessary disturbances such as ruts, and providing necessary road information in the form of vibrations has been realized.

Smaller steering gear ratios are known to make the vehicle behavior sensitive depending on the frequency band, and some research results have identified the tire relaxation length of the front wheels as the cause. It was also shown that this phenomenon can be remedied with a band-elimination filter.

Vehicle models enabling theoretical studies of the steering system are also being developed. A simple two-wheel model intended to facilitate use in system development has been used as the basis to propose a model that can express vehicle motion and SAT. Research has also been conducted on the analysis of vehicle specifications, and attempts have been made to understand the sense of unity between the front and rear that the driver feels when steering based on the relationship between the yaw moment of inertia and the position of impact. To verify these vehicle models, it is important to capture the dynamic state of the actual vehicle correctly, and efforts are being made to improve state estimation at low dynamic acceleration.

In the future, it is expected that integrated control technologies, which will be required to handle the spread and adoption of electric-powered vehicles and automated driving technologies, will continue to advance even further and that the technical level of stability and responsiveness of the base vehicle will also improve to help support those control technologies.

5 The Human-Vehicle-Environment

Many new control laws are being researched to improve vehicle responsiveness and stability. However, the driver is the most important control system in a human-driven closed system, and many studies have focused on ease of handling for the driver.

Efforts to evaluate the steering characteristics using the three parameters (th, h, tL) identified in the driver model are continuously pursued to realize human-centered vehicle development. In 2021, this technology was applied to the evaluation of changes in the driving environment, and it is expected that it can be used for seat evaluation through validation using a driving simulator.

Research was also conducted on human characteristics that should be considered when determining vehicle dynamic characteristics using actual vehicles. The result of investigating vehicle behavior from turning in and out of a corner, and its effects on humans, using an electric vehicle equipped with G vectoring control (GVC) suggested that the interlocking of the movement of the head and the rib cage and the gentle change of the pitch angular velocity of the line of sight are important. Efforts are also being made to quantify the difference in roll feeling using dampers with different damping forces. Validation based on double lane changes indicated that sport mode damper results in quicker steering operation timing even though there is no difference in yaw response characteristics. This is attributed to a human-vehicle system influence that can be explained by musculoskeletal characteristics. This difference in steering operation could provide an objective measure to quantify the roll feeling.

It is not hard to imagine that chassis and vehicle dynamic control will evolve to high degree in the future, and it is hoped that the technologies introduced in this section will be applied to create truly human-friendly vehicles.

6 Limit Performance

The mandatory installation of electronic stability control (ESC) devices in passenger vehicles and of electronic vehicle stability control (EVSC) in heavy-duty vehicles has provided an opportunity to achieve remarkable improvements in understanding vehicle dynamics in limit regions, improving active safety performance, and even technologies for the theoretical study of the limit behavior of vehicles, including control. Automakers have been focusing on carrying out system engineering that forecasts performance with minimal reliance on actual vehicles, and model-based development based on the idea of V-shaped process development. Approaches enabling the efficient theoretical comprehensive allocation performance for both limit performance and normal range dynamic performance across a broad range of fields that includes ADAS, as well as to calibrate a significant portion control constants, have been achieved. In addition, a braking system that takes into account trailer characteristics based on model predictive control has been designed to prevent lane departure and jackknifing during an emergency stop while the trailer is turning. Examples of validating its effectiveness through simulation have also been reported.

Although model-based development can lead to efficient and highly accurate answers, getting a bird's-eye view of the overall dynamics is difficult, even more so for limit performance, which is highly nonlinear. On approach to solving the problem is an analysis method called the contour method, which uses a driving simulator to confirm the relationship between the local stability and steerable regions of the vehicle, which switch between oversteer and understeer as lateral acceleration increases. It was shown that convergence stability does not necessarily equate to drivability and that divergence can result from the driving performed by the driver.

7 Chassis Body

Many new proposals have been made based on multifaceted analyses of the performance of the chassis and body that support vehicle dynamics. A new rear suspension that focuses on the road-holding performance of the rear wheels to improve stability when cornering on uneven roads has been proposed. This rear suspension has different toe angle and camber angle change characteristics in the two input modes of same phase bump input in the left and right wheels and opposite phase roll input in the left and right wheels. The aim is to improve stability by suppressing the generation of lateral force on uneven road surfaces, ensuring steering stability at high speeds. The use of CAE is anticipated to provide sufficient effectiveness, and future practical application assessments are expected. CAE technology for chassis with nonlinearity has also been reported. It enables analyses of driving by combining a torsion beam suspension model with nonlinear reduction and mechanism analysis, and attempts to extract the effects of nonlinear elements of the torsion beam.

The effect of frame stiffness on weave mode and wobble mode has been studied in the context of the analysis of two-wheeled vehicles dynamics. Using a motion model that includes frame stiffness, a method to analyze the effects of individual frame stiffness on straight-line stability was proposed. Furthermore, concerns were raised about the modeling method that separates the rear frame from the specifications of the main frame. The contribution of frame stiffness manifests as a large impact of the torsional rigidity of the rear swing arm on the weave mode, and of the torsional rigidity of the front fork on the wobble mode.

Efforts have also been made to analyze the nonlinear effects of the chattering that occurs during braking on two-wheeled vehicles using a two-degree-of-freedom model.