An overview on vehicle lateral dynamics and yaw stability control systems

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Abstract

Various advanced active chassis control systems, e.g., four wheel steering (4WS), active front steering (AFS), steer-by-wire (SBW), direct yaw moment control (DYC) and active suspension system, have been dynamic fields of studying interest. Yaw stability control system plays a vital role in vehicle lateral dynamics and stability in order to enhance the vehicle handling and ride performances. Yet, there is little known about the performances improvement of vehicle yaw rate and sideslip tracking control. This paper focuses on the control system designs of Various advanced active chassis control systems such as four wheel steering (4WS), active front steering (AFS), steer-by-wire (SBW), direct yaw moment control (DYC) and their performances. For road-vehicle dynamic, lateral dynamic control is important in order to determine the vehicle stability which is the vital approach for vehicle lateral dynamics where the actual yaw rate and sideslip should be tracked by the controller close to the desired response. Based on this review, this paper discusses a basic concept of four wheel steering (4WS), active front steering (AFS), steer-by-wire (SBW), direct yaw moment control (DYC) and their performances.

Keywords: Four wheel steering (4WS); Active front steering (AFS); Steer-by-wire (SBW); direct yaw moment control (DYC)

1. Introduction

Vehicle dynamics discusses about the dynamics of vehicles while it is a part of engineering primarily based on classical mechanics. Controls play a significant role in determination of the final response of the system and the effect of inputs to the output. In vehicle dynamic control, controlling the lateral dynamic behavior is critical since it will control the stability of the vehicle. There are many approaches being used to control the vehicle lateral dynamics. In vehicle dynamics studies, vehicle stability is determined by the lateral dynamic motion where yaw stability control system is one of the prominent approaches for lateral dynamics control and it can be controlled by using steering and braking subsystem. Yaw stability of a vehicle is concerned with the steering, maneuvering and is critical to the overall safety of the vehicle. In yaw stability control strategy, it is needed to designed controller which is able to control the actual vehicle yaw rate and sideslip angle with quick reactions and reasonable tracking ability in following the desired responses since unsuitable commands to steering and braking subsystems in critical driving situations can lead to the vehicle instability [1]. An active control is required to contribute the operator to experience a stable motion on the desired path while it should be noted that the active steering and braking control can enhance the handling and stability performances if the actual yaw rate and sideslip is kept near to the desired responses [1-2]. However, it is possible that some noise disturbances and uncertainties to affect the yaw stability control performances.

The aforesaid perturbations could affect the yaw rate and sideslip following control performances while the transient performance of yaw control is essential. Thus, a suitable robust control approach can be adopted to improve the transient performances of the yaw rate and sideslip control while disturbances are applied to the system. If the side-slip motion is controlled to track a model response, the vehicle response gain is separately limited to the worsening of rear tire characteristics due to low friction coefficient between tire and road surface, large side-slip angle, load transfer from rear to front during braking, etc. [3-4].

Various advanced active chassis control systems, e.g., four wheel steering (4WS), active front steering (AFS), steer-by-wire (SBW), direct yaw moment control (DYC) and active suspension system, have been dynamic fields of studying interest. There are three active steering structures: four wheel steering/active rear steer (4WS/ARS), active front steering (AFS) and four-wheel active steering (4WAS) [5]. 4WS/ARS can increase transient response of vehicle during different operating condition particularly when rear steering angles are controlled by steering controllers while AFS system can provide improved handling performance and enhance the directional stability in unstable conditions such as uneven road through addition of steering angle, and braking system operates when tire lateral force soaks [5].
2. Vehicle Dynamics Models

In order to design and adopt a controller for vehicle yaw stability control, vehicle dynamics models should be developed based on the second law of Newton which describes the forces and moments acting on the vehicle body and tires. It is noteworthy that there are two categories of vehicle dynamic model being linear and nonlinear vehicle models being depicted in Fig. 1.

The nonlinear vehicle model is usually used to characterize and simulate the actual vehicle for controller evaluation and validation [6–13] have utilized nonlinear vehicle model for vehicle handling and stability improvement studies. The input of this model is front wheel steer angle \( \delta_f \) while the output variables to be controlled are vehicle sideslip \( \beta \) and yaw rate \( r \).

The vehicle parameters are vehicle width track \( d \), distance from front, and rear axle to center of gravity (CG) \( l_f \) and \( l_r \), respectively. The vehicle forward velocity of center of gravity \( V \), lateral velocity is \( V_y \), and longitudinal velocity is \( V_x \).

Other important vehicle parameters are vehicle mass \( m \), and moment of inertia \( I_z \), and \( M_z \) is yaw moment.

\[
ma = m\left( v_x - rv_y \right) 
\]

\[
ma = (F_{y1}+F_{y2})\cos\delta_f + F_{x1}+F_{x2}-(F_{y1}+F_{y2})\sin\delta_f
\]

\[
ma = m\left( v_y + rv_x \right)
\]

\[
I_r \dot{r} = I_r \left( F_{y1}\cos\delta_f + F_{x1}\cos\delta_f + F_{y2}\sin\delta_f + F_{x2}\sin\delta_f \right)
\]

\[
-l_i (F_{y1}+F_{y2}) + M_z
\]

In vehicle dynamic studies, each wheel represents 1 DOF. Thus, there are 4 DOF for road-vehicle with 4 wheels. The dynamic motion for each wheel is described as follows:

\[
I_w \dot{\omega} = -R_w F_{sz} + T_{sz} - T_{sz}
\]

where \( \dot{\omega} \) is wheel angular acceleration, \( n \), \( R_w \) is wheel radius, \( I_w \) is wheel inertia, \( T_{sz} \) is braking torque, and \( T_{sz} \) is driving torque.

Another nonlinear vehicle model used in the literature is 8 DOF vehicle models that are widely used in literature [14–20].

Then the linearized dynamics can be represented as follows:

\[
\begin{bmatrix}
\dot{\beta} \\
\dot{r}
\end{bmatrix} = \begin{bmatrix}
\frac{-2(C_f + C_r)}{mV} & \frac{-2(C_f l_f + C_r l_r)}{I_z} \\
\frac{-2(C_f l_f - C_r l_r)}{I_z} & \frac{-2(C_f l_f^2 + C_r l_r^2)}{I_z}
\end{bmatrix} \begin{bmatrix}
\beta \\
r
\end{bmatrix}
\]

Dynamic inversion is a control method that replaces the inherent plant dynamics into the user-selected dynamics. Consider the following dynamic systems:

\[
\dot{x} = Ax + Bu
\]

where, \( x \in \mathbb{R}^n \) is a state vector and \( u \in \mathbb{R}^m \) is an input vector. If \( B \) is assumed to be invertible, then the DI control input \( u_{DI} \) can be given by [21]:

\[
u_{DI} = B^{-1}(x_{des} - Ax)
\]

\( x_{des} \) denotes the desired dynamics selected to satisfy the specific performances/requirements of the system.

Figure 1. The typical nonlinear vehicle model in cornering [2]
3. Design of Control System

Steer-by-wire systems have been considered to act as the important kind of road vehicles for improving steering performance, enhancing vehicles’ maneuverability, ride comfort and active safety. The clear features of such systems are the mechanical linkage used to connect the hand wheel with the steered front wheels in conventional steering systems is removed, an AC or DC motor is adopted to steer the front wheels so that the steered front-wheel angles closely track the hand-wheel reference angle, and another motor is coupled with the hand-wheel shaft to provide a driver with a feeling of the interactions between the front tires and road surface [21]. Compared to the active front steer, there is no physical connection between the steering wheel and front wheels anymore leading to a greater flexibility. The vehicles yaw dynamics can be influenced easily with steer-by-wire, not only in limit handling situations, but also for normal driving [22].

Accurate steering control based on the fast intervention of SBW systems can provide enhanced safety and handling performance relative to the steering action of a skilled driver. This motivates active steering control based on feedback control. In addition, human friendly steering control through driver-SBW interaction is required to simultaneously provide improved safety and steering feeling, which may potentially be problematic in practical applications to commercial vehicles [23].

Steer-by-Wire systems do not have a direct mechanical connection between the steering wheel and the wheels of the vehicle and instead, turning the steering wheel sends instructions to an electronic control unit, the control unit actuates an electric motor that controls the steering angle of the wheels [24]. Steer-by-Wire systems have the following advantages.
[24]:
- Interior styling is easier and more versatile due to the absence of the steering column
- There is more space available in the engine compartment
- This system can be modeled and installed as a modular system
- Allows designs that prevent the steering wheel from rigidly impacting the driver during a frontal crash
- Driving characteristics can be monitored and the steering response can be easily adjusted
- Simplifies designs and lowers manufacturing costs

There are different models for steer-by-wire systems. Fig. 2 is an illustration of a SBW system:

Steering wheel position and angle is measured by handwheel sensor which is linked to ECM through an ECU linkage which generates torque while environmental sensors analyze environmental factors like yaw, roll over position and positions using cameras which are translated into the engine control module [24].

In steer-by-wire the physical connection between the steering wheel and front wheels is removed and replaced by a computer controlled system. Advantages of this strategy include increased safety in limit handling situations. Research has taken place using a model of a large saloon car fitted with a steer-by-wire system. From this it becomes clear that a vehicle can respond beyond human capabilities and that safety can be enhanced by incorporating steer-by-wire. From experiments it became clear that there is a huge diversity in human preference concerning the steering feel. The SBW is reproducing realistic steering feel, improving the vehicle return-ability and it reduces the oscillatory effect of the steering system when the vehicle passes through an uneven road.

Fig. 3 demonstrates an overview of SBW with hydraulic steering system. SBW structure includes steering wheel, steering wheel sensor, torque sensor, electric control unit (ECU), DC motor, reduction gears and rack and pinion while the system will set the steering wheel signal, steering wheel torque signal that is gathered by ECU as input, the controller intended the motor angle and torque as output, which transmitted through the reduction gears provided smooth steering torque to support the driver steering with hydraulic assistant system [24].

Fig. 4 depicts the SBW system response with step desired input when steering wheel turns from right to left and left to right. Fig. 5 shows the SBW response velocity, the maximum fluctuation and setting of system reaches in rack response.

Figure 4. The SBW system response at right and left turning [26]

Figure 5. The SBW system velocity response [2]
4. Active Front Steering

Active front steering (AFS) system can realize steering intervention independent of the driver, optimize vehicle’s response to driver’s input and enhance the stability in emergencies by add an additional steering angle to the input of driver. In low-speed section, reduces steering gear ratios, in order to achieve steering lightweight and flexible requirements; In high speed section, increases the steering gear ratios, in order to enhance the high-speed steering stability. So far as safety and steering feelings are concerned, AFS is a main trend of the development of current steering system, the principle of AFS is add an additional angle to the steering wheel input by motor, so as to improve the stability, maneuverability and keep track ability. Compared with DYC-based VSC systems, steering-based VSC systems such as active front steering (AFS) and active rear steering, can assist the driver to generate the desired lateral force and yaw moment more quickly with less intervention to the driving comfort \[26\]. A typical example of AFS system is shown in Fig. 6.

Results for a fishhook maneuvers with maximum driver commanded steering angle $\delta = 12^\circ$ carried out on a road with adhesion coefficient $\mu = 0.4$ are shown in Fig. 7. Responses of the controlled vehicle are quite satisfactory as displayed by the sideslip angle and yaw rate curves. Among many possible strategies, it is here decided to activate controller K1 only when the driver commanded steering angle exceeds $5^\circ$. The action of active front steering control has a tendency of decreasing the commanded steering angle under the value resulting in marginal vehicle stability ($\approx 5^\circ$).

5. Direct Yaw Control

During the last two decades, many methods have been proposed in the literature for direct yaw-moment control (DYC) to improve vehicle stability and handling. DYC controls vehicle motions through a yaw moment generated by the longitudinal tire forces \[29-30\]. With the quick development of electric and hybrid vehicles with independent motors (e.g., in-wheel motors/hub motors), a new group of DYC methods has been adopted based on providing a yaw moment using separate traction forces formed by independent driving motors which offer itself as a promising supplement to the conventional DYC systems for several reasons: Firstly, the differential braking DYC only operates during critical driving conditions when the vehicle is about to lose control, while the traction-based DYC is able to continuously produce differential traction forces to regulate vehicle motions \[29\]. In general, the existing DYC solutions employ the yaw rate, or the vehicle side-slip, or both states simultaneously as the main control variable(s). The yaw rate plays a crucial role in vehicle dynamics control. Firstly, the steady-state yaw rate (derived from the common bicycle model) is directly dependent on the driver’s steering input \[29\]. The structure of the proposed DYC system is shown in Fig. 8.

The yaw rate feedbacks provided by the proposed DYC method closely follow the optimal yaw rate, which provides the vehicle with unbiased steer performance while the other two methods lead to generally under-steer behaviors (yaw rates smaller than ideal) \[29\]. The conventional DYC presents a very small steady-state error in the yaw rate response when $\rho = 0.75 \ ( \zeta = 5/3)$, yet the magnitude of this steady-state error increases when a smaller value of $\rho$ (a larger value of $\zeta$) is selected. The passive system exhibits a yaw rate response that eventually converges to the ideal value, however, with a remarkable lag.

![Figure 6. A typical prototype of AFS system [27]](image-url)
Figure 7. Active front steering controller performance on road with adhesion coefficient ($\mu = 0.4$) under full information conditions [28]

Figure 8. Schematic of the proposed DYC system [29]

Figure 9. Structure of DYC system [31]
DYC stabilizes vehicle yaw motion and increases vehicle maneuverability by means of applying differential longitudinal forces (driving or braking force) between the inner and outer wheels. DYC is achieved through one of three methods: braking, driving, or both. Braking DYC is the most popular control type due to its simple realization, but the mandatory deceleration may violate the driver’s intention and hence cause an accident [31]. The structure of DYC system is shown in Fig. 9.

The vehicle under CDYC fails to stabilize the vehicle to some extent, as illustrated in Fig. 10(c), because of the relatively large slip angle. However, the longitudinal velocity of the vehicle under DDYC is even higher, as in Fig. 10(e). This means that DDYC has even more potential to stabilize the vehicle, because when the speed decreases, the vehicle is easier to stabilize. Fig. 10(f) shows the influence of the controller on the driver: in an emergent condition, the driver steers the vehicle under CDYC with a larger steering wheel angle [31].

6. Conclusions

Various advanced active chassis control systems, e.g., four wheel steering (4WS), active front steering (AFS), steer-by-wire (SBW), direct yaw moment control (DYC) and active suspension system, have been dynamic fields of studying interest. Yaw stability control system plays a vital role in vehicle lateral dynamics and stability in order to enhance the vehicle handling and ride performances. Yet, there is little known about the performances improvement of vehicle yaw rate and sideslip tracking control. This paper focuses on the control system designs of Various advanced active chassis control systems such as four wheel steering (4WS), active front steering (AFS), steer-by-wire (SBW), direct yaw moment control (DYC) and their performances. For road-vehicle dynamic, lateral dynamic control is important in order to determine the vehicle stability which is the vital approach for vehicle lateral dynamics where the actual yaw rate and sideslip should be tracked by the controller close to the desired response. Based on this review, this paper discusses a basic concept of four
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