Integrated Control Systems of Active Front Steering and Direct Yaw Moment Control Using Dynamic Inversion

Inseok Yang, Sungil Byun, Byungseok Seo, Dongik Lee, and Dong Seog Han

Abstract—AFS and DYC are the active safety devices of vehicles by improving vehicle handling and stability. In this paper, the integrated control systems of active front steering (AFS) and direct yaw moment control (DYC) using dynamic inversion (DI) control law is proposed. DI is a novel control technique which has been applied in vehicles operated in various conditions like aircrafts. A set of simulation results demonstrates that the proposed control systems of AFS and DYC controlled by DI can achieve fast and accurate tracking performance.

I. INTRODUCTION

Systems such as automotive vehicles, aircrafts etc which lead to a catastrophic accident involving the loss of life are defined as “safety-critical systems”. These systems require high level of dependability. For this reason, safety is one of the crucial issues in designing vehicles. The 4 wheel steering (4WS) system has been regarded as an effective safety device since the beginning of 1980s [1]. However, the 4WS systems require high tag price and increase the system complexity due to additional rear steering device. Recently, there have been proposed various techniques to achieve safety of vehicles, e.g. active front steering (AFS), direct yaw-moment control (DYC), etc [1]-[4]. Firstly, the AFS system studied as a steer-by-wire system provides an additional front steer angle to improve vehicle handling and stability. In contrast to the 4WS that adopts additional steering devices in rear wheel, the AFS system can be achieved by simply inserting control algorithm in the electric control unit (ECU) without any hardware devices. So the advantages of the AFS system is ease to implementation and maintenance, cost effectiveness etc. The DYC system generates yaw moment by distributing brake forces of four tires to improve handling performance and stability. Similar to the AFS system, the DYC system can be designed by inserting control algorithm without adopting any devices. Recently, the integrated system of the AFS and DYC systems has been studied widely [1]-[3]. Most of these studies focus on controller design for the integration system.

In this paper, the integrating method for AFS and DYC based on dynamic inversion (DI) control technique is proposed. DI is a nonlinear control technique that replaces the inherent plant dynamics into the user-defined desired dynamics. Actually, the original dynamics is eliminated by inverting directly by DI controller, it can be adopted in systems which operate in various environments such as aircrafts [5]-[8] without any help of gain-scheduling. For this reason, DI is considered as the suitable controller for vehicles which operates in various environment conditions such as weather, road, etc. Recently, DI controller has been applied in various fields of industries such as unmanned underwater vehicles [9], electric throttle systems [10], etc.

The rest of this paper is organized as follows: The actual vehicle model is provided in Section 2. In Section 3, the DI control method is proposed. In following section, The performance of the proposed reconfiguration method is evaluated by numerical simulation.

II. VEHICLE DYNAMICS

A. Actual Vehicle Dynamics

The vehicle lateral dynamics based on the coordinate frame illustrated in Fig. 1 can be represented as follow [1]:

\[ m \ddot{\beta} + \gamma = \sum F_y = F_{yfl} + F_{yfr} + F_{yrr} + F_{yrl} \] (1)

\[ I_y \dot{\gamma} = \sum M_y = (F_{yfr} + F_{yfl}) L_f - (F_{yrr} + F_{yrl}) L_r + M \] (2)

\[ m \ddot{V} = \sum F_x = F_{xfl} + F_{xfr} + F_{xrr} + F_{xrl} \] (3)

where, \( V \) is the longitudinal velocity of the vehicle. And \( \beta \) and \( \gamma \) denote sideslip and yaw rate, respectively. From [1], the direct yaw moment generated by braking forces of four tires can be expressed as follow:

\[ M = \frac{w}{2} \left( F_{xfr} - F_{xfl} + F_{xrl} - F_{xrr} \right) \] (4)

B. Simplified Dynamics for Designing Controller

In this section, simplified dynamics for the actual model provided in the previous section is derived to design controller.
It is assumed that the lateral forces acting on the left and right tires are similar, i.e. \( F_{yfr} \approx F_{yfl} \approx F_{yf} \) and \( F_{yrr} \approx F_{yrl} \approx F_{yr} \). Then the vehicle dynamics can be expressed as follows [1]:

\[
\begin{align*}
\beta_l &= \sum F_y = 2F_{yf} + 2F_{yr} \\
\gamma &= \sum M_z = 2F_{yf}L_f - 2F_{yr}L_r + M \\
mV \frac{\dot{\beta} + \gamma}{r} &= \sum F_y = 2F_{yf} + 2F_{yr} + F_{yrr} + F_{yrl} \\
\end{align*}
\]

where,

\[
F_{yf} = -C_f \left( \beta + \gamma L_f / V - \delta_f - \Delta \delta_f \right) \\
F_{yr} = -C_r \left( \beta - \gamma L_r / V \right).
\]

Moreover, \( \delta_f \) and \( \Delta \delta_f \) are the front steering angle and the additional front angle generated by the AFS system, respectively. The nomenclature and its values are listed in Table 1.

Then the linearized dynamics can be represented as follows:

\[
\begin{bmatrix}
\dot{\beta} \\
\dot{r}
\end{bmatrix} = \begin{bmatrix}
-2(C_f + C_r) & mV \\
-2(C_f L_f - C_r L_r) & l_r
\end{bmatrix} \begin{bmatrix}
\dot{\beta} \\
\dot{r}
\end{bmatrix} + \begin{bmatrix}
2C_f \frac{mV}{l_r} \\
2C_r \frac{mV}{l_r}
\end{bmatrix} \begin{bmatrix}
\Delta \delta_f \\
\delta_f
\end{bmatrix}
\]

III. DYNAMIC INVERSION

Dynamic inversion is a control method that replaces the inherent plant dynamics into the user-selected dynamics.

Consider the following dynamic systems:

\[
\dot{x} = Ax + Bu \tag{11}
\]

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 [5]:

\[
u_{DI} = B^{-1}(\dot{x}_{des} - Ax) \tag{12}\]

where, \( x_{des} \) denotes the desired dynamics selected to satisfy the specific performance/requirements of the system. For example, in aerospace applications, the ride quality desired dynamics method can be used to satisfy the specific flying qualities [5]. Fig. 2 shows various types of desired dynamics: proportional, proportional integral, flying quality, and ride quality. In (12), the only necessary condition of existing DI control law is existence of \( B^{-1} \). In fact, \( B \) is not full rank for

Fig. 1. A front-wheel-driven model [1]

**TABLE I. PARAMETERS OF THE VEHICLE MODEL [1].**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m )</td>
<td>1430 kg</td>
<td>Vehicle mass</td>
</tr>
<tr>
<td>( I_z )</td>
<td>2430 kgm^2</td>
<td>Yaw moment of inertia</td>
</tr>
<tr>
<td>( L )</td>
<td>2.5 m</td>
<td>Wheel base</td>
</tr>
<tr>
<td>( w )</td>
<td>1.5 m</td>
<td>Axle tread</td>
</tr>
<tr>
<td>( h )</td>
<td>0.36 m</td>
<td>Height of c.g.</td>
</tr>
<tr>
<td>( L_f )</td>
<td>1.1 m</td>
<td>Distance from c.g. to front axle</td>
</tr>
<tr>
<td>( L_r )</td>
<td>1.4 m</td>
<td>Distance from c.g. to rear axle</td>
</tr>
<tr>
<td>( C_f )</td>
<td>40,000N/rad</td>
<td>Front cornering stiffness</td>
</tr>
<tr>
<td>( C_r )</td>
<td>42,530N/rad</td>
<td>Rear cornering stiffness</td>
</tr>
</tbody>
</table>

It is assumed that the lateral forces acting on the left and right tires are similar, i.e. \( F_{yfr} \approx F_{yfl} \approx F_{yf} \) and \( F_{yrr} \approx F_{yrl} \approx F_{yr} \). Then the vehicle dynamics can be expressed as follows [1]:

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\end{bmatrix} \begin{bmatrix}
\Delta \delta_f \\
\delta_f
\end{bmatrix}
\]

Fig. 2. Various types of desired dynamics [5]: CV denotes control variables.

Fig. 3. The structure of dynamic inversion [5].
nonflat systems that have more the number of states than the number of control inputs. Thus the number of states less than or equal to the number of control inputs can be inverted. To achieve $B^1$ in these systems, multi-time scale DI method that divides states into two or more groups whether states are perturbed by input signals/forces directly or not has been used widely [5]-[6].

By substituting (12) into (11), the control system designed by DI controller can be represented as:

$$\dot{x}_{des} = \hat{x}$$  

(13)

Fig. 3 shows the structure of the control system using DI controller. From (13), the dynamic inversion block and the plant block can be reduced as an integrator as shown in Fig. 3. Consequently, the original nonlinear dynamics are replaced by the desired dynamics.

IV. SIMULATION RESULTS

A. Desired Model

The desired model is an ideal response of the vehicle for a driver to provide the identical feeling during steady cornering whether the controller is used or not. Commonly, the desired model is represented by the first order delay system as follows [1]:

$$\begin{bmatrix}
\beta_d \\
r_d
\end{bmatrix} =
\begin{bmatrix}
0 & 0 \\
0 & -1/\tau_y
\end{bmatrix}\begin{bmatrix}
\beta_d\\ r_d
\end{bmatrix} +
\begin{bmatrix}
k_f
\end{bmatrix}\delta_f$$  

(14)

where,

$$k_f = \frac{V}{L_f + mL_f V^2 / 2C_f L_f (L_f + L_r)}$$  

(15)

$$\tau_y = \frac{1}{2C_f L_f (L_f + L_r) + mL_f V^2}$$  

(16)

B. Simulation Descriptions

The objective of the control system designed with the proposed DI controller is to track the response of the desired model. To evaluate the control performance, two maneuvers are conducted: cornering maneuver ($J$-turn motion) and lane change maneuver. To maneuver $J$-turn motion and lane change, the steering angle inputs ($\delta_f$) represented in Fig. 4 are applied to the vehicle.

It is assumed that the vehicle is driven at 80 km/h (road condition $\mu = 0.9$). And the dynamics of the steering and brake actuators are modeled, respectively, as

$$\frac{\Delta \delta_{b, output}}{\Delta \delta_{b, input}} = \frac{20\pi}{s + 20\pi}$$  

(17)

$$\frac{\Delta \delta_{b, output}}{\Delta \delta_{b, input}} = \frac{20\pi}{s + 20\pi}$$  

(18)

The structure of the proposed DI based control is described in Fig. 5.

C. Simulation Results

Cornering maneuver: Fig. 6 shows the results of cornering maneuver describing $J$ motion. In Fig. 6 (a), the sideslip angle is reduced by applying the integrated control systems of AFS and DYC systems designed by DI controller. And in Fig. 6 (b), the vehicle without the control system cannot achieve accurate reference having 10 deg/sec of tracking error. However, it is observed that the controlled yaw rate can track the desired yaw rate within 0.5 deg/sec of tracking error.

Lane change maneuver: The results of lane change maneuver with/without the integrated control systems are described in Fig. 7. The vehicle without the control system cannot track the desired yaw rate having almost 10 deg/sec of tracking error as shown in Fig. 7 (b). In contrast, the vehicle controlled by the proposed DI based integrated control system can track the reference yaw rate within 0.5 deg/sec of tracking error. Moreover, in Fig. 7 (c), the vehicle with controller can change the lane within 5m distance. However, the vehicle without controller is slid almost 7m.

V. CONCLUSION

In this paper, the integrated control system of active front steering and yaw moment using dynamic inversion is proposed. The DI is a nonlinear control method that replaces the original dynamics into the desired one that satisfies the specific performances/requirements of the system. So DI controller can be applied in systems that drive various
operating environments such as electric vehicles. Simulation results show that the proposed DI control method can track the desired model fast and accurately. For the future work, it is planned to implement the proposed method in real-time Steer-by-Wire system.

REFERENCES


