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Steering control of a steer-by-wire system vehicle with time delay and actuator saturation via anti-windup controller

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Abstract

This paper presents a design of an anti-windup controller that aims to improve vehicle handling and stability of a Steer-by-Wire (SbW) system with consideration of time delays and actuator saturation. Due to the physical constraints of road wheel steering actuators, control saturation is considered in controller design. A controller that is designed without a saturation condition, and is only to operate in a linear region might have significantly deteriorated performance in the presence of actuator saturation. In this study, an anti-windup controller employing a back-calculation method was used to handle the effect of actuator saturation in the system. The designed controller was used on a SbW system with a linearized vehicle model to verify the effectiveness of the proposed strategy. The vehicle-body sideslip angle and the yaw rate at the centre of gravity of the vehicle while turning can be used to indicate vehicle stability. The simulation results demonstrated that the designed controller promotes better handling during steering and preserves vehicle stability regardless of the changes in the time delays in the system.

Keywords: Actuator saturation, Anti-windup control, Steer-by-wire, Time delays

1. Introduction

Nowadays, autonomous vehicles (AV) or also known as self-driving vehicles are appearing more often as commercial vehicles using advanced driver assistance systems (ADAS). In October 2015, Tesla Motor Company rolled out autopilot software in the Tesla Model S vehicle, which allows automatic steering within highway lane markers, changing lanes and parallel parking. With test vehicles having travelled over one million miles to date, Waymo, the Google self-driving car project has achieved a testing stage in California. Volvo and Uber are collaborating to develop AVs where Volvo produces the base vehicles and Uber adding its own autonomous driving software to the vehicles. AV depends on sensor fusion, a combination of radars, light detection and ranging (LiDAR) and cameras mounted on the roof and the vehicle body to navigate through pre-mapped environments [1-2]. The needs in precision sensing and controlling vehicle motions are increased with the development of AV that leads to further enhancement of Drive-by-Wire (DbW) systems where the conventional mechanical subsystems in vehicle are replaced by electronic sensors, controllers and actuators.

One of a class of system in the DbW family, Steer-by-Wire (SbW) draws the concern of many academic and industrial researchers, as it is one of the important keys in self-driving technology. In SbW systems, rather than the front road wheels being steered by a mechanical linkage connected to the steering wheel, an electronically controlled vehicle system is used to analyze a driver's intentions through sensors and sends electrical signals to actuators by wire. The benefits from implementation of SbW in passenger vehicles include: 1) the interior of the cabin has more freedom in design, leading to more space and lower risk in the case of car collisions, and 2) vehicle stability, dynamics and maneuverability are enhanced [3-4]. Nevertheless, by detaching the mechanical linkage between the steering wheel and the front road wheels, it is essential to design a good steering controller to perform excellence tracking regarding to driver's commands. The comparison between a conventional steering system and a SbW system is shown in Figure 1.

Vehicle steering control systems have been a focus of research. A number of researchers have proposed broad control methods. In early development of SbW control schemes, conventional proportional-integral-derivative (PID) control methods were adopted [5] to emulate the shaft operation to turn the road wheels in the same manner as in a conventional steering system. SbW feedforward-based controllers were used to modify the vehicle's handling characteristics relying on the driver's selections to be more or less responsive [6]. Using this method, the desired vehicle

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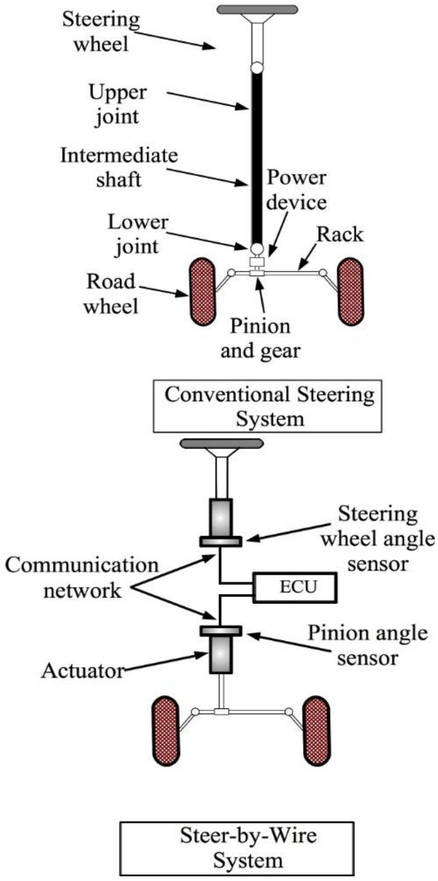


Figure 1 Comparison of a conventional steering system and SbW systems.

behavior can be preserved under varying operating conditions. Fault-tolerant control techniques have been used to develop SbW systems that tolerate failure without degrading control system performance [7]. In the event of a fault, the control algorithm will automatically reconfigure the steering mechanism to maintain vehicle safety. Additionally, a few approaches to intelligent control methodologies, such as particle swarm optimization (PSO) [8] and imperialist competitive algorithms (ICA) [9] have been employed for the purpose of improving the control performance by suppressing yaw and lateral motion errors of a SbW vehicle.

In a motor-driven device, vehicle steering actuator saturation may affect its overall performance and has serious safety concerns. To improve the safety and reliability of SbW systems, research on controlling the saturation of SbW systems has received considerable attention over the last decade. A controller that uses an anti-windup scheme was proposed to moderate the saturation properties of steering actuators [10]. A control allocation algorithm that incorporates a pseudo-inverse technique was applied on a SbW electric vehicle [11] to preserve vehicle stability when the steering actuators are saturated. Apart from the actuator saturation problem, properly managed time delays in a SbW system are another significant issue in the system along with the development of by-wire technologies. In [12], a H_∞ controller was designed based on a delay-tolerant linear quadratic regulator (LQR) was employed to improve vehicle lateral motion stability. Alternatively, various steering control methods were presented in where the control law was formulated in the form of linear matrix inequalities (LMIs) with inclusion of a delay function [13]. In spite of these comprehensive methodologies, only a few research studies have examined the design of steering controller for SbW systems with time delays and actuator saturation. This is the motivation of the current work.

The remainder of this paper is arranged as follows. After the Introduction, the SbW system modeling consisting of a steering rack and vehicle dynamics model is developed in Section 2. The anti-windup controller design for a SbW system vehicle is presented in Section 3. Results of the simulation studies and its discussion are given in Section 4. Finally, the conclusions drawn from this work are offered in Section 5.

2. SbW system modeling

A SbW system consists of three components, the steering wheel unit, electronic control unit (ECU) and the front road wheel unit. The steering wheel unit utilizes and processes the driving inputs. The ECU is where the steering wheel input is monitored and control law is executed. The front road wheel unit receives the control signal and actuates the electric motor based on the driver's preference. All the sensing and control signals travel by-wire throughout the system.

For the SbW steering rack, a comprehensive model consisting of a DC motor that rotates the rack and pinion to the desired angle was developed [14]. On that basis, the state space equations of the steering rack model are given by:

$$\begin{bmatrix} \dot{\theta}_r \\ \ddot{\theta}_r \\ \dot{i}_r \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{b_r}{J_r} & \frac{\eta K_{tr}}{J_r} \\ 0 & -\frac{K_{er}}{L_r} & -\frac{R_r}{L_r} \end{bmatrix} \begin{bmatrix} \theta_r \\ \dot{\theta}_r \\ i_r \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L_r} \end{bmatrix} V_r + \begin{bmatrix} 0 \\ -\frac{1}{J_r} \\ 0 \end{bmatrix} \tau_a + \begin{bmatrix} 0 \\ -\frac{1}{J_r} \\ 0 \end{bmatrix} \tau_f \quad (1)$$

where θ_r is the road wheel angle, $\dot{\theta}_r$ is road the wheel angle rate, i_r is the motor current, b_r is the viscous damping coefficient, J_r is the moment of inertia of the road wheel, η is a steering ratio, K_{tr} is a motor torque constant, K_{er} is an electromagnetic force constant, L_r is motor inductance, R_r is motor resistance, V_r is motor voltage, τ_a is self aligning torque and τ_f is friction torque. In this control system, the SbW motor voltage, V_r, is the input and the road wheel angle θ_r is the output which is the control objective of the system.

The self-aligning torque τ_a is defined as the forces from tyre contact that act on the steering system resisting the steering's straight-ahead position. The friction force τ_f is due to a Coulomb friction force. The following equations describe both torque parameters:

$$\tau_a = -C_\alpha^F \alpha_F (t_p + t_m) \quad (2)$$

$$\tau_f = g t_p \mu W_f \operatorname{sgn}(\dot{\theta}_r) \quad (3)$$

where C_α^F is front tyre cornering coefficient, α_F is front tyre slip angle, t_p is tyre pneumatic trail, t_m is tyre mechanical trail, g is the acceleration of gravity, μ is the friction coefficient and W_f is the front tyre weight. The notation, 'sgn', is a standard mathematic signum function.

From the vehicle dynamic model, the sideslip angle of the tyres and the vehicle motion stability while turning can be observed. A linearized vehicle dynamic model can be

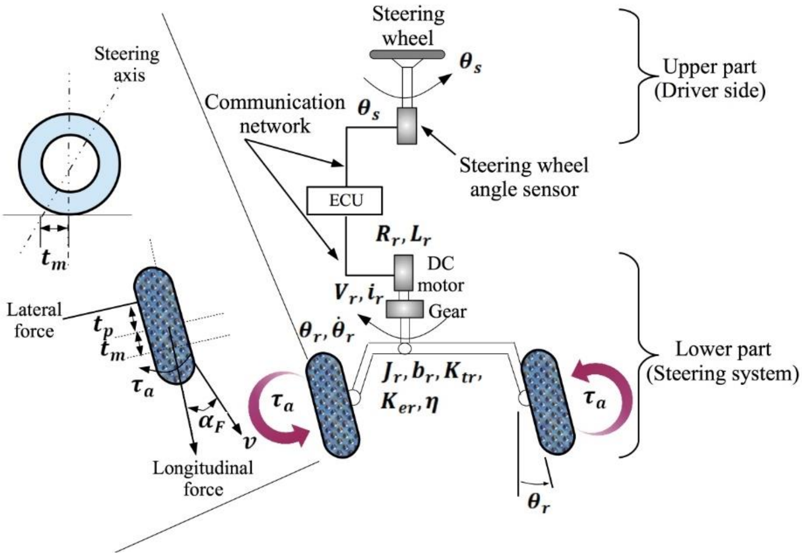


Figure 2 Parameters and state variables of a SbW vehicle system.

represented as in [14], which is derived from a single-track vehicle model.

$$\begin{bmatrix}\dot{\beta}\\ \dot{r}\end{bmatrix} = \begin{bmatrix}\dfrac{-C_\alpha^F - C_\alpha^R}{mv} & -1 + \dfrac{C_\alpha^R b - C_\alpha^F a}{mv^2}\\ \dfrac{C_\alpha^R b - C_\alpha^F a}{I_z} & \dfrac{-C_\alpha^R a^2 - C_\alpha^F b^2}{I_z v}\end{bmatrix}\begin{bmatrix}\beta\\ r\end{bmatrix} + \begin{bmatrix}\dfrac{C_\alpha^F}{mv}\\ \dfrac{C_\alpha^F a}{I_z}\end{bmatrix}\theta_r \quad (4)$$

where β is the vehicle body slip angle, r is a yaw rate, C_α^R is rear tyre cornering coefficient, m is vehicle mass, v is vehicle longitudinal velocity, a is distance from the front tyre to the vehicle's centre of gravity (CoG), b is distance from the rear tyre to the vehicle's CoG and I_z is the vehicle's moment of inertia. This vehicle dynamics model, (4), is usable under the following conditions [14]:

1) The vehicle is not in braking mode and the friction force in the x-direction is negligible.
2) The left and right steering angles are similar, such that $\theta_L = \theta_R = \theta_r$.
3) The vehicle is built symmetrically.
4) The longitudinal and lateral direction for both the left and right tyres have similar front tyre contact forces.

The slip angles of front-tyre α_F and rear-tyre α_R can be approximated following equation (5) when the sideslip angle is small, < 4° [14].

$$\begin{bmatrix}\alpha_F\\ \alpha_R\end{bmatrix} = \begin{bmatrix}1 & \dfrac{a}{v}\\ 1 & \dfrac{-b}{v}\end{bmatrix}\begin{bmatrix}\beta\\ r\end{bmatrix} + \begin{bmatrix}-1\\ 0\end{bmatrix}\theta_r \quad (5)$$

Figure 2 illustrates the parameters and state variables of a SbW system related to the physical system.

3. Anti-windup PID controller

Due to its simplicity, ease of use and clear functionality, PID controllers are still widely used in industry. Despite its advantages, PID closed-loop performance remarkably deteriorates with regard to anticipated linear performance because it is designed to perform in a linear region that neglects the constraint of control input. The phenomenon known as windup causes slow settling time, large overshoots and even unstable responses. For the purpose of countering this windup phenomenon, a back-calculation method is an approach that is widely used [15-16].

The following equation is used to describe the PID controller output u:

$$u = K_p\left(e + \frac{1}{T_i s}e - \frac{T_d s}{1 + \left(\frac{T_d}{N}\right)s}\right) \quad (6)$$

where K_p is the proportional gain, T_i and T_d are the integral and derivative time constants, respectively, and N is a filter time constant for the derivative term. For the design of a SbW system, the tracking error e is defined as:

$$e = \theta_s - \theta_r \quad (7)$$

where θ_s and θ_r are the reference driving input and the road wheel angle, respectively.

Integrator windup occurs when a change in θ_s causes the actuator to saturate. Unlike in the ideal case where there are no input limitations, in the case of inclusion of windup, the system tracking error reduces more gradually. For this reason, the value of the integral term becomes large. The controller still saturates even when the value of the θ_r reaches that of θ_s due to the integral term.

By applying a back-calculation method, once the controller saturates, the integral term in (6) will be re-calculated. Specifically, the integral value is reduced by feeding back the difference of the saturated u_s and unsaturated u control signal. This feedback K_b is known as a back-calculation constant. The integrator input e_i can be described as follows:

$$e_i = \frac{K_p}{T_i}e + \frac{1}{K_b}(u_s - u) \quad (8)$$

The rate at which the integral term is reset is governed by the value of K_b. The controller parameters, K_p, T_i, T_d and K_b need to be designed carefully to achieve excellent performance of a SbW system.

4. Simulation results and discussion

Simulation studies were performed on a SbW vehicle model in (1) with MATLAB Simulink to investigate the performance of the designed control method. The overall closed loop system consisted of a steering rack model, vehicle dynamics and controller. As the sensing information from the road wheel angle sensors was send to the ECU and the reference signal from the steering wheel sensor to the ECU required time for data transmission, therefore, a time delay needs to be considered. A number of simulations were performed, varying time delay parameters to replicate the actual operation of the SbW.

In the simulation setup, the following SbW and vehicle parameters were considered [14]: $C_\alpha^F = 2300$ N/rad, $C_\alpha^R = 4600$ N/rad, $m = 1961$ kg, $v = 5$ m/s, $a = 1.05$ m, $b = 1.71$ m, $I_z = 3136$ kg.m^2, $t_p = 0.0381$ m, $t_m = 0.04572$ m, $J_r = 3.5$ N.m.s^2/rad, $b_r = 70$ N.m.s/rad, $W_f = 150$ kg, $\eta = 150$, $\mu = 0.192$ N.m, $g = 9.8$ m/s^2, $K_{er} = 0.573$ V/rad/s, $K_{tr} = 0.573$ N.m/A, $R_r = 5.68\,\Omega$ and $L_r = 20.3 \times 10^{-3}$H. The DC motor on the steering rack had a nominal voltage of ± 24 V. Thus, if the controller generated input more or less than the nominal voltage, the actuator became saturated. The solution technique that was used in the simulation was an ODE (Dormand-Prince) with a variable-step.

Based on the SbW system model and DC motor characteristics represented in Section 2, the most suitable control parameters in (6) were determined using the PID tuning tool provided in MATLAB Simulink. The values of the controller gain parameters were chosen as follows:

$$K_p = 150.02, T_i = 1.005, T_d = 0.001, K_b = 1.75, \quad (9)$$
$$N = 100$$

A controller without an anti-windup scheme, i.e., a conventional state feedback control, was used to compare and verify the results of the designed AWC. This baseline controller was designed using a pole placement method [17]. In this method, a state feedback controller gain matrix K can be determined as:

$$K = [830.5641 \quad 21.8504 \quad 0.6854] \quad (10)$$

For the purpose of further demonstrating control performance, the integral of the absolute error (IAE) of the tracking error was used as a performance index assessment. It was employed in favor of distinct comparison between the two controllers.

$$IAE = \int_0^L |r_s(t) - c_s(t)| dt \quad (11)$$

where $r_s(t)$ is the desired steering wheel angle input θ_s of a driving maneuver and $c_s(t)$ is the road wheel angle θ_r. A lower IAE index value means better tracking control.

Another important performance measure in a SbW system design is the ability to consume the energy efficiently. The following equation was utilized to investigate the energy use of these two control strategies.

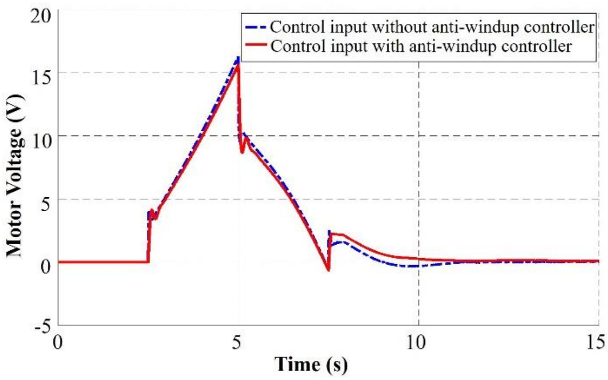
$$E = \int_0^t |V_r i_r| dt \quad (12)$$

where a lower value of E signifies more efficient energy use.

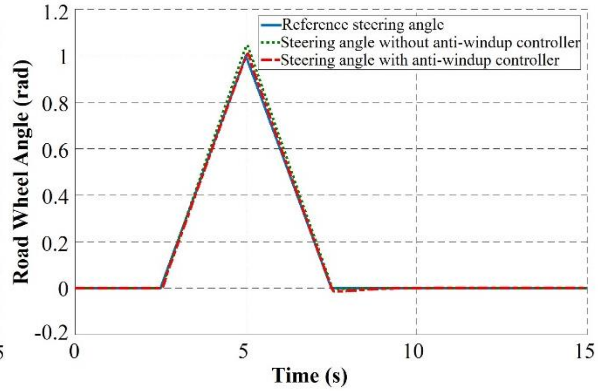
The steering angle input θ_s of a driving maneuver is a triangle signal that start gradually from 0 rad at 2.5 s, increases linearly and has maximum amplitude of 1 rad at 5 s. Then, it returns to 0 rad at 7.5 s. The simulation is executed for 15 s. The target of this control system is to drive the steering actuator DC motor so that the road wheel angle θ_r performs tracking with the reference input of the driving maneuver θ_s with minimal control effort. This should happen not only under normal conditions, but also in the presence of a time delay. Hence, the results and analysis was assessed as follows: 1) the time delay τ was set to 0 ms, and 2) the time delay τ was set to 60 ms.

Figure 3 shows the system response of the SbW system with and without AWC for case 1. This is under a normal condition without a time delay. In this case, both controllers produce smooth control signals to the DC motor as indicated in Figure 3(a). Additionally, these two SbW controlled system vehicles with and without AWC gave satisfactory results in their tracking performance as shown in Figure 3(b). Throughout the entire simulation time, it was observed that the road wheel angle narrowly tracked the steering wheel reference angle for both controllers. The corresponding IAE values for the SbW systems with AWC and without AWC were 0.006407 and 0.1286, respectively. The energy that is consumed by the motor during the 15 s simulation was 58.49 J and 62.97 J for AWC and without AWC, respectively, as shown in Figure 3(c). In this case study both controllers preserved the vehicle stability specified at a yaw rate angle response as shown in Figure 3(d). Under these conditions, passenger comfort is promoted.

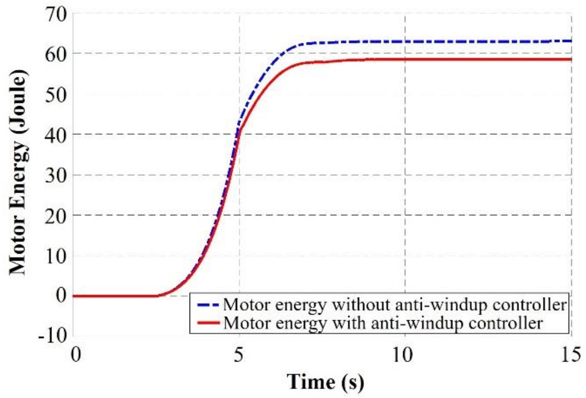
Then, with a time delay of 60 ms introduced into the system, the simulation studies continued to further show the priority of the designed controller. In Figure 4(a), due to time delay introduced into the system, the SbW system without AWC produced strong chattering signals that caused the steering actuator to saturate. This noise in the voltage input reached the maximum voltage level, intensifying the load on the motor actuator and the ECU, preventing acceptable steering control. The designed AWC generated a bounded amplitude of the control voltage input within the nominal operating voltage. Although the system time delay was changed to 60 ms, good steering performance was still achieved when the SbW system implementing AWC, as shown in Figure 4(b). Such good steering performance indicates that the designed AWC is capable of eliminating the effects of time delays and actuator saturation. The steering performance without AWC was not as good as the designed AWC scheme as it was observed that: 1) the steering tracking performance started to deteriorate from 5 s to 7.5 s, and 2) the steering response kept oscillating even without any steering input beginning 7.5 s into the simulation. Additionally, the IAE for the steering performance without AWC was 0.1006, which is larger than 0.04369 of the SbW system with AWC. Figure 4(c) shows that the energy consumption for the SbW system without AWC is very large, 613.6 J, whereas with the designed AWC, the energy consumption was 75.27 J. This is certainly an advantage of implementing AWC. As the time delay further affected the system, the vehicle dynamics eventually became unstable for the SbW system without AWC as indicated in Figure 4(d). The oscillations in the yaw rate angle still occurred even there was no steering inputs at 8 s. By contrast, the vehicle dynamics with the designed AWC remained stable.



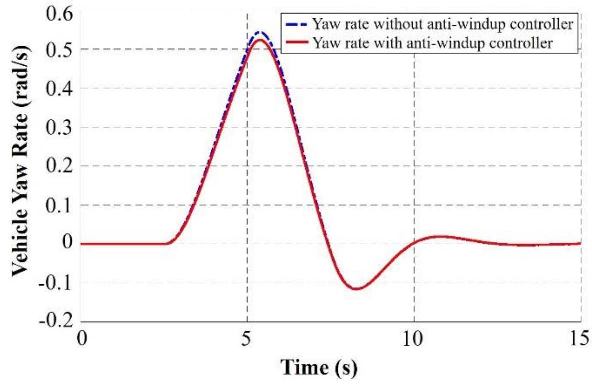
(a) Control input motor voltage V_r of the SbW system



(b) The response of road wheel angle θ_r of the SbW system

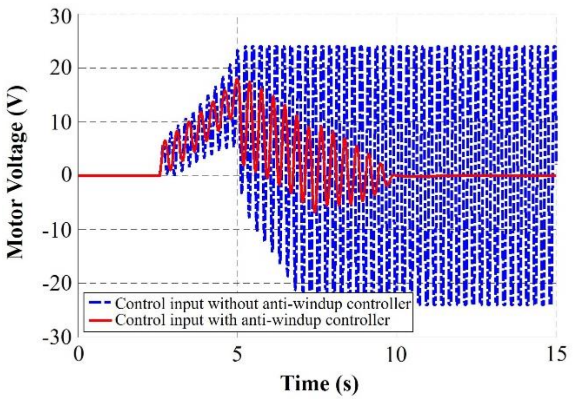


(c) Motor energy E of the SbW system

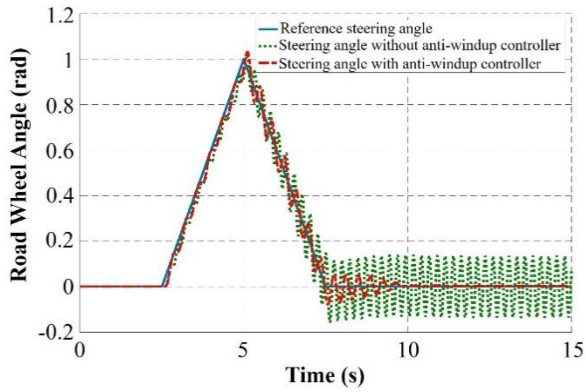


(d) The response of vehicle yaw rate angle r of the SbW system

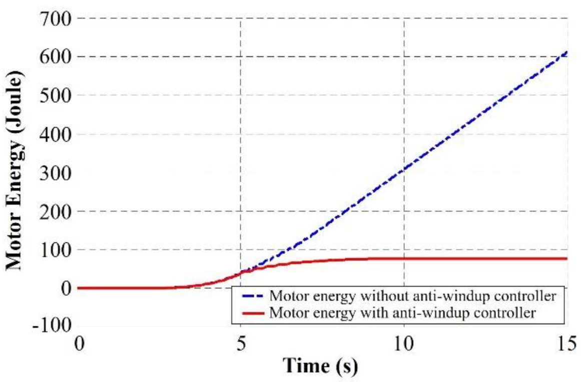
Figure 3 Simulation results for case 1 under no time delay



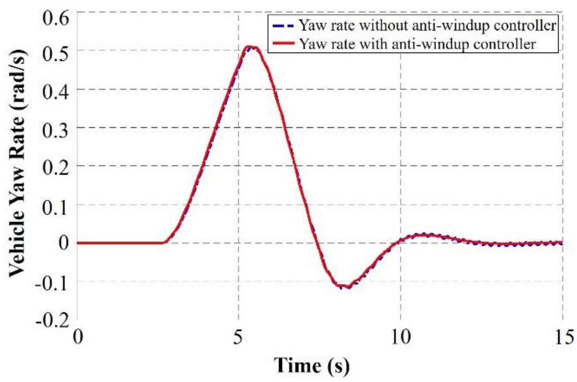
(a) Control input motor voltage V_r of the SbW system



(b) The response of road wheel angle θ_r of the SbW system



(c) Motor energy E of the SbW system



(d) The response of vehicle yaw rate angle r of the SbW system

Figure 4 Simulation results for case 2 under a time delay $\tau = 60$ ms

Table 1 Performance comparison between SbW systems with and without AWC

	Case 1 $\tau = 0$ **ms**		**Case 2** $\tau = 60$ **ms**	
	With AWC	**Without AWC**	**With AWC**	**Without AWC**
Maximum control input, V_r (V)	15.63	16.28	17.91	24.00
IAE	0.006407	0.1286	0.04369	0.1006
Energy, E (J)	58.49	62.97	75.27	613.6
Maximum yaw rate angle deflection, r (rad/s)	0.5235	0.5434	0.5105	0.5092

Table 1 shows a performance comparisons of the two controllers. According to the data, the following information is highlighted. The control input voltage of the SbW system without AWC exhibited almost as good performance as with AWC in case 1, but exhibited much worse control input in case 2. The IAE value of the tracking error for the designed AWC was smaller in all cases compared to the system without AWC. Energy consumption was greatly reduced by implementing the designed AWC. The maximum yaw rate angle deflection for both controllers was about the same in case 2, but the AWC provided a much smoother response.

5. Conclusions

In this study, an anti-windup controller was designed for SbW systems with vehicle dynamics experiencing time delays and actuator saturation. It was shown that the designed control system with an anti-windup scheme exhibited a strongly robust steering performance and convergence in tracking error. Computer simulations of a triangle signal of a steering maneuver with two different time delays conditions were done using a SbW vehicle to verify the efficiency of the designed anti-windup control system. It was compared with other control methods that did not implement anti-windup control. Future work will further enhance the anti-windup control law for stabilization assurance and more accurately model vehicle performance. Specifically, the stability of the anti-windup control system design was shown in the sense of Lyapunov. Additionally, the dynamic model of the vehicle-body sideslip angle and yaw rate angle will be further investigated to include system nonlinearity in the controller design.

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