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Robust Steering Control with Side Slip and Yaw Damping Compensation Using Time Delay Control

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TDC 제어를 이용한 측면슬립 및 댐핑보상 강성제어

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ABSTRACT

In this paper, we report a robust steering control using time delay control for the vehicle dynamics variation due to tire/road contact condition variation, the lateral disturbance force due to the side wind, and the yaw disturbance moment due to the difference between the left and right tires' pneumatic pressure. We controlled the side slip and yaw damping compensation for rapid steering at the high velocity of the vehicle. Based on the developed control, the driver can only consider the desired path without concerning on the vehicle dynamics variation, disturbances, and undesired side slip and yaw oscillations. Simulation results show that robustness from the vehicle dynamics variation and disturbances was achieved by using the developed time delay control. We evaluated the side slip and yaw damping compensation capability for the rapid steering at the high velocity of the vehicle in the cases of three control methods.

Keywords : Robust Steering Control(강성운전제어), Time Delay Control(시간차제어), Side Slip(측면슬립), Yaw Damping(요우댐핑)

1. Introduction

In driving a vehicle, it is inevitable to avoid the variation of the center of gravity, velocity, and tire/road contact conditions[(1)]. Especially in agricultural equipment, the steering control should be robust enough for uncertain external disturbances and uneven/slippery land conditions. This steering issue can be critical to drivers' safety on inclined land conditions[(1-2)]. Such land environment can lead to the variation of the vehicle dynamics which exerts reversed forces on the driver as the driving workloads. In addition, the lateral disturbing forces by lateral wind and the yaw directional disturbance moment due to the difference between the left tire's pneumatic pressure and the right one's can be occurred. The research of the robust control technique for the vehicle dynamics variation and the disturbances as the above will be meaningful.

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To resolve these issues, specific vehicle design and research projects have been carried out by many system engineers[3-4]. In case of the rapid steering in harvesting conditions, the side slip by land and the yaw oscillation can be another issue for unstable vehicle and it also exerts workloads on the driver. For this kind of situation, the development of the steering control algorithm which makes the vehicle follow the desired path and compensates for the side slip and the yaw oscillation will be able to reduce the driving workloads of the vehicle[4].

In this research, a robust steering control algorithm for the described situations is proposed. In the developed system, a driver commands only a desired path through the steering wheel, then the vehicle dynamics variation, the disturbances, the side slip, and the yaw oscillation are controlled by the developed robust steering control technique[5]. For the robust control technique, TDC(Time Delayed Condition)[6-7], which has remarkable robustness for the plant dynamics variation and the disturbances, was introduced. As an alternative steering angle control, steering by wire which is operated by electrical signals or the communication messages can be also implemented.

In previous researches yaw motion control was proposed to decouple the yaw motion from the lateral motion of the front axle by feedback of the yaw rate. In the control, the driver controls only the lateral motion of the front axle and the yaw motion was controlled automatically[8-9]. However, the desired yaw motion could not be obtained by the front wheel steering control but also the front rear wheel steering control was needed to obtain the desired yaw motion. In addition, “Dynamic look ahead” method was also tried to improve the yaw motion control[8-9].

Even though many researches have been implemented for the steering control, robustness of control system has been always an issue. In this research, a robust steering control algorithm using TDC in introduced. The TDC compensates the side slip and the yaw oscillation occurred by the rapid steering for vehicle dynamics variation and the external disturbances. As a driver commands a desired path through the steering wheel and the driving workloads due to the vehicle dynamics variation, the disturbances, the side slip, and the yaw oscillation are intended to be reduced by the control methods.

2. Vehicle Dynamics/Control Algorithm

2.1 Mathematical Model

A bicycle model of Fig. 1 as the vehicle dynamics model is used as a basic analysis model. The bicycle model is the most simplified vehicle dynamic model which is an ideal two degree of freedom bicycle model for the lateral and yaw motions.

In Fig. 1, x_0, y_0 are the inertial coordinate system and x, y are the fixed coordinate system on the vehicle with yaw angle (Ψ) and yaw rate(r) relative to the inertial coordinate system. The rate(r) is related to angle (Ψ) as $r = \Psi$. The δ_f and δ_r denote the front steering angle and the rear steering

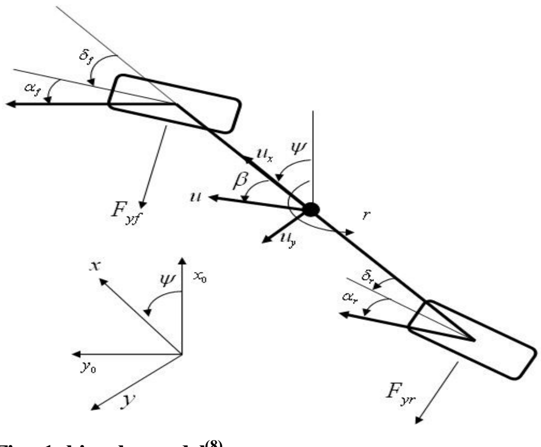


Fig. 1 bicycle model[8]

angle, respectively. The α_f and α_r denote the front tire slip angle and the rear tire slip angle. The F_{yf} and F_{yr} denote the lateral forces to the front and the rear wheel.

The u is the velocity vector of the vehicle's mass center and u_x and u_y denote the longitudinal and the lateral component of u. Finally, β denotes the side slip angle of the vehicle's mass center.

If $u_x = V$ is constant, the vehicle dynamics can be described as the state equation (1)[8-9].

$$\begin{bmatrix} \beta \\ r \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} \beta \\ r \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \begin{bmatrix} \delta_f \\ \delta_r \end{bmatrix} \qquad (1)$$

In equation (1) the system matrix components and the input matrix components can be described as follows.

$$\begin{aligned}
a_{11} &= -(C_f + C_r)/mV \\
a_{12} &= -1 + (-C_f a + C_r b)/mV^2 \\
a_{21} &= (-C_f a + C_r b)/I \\
a_{22} &= (-C_f a^2 - C_r b^2)/IV \\
b_{11} &= C_f/mV \\
b_{12} &= C_r/mV \\
b_{21} &= C_f a/I \\
b_{22} &= -C_r b/I
\end{aligned}$$

where m, I denote the vehicle's mass and the yaw directional inertial moment of the vehicle's mass. Parameters a and b denote the distances from the vehicle's mass center to the front axle and the rear axle. C_f and C_r denote the total cornering stiffness coefficient of the front and the rear tire.

Considering the vehicle dynamics of equation (1) as the object plant, the robust steering control was demonstrated using TDC which compensates for the side slip and the yaw oscillation occurred by the rapid steering for the vehicle dynamics variation and the disturbances.

2.2 Time Delay Control

The time delayed feedback control is relatively easy to implement and it constructs control parameters such as force or displace from the difference of the present state. By properly choosing the delayed value, it can stabilize the parameters. In this subsection, linearization technique is briefly described by using input/outputs. Considering a general system equation with m inputs, m outputs, and n states, the state equation can be described as

$$x = f(x) + G(x)u$$

$$y = c(x)$$

where, $x \in R^n$ is a state vector, $x \in R^m$ is an input vector, and $y \in R^m$ is an output vector.

As $f: R^n \to R^m$, $G: R^n \to R^{nxm}$ and $c: R^n \to R^m$, the output is assumed to be smooth functions of the state vector x. In the input/output linearization procedure, the output y_i is differentiated with respect to the time until at least one of the control inputs u_j appears.

2.3 Robust Steering Control Using TDC

When a driver intends desired path by steering wheel, steering wheel angle determines desired path. By the determined steering wheel angle, vehicle rotates and rotated angle determines the direction of vehicle. But the steering wheel angle by the driver's intention always does not make the desired path because of tire/road contact condition variation, disturbances, side slip of vehicle, and so on. Therefore, we need robust control to maintain the driver's desired path.

At this time an additional steering angle is needed by control algorithm. In addition to the simple TDC, a robust steering control technique is applied. The robust control TDC is an approach to explicitly deal with uncertainty of the system. The robust control is additionally provided to minimize the disturbance by uncertainty or stability in the bounded modelling errors.

The algorithm can be implemented by the steer by wire which is operated by the electrical signals or the communication messages, not by the mechanical connection.

In the following control methods, we deal with the case that driver commands the steering angle only for the driver's desired path. In other words, the driver does not consider the vehicle dynamics variation, disturbances, side slip, and yaw oscillation.

3. Results and Discussion

3.1 Robust Control with Side Slip Compensation using Front Wheel Steering Control

As an example of algorithm demonstration, the following simulation conditions which are measured and calculated were appled.

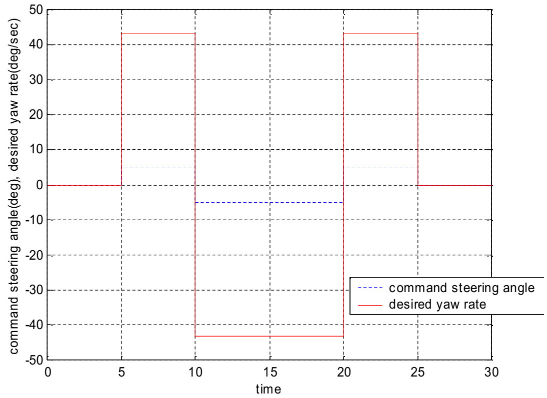
In the simulation condition, at vehicle rotating or steering time in 12≤t≤14 sec, the tire/road contact condition varies as the values of C_f, C_r decreased by 1/4. The simulation was carried out for 30sec where it starts at 5sec and ends at 25sec. A special temporal region was selected for the vehicle rotating or steering time simulation.

Table 1 Input parameters and values

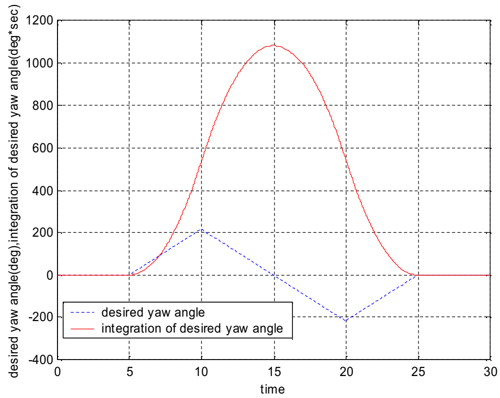
Parameters	unit	Value
m	kg	1,296
I	$kg \cdot m^2$	1,750
a	m	1.25
b	m	1.32
C_f	N/rad	84,243
C_r	N/rad	95,707
L	sec	0.001
α_1	-	20
α_2	-	100
V	km/h	80

At the time interval 17≤t≤19 sec the lateral disturbance force is 5000 N and the yaw directional disturbance moment is 10,000 N·m. Fig. 2 shows the example of commanded steering angle and desired yaw rate(Fig. 2a) and resulted yaw angle(Fig. 2b).

Fig. 3 shows the simulation result of applying TDC for the front wheel steering control to the vehicle dynamics model by equation (1). Fig. 3(a) is the simulation result of the lateral displacement of the vehicle's mass center. The simulation result of



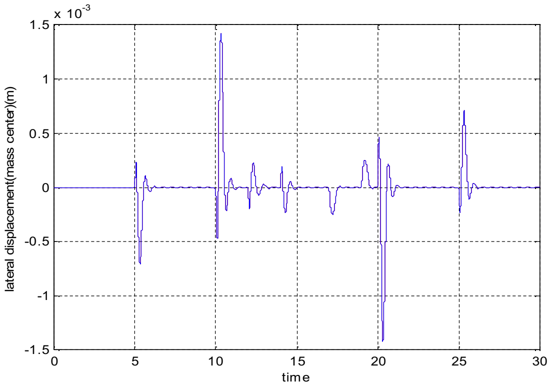
(a) Command steering angle and desired yaw rate



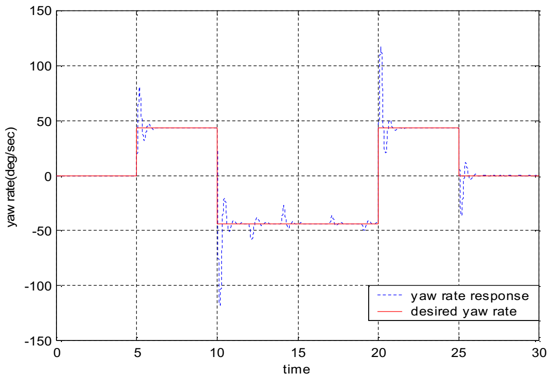
(b) Desired yaw angle and integration of desired yaw angle

Fig. 2 Simulation results for the command of steering angle, desired yaw rate, desired yaw angle and integration of desired yaw angle

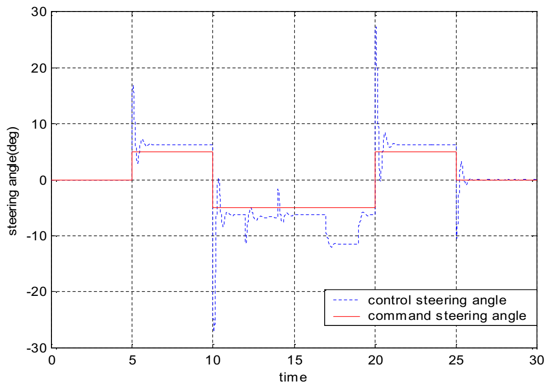
Fig. 3(a) indicates that the lateral displacement is very small for the step steering input, the tire/road contact condition variation, and the disturbances.



(a) Lateral displacement of mass center



(b) Yaw rate response



(c) Steering angle

Fig. 3 Simulation of robust control with side slip compensation using front wheel steering control

From the results, we can observe the good result of robust steering control with side slip compensation for the rapid steering, with the tire/road contact condition variation, the lateral disturbance force, and the yaw directional disturbance moment.

As shown in Fig. 3(b), a sudden rise of overshoot was observed at the time of 5sec, 10sec and 15sec. The sudden rise of overshoot helps to shorten the stabilization time to the steady state, however the lower overshoot can delay the time to the steady state. Additional algorithm may solve this issue, but it can result in the control responding time delay.

Fig. 3(b) is the simulation result of the yaw rate response. The simulation result of Fig. 3(b) indicates that the yaw damping is low at time of applying the step steering input t=5, 10, 20, 25 sec and indicates that the yaw rate response varies at time of the tire/road contact condition variation t=12, 14 sec and at time of the disturbances occurring and disappearing t=17, 19 sec. However, it also indicates that the yaw rate response does well follow the desired yaw rate during the variation does not arise. Fig. 3(c) indicates the command steering angle and the control steering angle.

4. Conclusion

In this research, we presented a robust steering control using TDC which compensates the side slip and the yaw oscillation due to the rapid steering at the high velocity. The control algorithm effectively controlled the vehicle from the disturbance caused by the vehicle dynamics variation due to the tire/road contact condition variation, the lateral disturbance force and the yaw directional disturbance moment exerting to the vehicle.

TDC is the robust control technique with distinguished robustness for the plant dynamics variation and the disturbances. TDC was Relatively simple algorithm using Time Delay Estimation, and with little burden of computation.

The control algorithm was demonstrated for the rapid steering(step input) at the high velocity, the tire/road contact condition variation, and the lateral disturbance force and the yaw directional disturbance moment. The robust control with side slip compensation using front wheel steering control indicated good side slip compensation capability but relatively low yaw damping characteristics.

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