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Sliding Mode Control for Longitudinal Control of a Platoon of Adaptive Cruise Control Vehicles

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Abstract. Automotive vehicle following systems are essential for the design of automated highway system. Vehicles equipped with adaptive cruise control system can operate on automated highway system during the vehicle following mode. This paper presents the sliding model control algorithm for the longitudinal control of a platoon of adaptive cruise control vehicles in the presence of noise signal and investigates the performance of platoon under the influence of sudden acceleration. This model has been applied on 3 vehicles moving in a platoon. The platoon has been analysed to retain the uniform velocity and safe spacing among the vehicles. Two different vehicle longitudinal models have been analysed and the simulation results obtained from them have been compared. Sliding mode control method is found suitable for the automotive vehicle following. Model simulations, in comparison with the literature, are also presented.

Keywords Terms: Adaptive Cruise Control, longitudinal dynamics, vehicle control, sliding mode control, acceleration tracking.

1 INTRODUCTION

Standard cruise control is a very familiar example of longitudinal controller that controls the longitudinal motion of a vehicle i.e. its longitudinal velocity, acceleration and longitudinal distance. Standard cruise control system automatically controls the throttle to maintain the desired speed specified by the driver. The cruise control system can become a source of irritation for the driver if he/she has to set the speed or disengage the cruise control in a heavy traffic. The performance of cruise control can be improved by adding a distance sensor or radar sensor which measures the distance, the relative speed and the relative position of the preceding vehicle and a limited authority braking system which controls the distance and relative velocities between a vehicle and a preceding vehicle. This modified cruise control system is termed as Adaptive Cruise Control (ACC) system. ACC vehicle has two modes of steady state operations; speed control and vehicle following mode. This paper presents the ACC vehicle longitudinal dynamics control using the well-known sliding mode control technique.

Rajamani and Zhu (2002) have proposed the longitudinal control system architecture for an ACC vehicle which is typically designed to be hierarchical, with an upper level controller and lower level controller as shown in (Fig. 1). The upper level controller determines the desired acceleration for each vehicle. The lower level controller determines the throttle and /or brake commands required to track the desired acceleration.

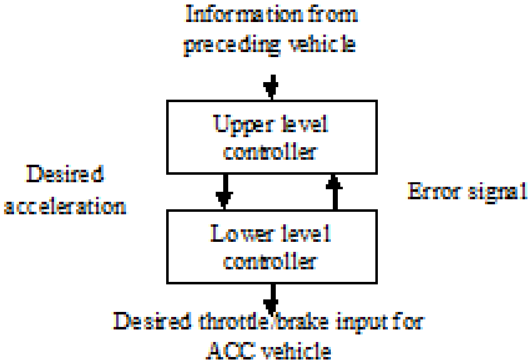


Fig. 1. ACC vehicle longitudinal control system (Rajamani 2006)

Huang and Chen (2001) introduced a control theorem for merging and splitting of the vehicle platoon with other platoon based on safe velocity profile. They have used the relative distance, relative velocity, and relative acceleration between the platoons and the same approach is used in this study for a member vehicle of the platoon. (Kato *et al.*, 2002) have proposed the model which uses the current speed of the preceding vehicle as an input for the following vehicle. They use the longitudinal velocity as the control input; tracking the maximum acceleration and deceleration coupled with road geometry and adapt the real-time data transmission characteristics for the inter-vehicle communication control.

Yi and Chong (2005) designed an impedance control system which uses serial chain of spring-damper to generate the link between the vehicles. The lead vehicle's information propagates to the following vehicles through the elasticity of the spring-damper. The spring-damper is a force control strategy to minimize the effects of forces exerted from uncertain environment. Although their model is stable in the presence of noise and parametric uncertainties but it lacks the situation when high acceleration and deceleration are applied to any one of the platoon vehicle. (Girard *et al.,* 2005) have tested an Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) system using real-time, embedded, hybrid control software while tracking the speed profile and vehicle following applications for passenger vehicles. (Girard *et al.,* 2005) designed the controller as function of spacing error, derivative of error and/or integral of errors. Martinez and Canudas de Wit (2007) proposed a non-linear model with simple feedback loop to compensate the un-modelled dynamics and external disturbances and uses the acceleration signal of the lead vehicle to maintain the safe distance among vehicles.

In the literature, much effort has been made on developing various platoon-stable control schemes based on different spacing policies. Canudas de Wit and Brogliato, (1999) have discussed linear control strategies, based on inter-vehicle spacing policy, for the string stability of the platoon of vehicles. They analysed that for unidirectional operation, a platoon will be string unstable if constant spacing policy is used and designed a stable controller with speed-dependent inter-vehicle spacing which ensures the string stability of the platoon of vehicles. (Swaroop *et al.* 2001) has presented a decentralized adaptive control algorithm for a platoon of vehicles which is based on constant spacing policy. For the constant spacing policy the desired inter-vehicle distance is independent of the velocity of the controlled vehicle. Different performance criterions for a platoon of vehicle have been discussed in literature. Many researchers have designed a control law based on sliding mode technique (Swaroop *et al.* 2001; Girard *et al.* 2005; Rajamani 2006; Ferrara and Vecchio 2007).

1.1 Sliding mode control

Sliding mode is an advanced type of variable structure system. Sliding mode control is an efficient tool to control complex high-order dynamic plants operating under uncertainty conditions. Sliding mode control can be conveniently used for both non-linear systems and systems with parameter uncertainties due to its discontinuous controller term. That discontinuous control is used to negate the effects of non-linear ties and/or parameter uncertainties (Drexel). Sliding mode as a phenomenon may appear in a dynamic system govern by ordinary differential equations with discontinuous right-hand sides. The term sliding mode first appeared in the context of relay systems. It may happen that the control as a function of the system state switches at high (theoretical infinite) frequency; this motion is called sliding mode (Utkin *et al.* 1999). The sliding mode approach is method which transforms a higher-order system into first-order system. In that way, simple control algorithm can be applied, which is very straightforward and robust (Utkin *et al.* 1999).

Two main properties of an ideal sliding motion, disturbance reduction and order reduction, are the key properties that have motivated the study of controllers which induce sliding motions (Edwards and Spurgeon 1998). The major advantage of sliding mode is low sensitivity to plant parameter variations and disturbances which eliminates the necessity of exact modelling. Sliding mode control enables the decoupling of the overall systems motion into independent partial components of lower dimension and, as a result, reduces the complexity of feedback design (Utkin 2008).

1.2 The Sliding Surface

Variable structure control (VSC) systems, as the name suggests, are a class of systems whereby the 'control law' is deliberately changed during the control process according to some defined rules which depends on the state of the system (Edwards and Spurgeon 1998). Due to non-linearities and uncertainties in a system the control objectives cannot be achieved with a strict pairing (gains) on one sensor/controller/valve. We need the flexibility to change the pairing automatically, as part of the control systems. This section investigates VSC as a high-speed switched feedback control resulting in sliding mode. For example, the gains in each feedback path switch between two values according to a rule that depends on the value of the state at each instant. The purpose of the switching control law is to drive the nonlinear plant's state trajectory onto a pre-specified (user-chosen) surface in the state space and to maintain the plant's state trajectory on this surface for subsequent time. The surface is called a switching surface. When the plant state trajectory is above the surface, a feedback path has one gain and a different gain if the trajectory drops below the surface. This surface defines the rule for proper switching. This surface is also called a sliding surface (sliding manifold). Ideally, once intercepted, the switched control maintains the plant's state trajectory on the surface for all subsequent time and the plant's state trajectory slides along this surface (Edwards and Spurgeon 1998; Utkin *et al.,* 1999).

The most important task is to design a switched control that will drive the plant state to the switching surface and maintain it on the surface upon interception.

2 MATERIAL AND METHODS

In this study the sliding mode control approach is used for the longitudinal control of a platoon of ACC vehicles. A platoon, consisting of 3 vehicles, has been considered in this study, see Fig. 2. It is assumed that all the vehicles of the platoon are identical for simplicity. A simple PID feedback control algorithm has been used for the lead vehicle to achieve the desired velocity, where the only feedback signal is the actual velocity of the lead vehicle. A PID control algorithm is used for the lead vehicle to generate a reference input for the following vehicle controller. The error signal for the PID controller is the velocity error between the desired velocity for the lead vehicle to be achieved and the actual velocity of the lead vehicle.

Two different longitudinal dynamics models from (Ferrara, Vecchio 2007 and Rajamani 2006) have been adopted for the purpose of demonstration of sliding mode control approach. The control algorithm based on sliding mode method is used for both models. For both models the traction force, as shown in (Fig. 3**)**, is calculated using the sliding mode control method. The simulation results obtained from both models are then analysed and compared to observer the suitability of sliding mode control method. Moreover, the performance of the platoon has been analysed under the influence of a noise signal in the lead vehicle.

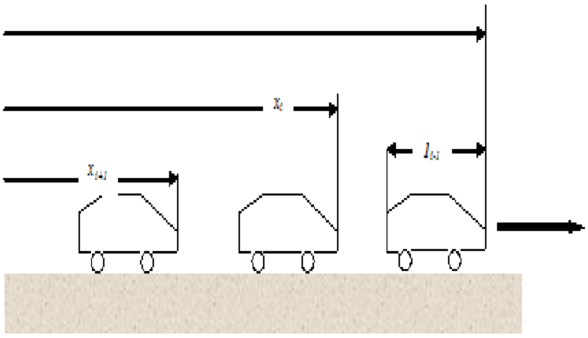


Fig. 2. A three-vehicle platoon

The block diagram for feedback control system is shown in Fig. 3.

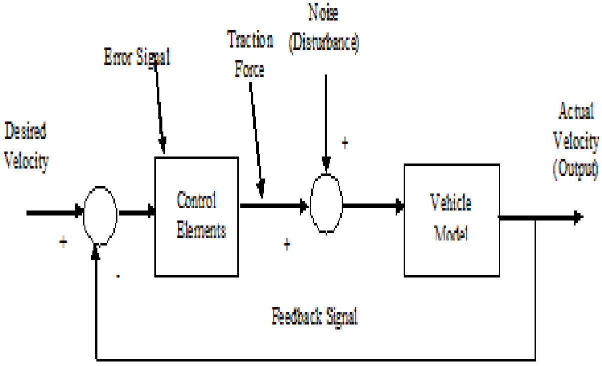


Fig. 3. Block diagram for the feedback control system.

The control signal is F_x, the traction force at the contact point between the tyre and the ground.

$$F_x = K_p(V_d - V) + K_i\int_0^t (V_d - V)d\tau + K_d\frac{d(V_d - V)}{dt} \quad (1)$$

where V_d = 7 m/s is the desired velocity of the lead vehicle, V is the actual velocity of the lead vehicle, K_p = 3000 is proportional gain, K_i = 800 is integral gain and K_d = 500 is derivative gain, mass of all vehicles is 1200 kg, aerodynamic drag coefficient is 0.3, and the coefficient of rolling resistance is 0.01.

The gains for the PID controller chosen using the hit and trail method. After many attempts these values has been found satisfactory.

3 A Simple Model of a Member-Vehicle of the Platoon

A platoon, consists of 3 vehicles, has been considered in this study. All the vehicles are controlled in the sense that their longitudinal speeds and longitudinal positions are determined by the controller. It is assumed that all the vehicles of the platoon are identical for the simplicity.

Ferrara and Vecchio (2007) longitudinal model for a member vehicle has been considered using sliding mode controller with constant headway policy

$$Ma_i = M\ddot{x}_i = -Mfg + \dot{x}_i^{\,2}(fK_1 - K_2) + F_x \quad (2)$$

where

M = mass of the vehicle (kg)
a_i = longitudinal acceleration of the vehicle
x = displacement (m)
F_x = traction force (N)
V = vehicle longitudinal velocity (m/s)
f = rolling resistance coefficient
K_1 = lift parameters from aerodynamics (N s^2/m^2)
K_2 = drag parameters from aerodynamics (N s^2/m^2)

Here F_x in equation (1) is used for lead vehicle and $d_i = x_{i-1} - x_i$ is introduced which is the relative distance between the (*i-1*) th and *ith* vehicle measured by vehicle *i*.

The control objective is to make the relative distance d_i be equal to (3)

$$L_i(\dot{x}_i) = S_{d_o} + h\dot{x}_i \quad (3)$$

Where S_{d_o} is the lower bound of the safety distance and h is the so-called ‘headway time’. With reference to the ith vehicle, the separation error is

$$e_i = L_i(\dot{x}_i) - d_i = S_{d_o} + h\dot{x}_i - x_{i-1} + x_i \quad (4)$$

To steer this error to zero by using the sliding mode control approach (Edwards and Spurgeon 1998; Utkin *et al.* 1999), one can select as a sliding variable

$$S_i = e_i = x_i - x_{i-1} + S_{d_o} + h\dot{x}_i \quad (5)$$

And design a variable structure control law capable of making the sliding variable vanish in finite time, thus generating a sliding mode on the manifold $S_i = 0$ (green line in Fig. 4(c)). According to Edwards and Spurgeon (1998) and Utkin (1999), the control law has to satisfy the so-called ‘reaching condition’.

$$\dot{S}_i S_i \le -\eta|S_i| \quad (6)$$

With η is a positive constant of sliding mode controller. Equation (6) yields that a suitable choice of the control signal has to guarantee

$$\dot{S}_i = -\eta sign(S_i) \tag{7}$$

Where η is chosen sufficiently high to satisfy equation (6), which automatically proves that the sliding manifold $S_i = 0$ is reached in finite time (Edwards and Spurgeon 1998; Utkin *et al.* 1999). By differentiating (5) with respect to time, one has

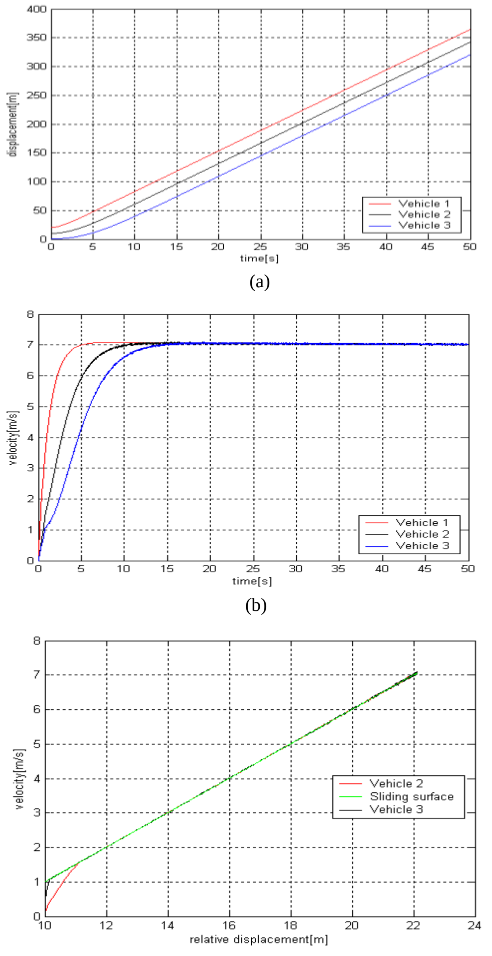
$$\dot{S}_i = \dot{x}_i - \dot{x}_{i-1} + ha_i \tag{8}$$

It should be noted that the value of η used in this model is 2 which has been chosen by hit and trial method. By substituting (7) in (8), it is possible to determine the acceleration which the *ith* vehicle should exhibit to satisfy condition (6), i.e.

$$a_i = \frac{1}{h}(-\eta sign(S_i) - \dot{x}_i + \dot{x}_{i-1}) \tag{9}$$

Substituting above equation in equation (2), the traction force F_{x_i} for a following vehicle will be

$$F_{x_i} = M\frac{1}{h}(-\eta sign(S_i) - \dot{x}_i + \dot{x}_{i-1}) + Mfg - \dot{x}_i^2(fK_1 - K_2) \tag{10}$$



(a)

(b)

(c)

Fig. 4. (a) Displacement of the three vehicles (b) longitudinal velocities of the three vehicles (c) Phase portrait of the relative displacement of two consecutive vehicles and velocity of the *ith* vehicle.

In another demonstration of sliding mode control method, a longitudinal dynamics model (Rajamani 2006) has been adapted to give a sufficiently accurate representation of the longitudinal dynamics of the lead vehicle in the platoon.

$$ma_i = m\ddot{x}_i = F_x - F_{aero} - mfg - mg\sin(\vartheta_F) \tag{11}$$

where

m = mass of the vehicle (kg)
a_i = longitudinal acceleration of the vehicle
x = displacement (m)
F_x = traction force (N)
F_{aero} = aerodynamic force (N) = $1/2\rho A_f C_d V^2$
V = vehicle longitudinal velocity (m/s)
C_d = aerodynamic drag coefficient (N s^2/m^2)
f = rolling resistance coefficient
A_f = frontal area of the vehicle (m^2)
ρ = mass density of air (kg/m^3)
ϑ_F = slope angle (degrees) = 0°

For the lead vehicle F_x in equation (1) can be used and the spacing error between two consecutive vehicles, based on constant headway policy, can be defined as

$$e_i = x_{i-1} - x_i - L - h\dot{x}_i \tag{12}$$

Where L is the desired distance between the vehicles and h is the 'headway time'. The control objective is to make this error zero. The sliding mode controller (Edwards and Spurgeon 1998; Utkin *et al.* 1999) can be used to achieve this task by introducing a sliding surface S.

$$S_i = e_i = x_{i-1} - x_i - L - h\dot{x}_i \tag{13}$$

High frequency switching between the two different control structures will take place as the system trajectories repeatedly cross the sliding surface *S*. This high frequency motion is described as chattering (Edwards and Spurgeon 1998). One can design a variable structure control law capable of making the sliding variable vanish in finite time, thus generating a sliding mode on the manifold $S_i = 0$. According to Edwards and Spurgeon (1998) and Utkin (1999), the control law has to satisfy the so-called 'reaching condition'.

$$\dot{S}_i S_i \le -\eta |S_i| \tag{14}$$

With η is a positive constant of sliding mode controller. Equation (14) yields that a suitable choice of the control signal has to guarantee

$$\dot{S}_i = -\eta sign(S_i) \tag{15}$$

Where η is chosen sufficiently high to satisfy equation (14), which automatically proves that the sliding manifold $S_i = 0$ is reached in finite time

(Edwards and Spurgeon 1998; Utkin *et al.* 1999). By differentiating (13) with respect to time, one has

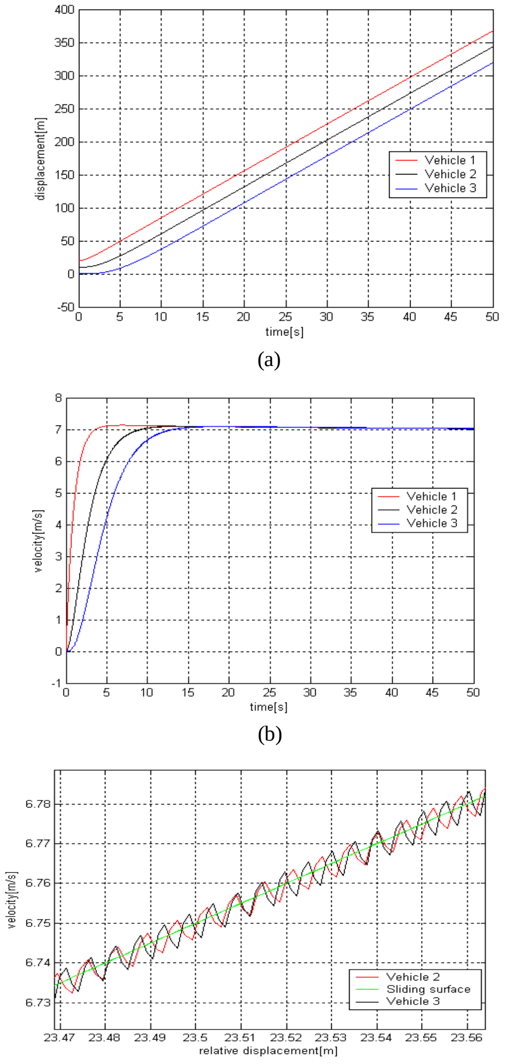
$$\dot{S}_i = \dot{x}_i - \dot{x}_{i-1} + ha_i \tag{16}$$

It should be noted that the value of η used in this model is 2 which has been chosen by hit and trial method. By substituting (15) in (16), it is possible to determine the acceleration which the *ith* vehicle should exhibit to satisfy condition (14), i.e.

$$a_i = \frac{1}{h}(-\eta sign(S_i) + K_1(x_{i-1} - x_i - L - h\dot{x}_i) + \dot{x}_{i-1} - \dot{x}_i) \tag{17}$$

Where, K_1 is the controller gain. Substituting equation (17) in equation (11), the control structures F_{x_i} for a following vehicle will be

$$F_x = m\frac{1}{h}(-\eta sign(S_i) + K_1(x_{i-1} - x_i - L - h\dot{x}_i) + \dot{x}_{i-1} - \dot{x}_i) + F_{aero} + mfg \tag{18}$$



(a)

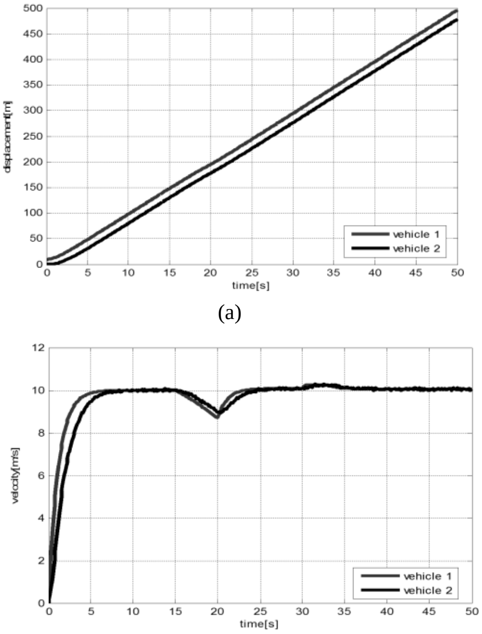
(b)

(c)

Fig. 5. (a) Displacement of the three vehicles (b) longitudinal velocities of the two vehicles (c) Phase portrait of the relative displacement of two consecutive vehicles and velocity of the *ith* vehicle.

4 Disturbance Effects On The Platoon Performance

This section focuses the effects of noise signals on the performance of ACC vehicle. The sources of noise considered in this study are sudden variations in acceleration and deceleration applied to the lead vehicle and the transition between steady-state to vehicle following mode. The lead vehicle decelerates at t = 15 s and then accelerates after t = 20 s and reaches the desired velocity of 10 m/s. The lead vehicle is further accelerated at t = 30 s and decelerated after t = 32 s. So the disturbance is applied at two different time durations. Fig. 6 shows that under the influence of the disturbance signals, the ACC vehicle smoothly achieves the required objectives, i.e. keeping the safe distance from the lead vehicle, maintaining the same velocity as lead vehicle and avoiding any collision.



(a)

(b)

Fig. 6. (a) Displacement of two vehicles (b) velocities of the two vehicles, this simulation shows the disturbance in the lead vehicle in the form of deceleration and then acceleration

5 DISCUSSION

The sliding mode control technique has been applied to both, Ferrara and Vecchio (2007) and Rajamani (2006), models. Fig. 4 (a) and Fig. 5 (a) show the displacements of the three-vehicle platoon with the initial positions for the vehicles of platoon are, X1 = 20 m, X2 = 10 m, X3 = 0 m. The spacing between the vehicles is likely to increase as spacing depends on the controlled vehicle velocity (not based on constant spacing as in Automated Highway System, but based on constant headway policy i.e. Adaptive Cruise Control System). Fig. 4 (b) and Fig. 5 (b) show the longitudinal velocity trajectories of the platoon. These simulation results shows very similar results when compared with the (Sun *et al.*, 2004) longitudinal dynamics model, which is also based on sliding mode control method.

The simulation results, Fig. (5), of the Rajamani (2006) longitudinal model, based on sliding mode controller, show the stability of the whole platoon and there is hardly any transient behaviour with no oscillation of the lead vehicle. The following vehicles do not overshoot and showing the similar behaviour like the lead vehicle.

The sliding mode controller can be ensured by observing Fig. 4 (c) and Fig. 5 (c) which show the phase portrait of the relative displacement of the two consecutive vehicles and velocity of the *ith* vehicle. The green line shows the sliding surface (user chosen surface) and the system state trajectories (red and black lines) are designed to slide along the sliding surface once they reach the sliding surface. High frequency switching occurs across the sliding surface defined by equations (5) and (13). These both Figs show the similar behaviour, thus, guarantying the sliding mode control approach.

Fig. 6 shows the response of the ACC vehicle under the noise signal (disturbance). This disturbance was applied to the acceleration of the lead vehicle. Initially the lead vehicle is decelerated and then it accelerates. It can be clearly observed that the sliding mode control approach perform well under the influence of this noise signal because the ACC vehicle is smoothly following the lead vehicle.

6 CONCLUSION

A platoon model consists of three vehicle has been presented in this study. The first vehicle is the lead vehicle and the two following vehicles are equipped with ACC system. Both ACC vehicles are operating under vehicle following mode. The longitudinal models of (Ferrara and Vecchio 2007) and (Rajamani 2006) have been analysed using the sliding mode control method. Simulation results show that the following ACC vehicles are smoothly following the lead vehicle during the steady-state operation and transient operation. The stability of the sliding mode method has been realised when the lead vehicle was subjected to the sudden noise signals. It has been observed that sliding mode method is suitable for the control of longitudinal dynamics of a simple vehicle model equipped with ACC system.

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