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Study on Lateral Stability Control for Tractor Semi-trailer Based on Sliding Mode Control

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Abstract: There are several factors that increase the likelihood of yaw instability with a loaded tractor semi-trailer. Lateral instability phenomena will likely occur in tractor semi-trailers on high speed obstacle avoidance under emergency or during high speed curve driving. The linearized three-axle model is utilized to predict the dynamics state of the tractor semi-trailer built in multibody dynamics simulation software. The lateral stability simulation was performed on the dynamic model based on virtual prototyping. The results show that the lateral stability control based on sliding mode control proposed in this paper can stabilize the tractor semi-trailer, prevent from rollover on high speed obstacle avoidance under emergency or during high speed curve driving.

Key words: Tractor semi-trailer, lateral stability, obstacle avoidance, curve driving

INTRODUCTION

There are several factors that increase the likelihood of yaw instability with a loaded tractor semi-trailer. These include a forward bias in the distribution of tire cornering stiffness, rearward placement of the fifth wheel coupling, a high center of gravity location of the trailer payload, low roll stiffness of the trailer's suspension and low adhesion coefficient road (Bennett and Norman, 2011).

In the past most literature focused on the longitudinal dynamics of the tractor semi-trailers. Effects of load transfer, brake type and Antilock Brake System (ABS) are well documented. However, much less is understood about the lateral dynamics of contemporary tractor semi-trailers.

Recent researches on modeling a tractor semi-trailer combination vehicle include classics dynamical models and flexible (Gafvert and Lindgarde, 2004) and modular nonlinear dynamic handling models.

Many feedback control systems have been introduced to improve tractor semi-trailers stability and handling performance. These systems take environmental information from the existing sensors in vehicle and command the actuators based on their inference of current situation. The sensors in the yaw control systems include four wheel speeds, steering angle, yaw rate, lateral acceleration and in some cases one or two pressure sensors. Hence, the existence of non-deterministic states limits numerous previously published, full-state feedback control methods of being applicable on an actual vehicle. Lateral instability phenomena will likely occur in tractor semi-trailers on high speed obstacle avoidance under emergency or during high speed curve driving (Zhou and Zhang, 2012), as shown in Figure 1. Yaw instability usually occurs on low adhesion surface and rollover occurs on a high adhesion surface (Zhou and Zhang, 2013).

In this study, a lateral stability control for tractor semi-trailer is proposed to mitigate oversteer or understeer conditions that can lead to loss-of-control of tractor semi-trailer, by automatically applying selective brakes to generate a yaw moment that helps the driver maintain directional control of the vehicle.

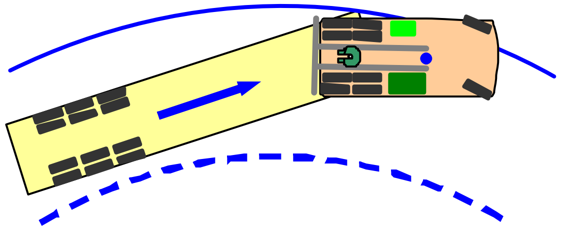

Fig. 1: High speed curve driving

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TRACTOR SEMI-TRAILER KINEMATICS

An articulated vehicle modeled as two rigid bodies hinged to each other has, in its motion on the road surface. The assumption of rigid bodies implies that the hinge is cylindrical and its axis is perpendicular to the road (Genta, 2006). In developing the equations of motion for the yaw plane model, the roll dynamics of the tractor semi-trailer are neglected. Also, the tractor semi-trailer is assumed to travel at a constant forward velocity. The degrees of freedom permitted in the model are therefore limited to lateral and yawing motion of the tractor and the semi-trailer units. The articulation angle is related through the yaw angles of the two units. The effect of the centrifugal force is therefore neglected so that the model is kinematic. The vehicle is also assumed to be moving on a hard, flat surface. Figure 2 presents the yaw plane model of articulated three-axle tractor-semi-trailer vehicle.

Three degrees of freedom are considered. Both the tractor and semi-trailer have one degree of freedom of yaw rate and one lateral velocity for tractor. The equations are constrained by the fifth wheel equation.

Owing to schemes of dynamics shown in Figure 2, the following set of equations for the tractor and the semi-trailer is obtained (Andrzejewski and Awrejcewicz, 2005, Rajamani, 2006):

$$m_1 u(\dot{\beta}_1 + \dot{\psi}_1) = C_{\alpha 1}\alpha_1 + C_{\alpha 2}\alpha_2 - F_H \tag{1}$$

$$m_2 u(\dot{\beta}_2 + \dot{\psi}_2) = C_{\alpha 3}\alpha_3 + F'_H \tag{2}$$

$$I_{z1}\ddot{\psi}_1 = aC_{\alpha 1}\alpha_1 - bC_{\alpha 2}\alpha_2 + hF_H \tag{3}$$

$$I_{z2}\ddot{\psi}_2 = cF'_H - dC_{\alpha 3}\alpha_3 \tag{4}$$

Where:

$$\alpha_1 = -\delta + \beta_1 + \frac{a\dot{\psi}_1}{u}$$

$$\alpha_2 = \beta_1 - \frac{b\dot{\psi}_1}{u}$$

$$\alpha_3 = \beta_1 - \frac{(h+c+d)\dot{\psi}_1}{u} - \frac{(c+d)\dot{\varphi}}{u} - \varphi$$

$$\beta_2 = \beta_1 - \frac{(h+c)\dot{\psi}_1}{u} - \frac{c\dot{\varphi}}{u} - \varphi$$

$$\dot{\psi}_2 = \dot{\psi}_1 + \dot{\varphi}$$

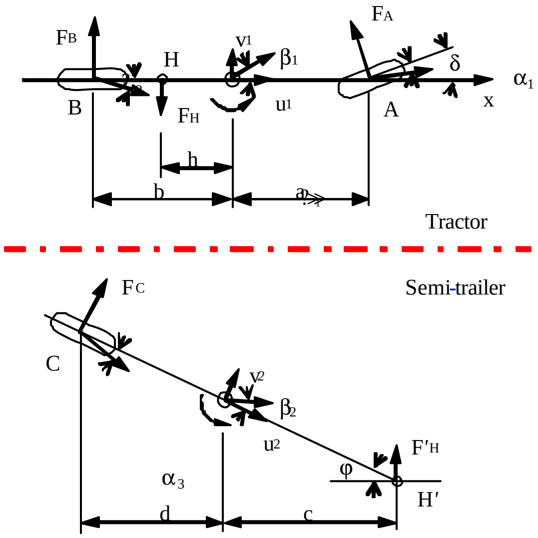

Fig. 2: Tractor semi-trailer model

Substituting the above expressions into Eq. 1-4 and using small angle approximations, introducing x as a new variable, $x = [\dot{\psi}_1 \quad \beta_1 \quad \dot{\varphi} \quad \varphi]^T$, we form the vector the tractor semi-trailer model can be rewritten in state-space representation:

$$\begin{aligned} \dot{x} &= Ax + B\delta \\ y &= Cx \end{aligned} \tag{5}$$

For the tractor semi-trailer model, the lateral velocity (slip angle), the yaw rate and articulation angle are considered as the state variables.

SLIDING MODE CONTROL

Sliding mode control, or SMC, is a nonlinear control method that alters the dynamics of a nonlinear system by application of a discontinuous control signal that forces the system to slide along a cross-section of the system's normal behavior. The motion of the system as it slides along these boundaries of the control structures is called a sliding mode and the geometrical locus consisting of the boundaries is called the sliding hypersurface.

Generally, sliding mode control uses practically infinite gain to force the trajectories of a dynamic system to slide along the restricted sliding mode subspace. Trajectories from this reduced-order sliding mode have desirable properties. The main strength of sliding mode control is its robustness. Because the control can be as simple as a switching between two states, it need not be precise and will not be sensitive to parameter variations that enter into the control channel.

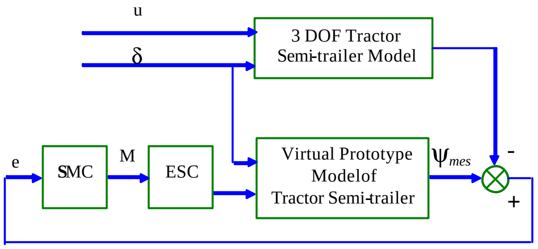

Fig. 3: Sliding mode control scheme

However, sliding mode control must be applied with more carefully than other forms of nonlinear control that have more moderate control action. In particular, because actuators have delays and other imperfections, the hard sliding-mode-control action can lead to chatter, energy loss, plant damage and excitation of unmodeled dynamics.

In this study, the proportional switch law was utilized to design the controller M[9]:

$$\begin{gathered} M=(w|e|+p\dot{e})\,\mathrm{sgn}(s) \\ s=qe+\dot{e} \end{gathered} \tag{6}$$

where, s is the switch function, e is the error between measured yaw rate $\dot{\psi}_{mes}$ and desired yaw rate $\dot{\psi}_{des}$, k and p are constant greater than zero.

Since the chattering of sliding mode control may cause damage to system components such as actuators. One way to alleviate the chattering is to use the quasi-sliding mode method which can make the state stay in a certain range at Δ neighborhood. Often we nameΔ as the boundary layer (Liu and Wang, 2011).

The sign function ‘sgn’ in Eq. 6 was replaced with saturation function ‘sat’:

$$\mathrm{sat}(s)=\begin{cases} 1 & s>\Delta \\ ks & |s|\le\Delta \quad k=\dfrac{1}{\Delta} \\ -1 & s<-\Delta \end{cases} \tag{7}$$

The sliding mode control scheme of tractor semi-trailer was shown in Fig. 3.

LATERAL STABILITY CONTROL

The desired yaw rate of steady-state is determined by the steering input and vehicle forward speed in a large extent. The yaw rate increases with the vehicle speed in the same steering angle and the yaw rate tends to be unstable if the speed or steering is excessive. Under oversteer or understeer conditions it is necessary to apply selective brakes to generate a yaw moment that helps the driver maintain directional control of the vehicle.

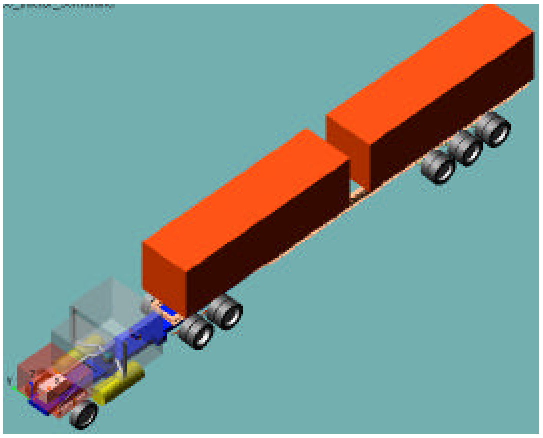

Fig. 4: Virtual prototype model of tractor semi-trailer

In order to verify the vehicle dynamics control strategy, a dynamic analysis was performed using ADAMS/CAR and Simulink. The control system was designed in Simulink and the full vehicle was assembled in ADAMS/CAR, as shown in Fig. 6.

We employ the linear bicycle model to generate the reference vehicle behavior, such as yaw rate of neutral steer. The difference of yaw rate between the reference model and the multi-body model is considered as control signal to the vehicle multi-body model. The vehicle multi-body model is shown in Fig. 4.

Figure 3 show that the additional yaw moment for maintaining directional control of the vehicle is generated by sliding mode control based on the difference between measured yaw rate from the virtual prototype model of tractor semi-trailer and desired yaw rate from the 3 DOF tractor semi-trailer model. The electronic stability control module decides which wheel will be applied brake pressure.

SIMULATION RESULTS

Many accidents show that lateral instability phenomena will likely occur in tractor semi-trailers on high speed obstacle avoidance under emergency or during high speed curve driving.

The obstacle avoidance maneuvers are similar to the lane change maneuvers. The main difference is that the maneuver time of the former is shorter than the latter. The simulation reveals that the yaw rate of steady-state is dominant by the steering input and vehicle forward speed in a large extent. The yaw rate increases with the vehicle speed in the same steering angle. In the obstacle avoidance maneuvers, the rapid steering obviously increases the yaw instability or rollover risk of a tractor

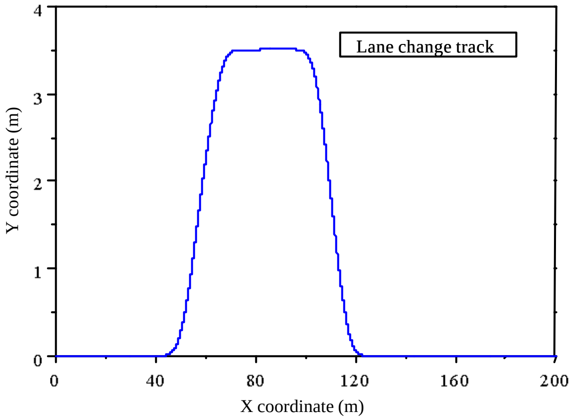

Fig. 5: Double lane change desired trajectory

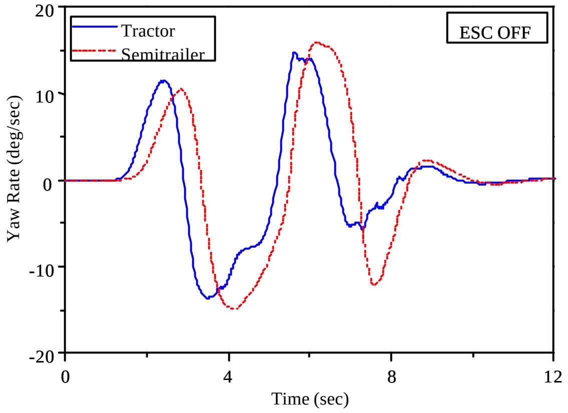

Fig. 6: Yaw rate with ESC off

semi-trailer. Figure 5 is the double lane change track for the simulation of a tractor semi-trailer. Figure 6 is the yaw rate response of the tractor semi-trailer at a speed of 80 km h^{-1}. As we can see that the yaw rate tends to be unstable at the third corner. So we need to control the yaw rate and the speed if necessary by applying selective brakes to generate a yaw moment.

Figure 7 is the tractor semi-trailer yaw rate with electronic stability control. From Figure 6, we can see that the tractor semi-trailer without electronic stability control became unstable. The yaw rate under electronic stability control is very close to the desired yaw rate (neutral steer). In addition, the yaw rate is steady without any obvious oscillation.

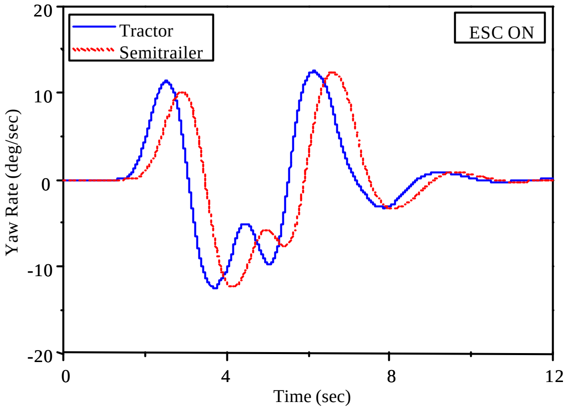

Fig. 7: Yaw rate with ESC on

The traditional yaw stability systems may aid in preventing a vehicle from spinning out and hence may indirectly reduce the potential for the vehicle to have a side collision with a barrier thus reducing the likelihood of a rollover. For under-steer vehicle, the yaw stability system will manage to make the vehicle neutral-steer. However, this action will unintentionally increase vehicle lateral acceleration and roll angle which will definitely deteriorate roll stability.

The electronic stability control proposed in this study also includes rollover prevention. The rollover prevention control system, i.e., roll stability, however, needs to make the vehicle under-steer more during the detected aggressive driving conditions that may contribute to vehicle roll instability. For an under-steer, the anti-rollover control system will stop the yaw stability systems when the rollover index exceeds the preset threshold values.

CONCLUSION

There are several factors that increase the likelihood of yaw instability with a loaded tractor semi-trailer. Lateral instability phenomena will likely occur in tractor semi-trailers on high speed obstacle avoidance under emergency or during high speed curve driving.

In this study, a lateral stability control for tractor semi-trailer is proposed to mitigate oversteer or understeer conditions that can lead to loss-of-control of tractor semi-trailer, by automatically applying selective brakes to generate a yaw moment that helps the driver maintain directional control of the vehicle.

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