INFLUENCE OF VELOCITY ON THE ROLL STABILITY OF TRACTOR - SEMI TRAILER

ẢNH HƯỞNG CỦA VẬN TỐC ĐẾN SỰ ỔN ĐỊNH CỦA ĐẦU KÉO - SƠ MI RƠ MOÓC

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ABSTRACT

Today, tractor - semi trailer is the most popular transport vehicle in the world due to its benefits. However, accidents related to this vehicle usually are serious and usually linked to the loss stability of tractor - semi trailer. The main leading factors to rollover accidents usually are the abrupt steering with high velocity by the driver. This paper surveys the effect of velocity on the stability of tractors - semi trailers. Tractors - semi trailer is modelled and simulated using Matlab - Simulink software on the time domain in the cornering manuever. The results show that rollover of the trailer - semi trailer occurred when the forward velocity at the front and rear axle of the tractor reached 62.97km/h and 54.62km/h. and the velocity at the rear axle of semi trailer is 57.91km/h.

Keywords: *Vehicle dynamic system, active anti roll bar, articulated vehicle dynamic, LQR control method.*

TÓM TẮT

Hiện nay, đầu kéo - sơ mi rơ moóc là phương tiện vận chuyển phổ biến nhất trên thế giới vì lợi ích của nó đem lại. Tuy nhiên, những tai nạn liên quan đến loại xe này rất nghiêm trọng và thường liên quan đến sự mất ổn định lật của đầu kéo - sơ mi rơ moóc. Các yếu tố chính dẫn đến mất ổn định lật thường do người lái đi với tốc độ cao khi quay vòng hoặc chuyển làn. Trong bài báo này, tác giả khảo sat ảnh hưởng của vận tốc đến sự ổn định của đầu kéo - sơ mi rơ moóc. Mô hình hóa của đầu kéo - sơ mi rơ moóc được mô phỏng bằng phần mềm Matlab - Simulink trên miền thời gian trong trường hợp ô tô quay vòng. Các kết quả thu được cho thấy hiện tượng mất ổn định của đầu kéo - sơ mi rơ moóc xảy ra khi vận tốc ở cầu trước, cầu sau của đầu kéo đạt giá trị 62,97km/h, 54,62km/h và vận tốc ở cầu sau của sơ mi rơ moóc bằng 57,91km/h.

Từ khóa: *Động lực học ô tô, hệ thống ổn định ngang chủ động, đoàn xe, phương pháp điều khiển LQR.*

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1. INTRODUCTION

Nowadays, tractor - semi trailer is used increasingly because tractor - semi trailer is an attractive choice for several advantages in terms of environmental and financial benefits in transportation field. Tractor - semi trailer can decrease in fuel consumption per ton per kilometer leading to less exhaust emission. Because the multiple units are connected together in a single combination vehicle, the aerodynamic performances are improved, there for the fuel consumptions are drastically decreased [1]. Moreover, economic benefits are also significantly improved, as fewer drivers are required by reducing total number of vehicles on the road for a given amount of goods to be transported [2].

However, the accidents related to AHVs usually are fatal and they often are caused by rollover. The main leading factors to rollover accidents usually are suspension system not good enough and the abrupt steering with high velocity by the driver. When driver controls tractor - semi trailer cornering or suddenly change the lane in high velocity, the outer wheels tend to lift off from road, leading to rollover of vehicle [1].

In [1 - 4], the authors summarized the dynamics of single tractor semi trailer and multi tractor full-trailer. Publications from the University of Michigan Transportation Research Institute are among the most comprehensive general reviews of heavy vehicle dynamics [5, 6, 7]. The roll dynamics of heavy vehicles in cornering manuevers are much more relevant to vehicle safety than those of automobiles [6].

The contributions of this paper are the following:

- A yaw - roll model is used for studying the stability of tractor - semi trailer, by considering the vertical and lateral displacement of the vehicle.

- The obtained results show that the rollover of tractor - semi trailer is occurred when the velocites of axles of tractor and semi trailer take different values.

2. VEHICLE MODELLING

2.1. Modeling of a tractor - semi trailer

In this paper, we use the model in [8] to describe the tractor - semi trailer dynamics. In this model we accept some assumptions: the articulated vehicle is assumed to be perfectly rigid; the affection of pitching and bouncing motions on roll and handling behaviour of the vehicle are small and so can be neglected; the aerodynamic input and road input have a small effect and they are also ignored; the steering angle is the unique disturbances of the yaw - roll model. The vehicle body has the roll axis with distance r upwards from the ground. The dynamic equations of the vehicle are formulated by equating the change of momentum (or, in the rotational case, moment of momentum) with the sum of external forces (or moments) acting on the system. A coordinate system (x', y', z') fixed in the vehicle using to describe the motions. The roll axis is replaced by an x' axis parallel to the ground, and the z' axis passes downward through the centre of mass of the tractor - semi trailer.

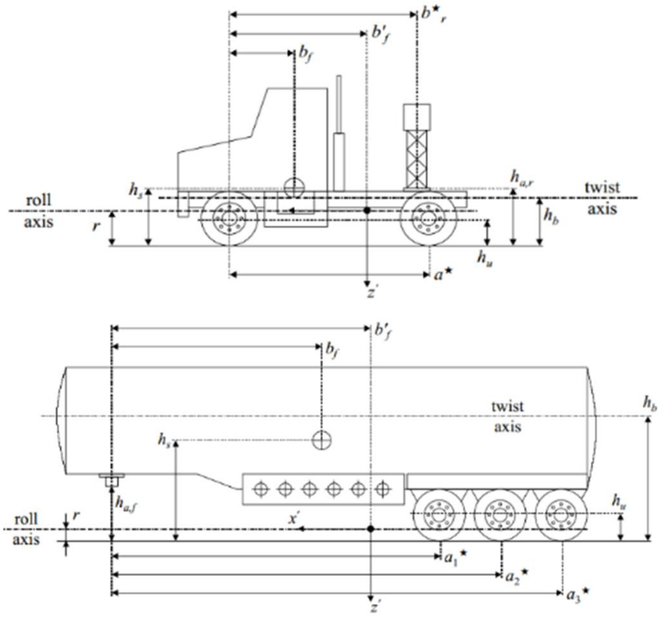

Figure 1. Yaw - roll model of tractor - semi trailer

Figure 1 shows the tractor - semi trailer model by combining two parts: tractor and semi trailer, in which $m_{s,i}$ is the sprung mass, $h_{s,i}$ is the height of center of sprung mass, $m_{uf,i}$ is the unsprung mass at the front axle, and $m_{ur,i}$ the unsprung mass at the rear axle, $h_{u,i}$ is the height of center of unsprung mass, $I_{x,i}$ is the roll moment of inertia, $I_{z,i}$ is the yaw moment of inertia, $I_{xz,i}$ is the yaw roll moment of inertia, $b_{f,i}$ is the longitudinal distance to articulation point, measured forwards from center of sprung mass, $b'_{f,i}$ is the longitudinal distance to articulation point, mesured forwards from center of total mass of tractor or semi trailer. The subscripts f and r denote the front and rear axle of the tractor or trailer, respectively. The subscripts i (1 and 2) denote the tractor and semi trailer, respectively. F_c is lateral force at the coupling point. The symbols and parameters of this model are shown in [8].

2.2. Dynamic equations of a tractor - semi trailer

The dynamic equations of the Yaw - Roll model of tractor - semi trailer are showed in equations (1) to (9), which include: The equations (1) to (5) describe the yaw moment, the roll moment of the sprung mass, the roll moment of the front and rear unsprung masses of tractor. The yaw moment of the sprung mass, the roll moment of the sprung mass, the roll moment of the rear unsprung mass of semi trailer are noted in equations (6) to (8). The equation (9) express the kinematic constraint between the tractor and the semi trailer at the vehicle coupling [12].

$$m_1 v(\dot{\beta}_1+\dot{\psi}_1)-m_{s1} h\dot{\phi}_1 = F_{yf}+F_{yr}-F_C \quad (1)$$

$$I_{xz1}.\ddot{\phi}_1-I_{zz1}.\ddot{\psi}_1 = F_{yr1}.dl_{r1}-F_{yf1}.dl_{f1}-b'_{r1}.F_C-k_{\psi1}(\psi_1-\psi_2) \quad (2)$$

$$\begin{aligned}&-m_{s1}.a_y.h_{s1}-m_{s1}g.\phi_1.h_{s1}+I_{xx1}.\ddot{\phi}_1-I_{xz1}.\ddot{\psi}_1+k_{f1}(\phi_1-\phi_{tf1})\\&+l_{f1}(\dot{\phi}_1-\dot{\phi}_{tf1})+k_{r1}(\phi_1-\phi_{tr1})+l_{r1}(\dot{\phi}_1-\dot{\phi}_{tr1})\\&+(h_{ar1}-r_1)F_C-k_{\phi1}(\phi_1-\phi_2)=0\end{aligned} \quad (3)$$

$$\begin{aligned}&-F_{yf1}.r_1+(r_1-h_{uf1}).m_{uf1}.v(\dot{\beta}_1+\dot{\psi}_1)+k_{tf1}.\phi_{tf1}\\&+(r_1-h_{uf1}).m_{uf1}.g.\phi_{tf1}-k_{f1}(\phi_1-\phi_{tf1})-l_{f1}(\dot{\phi}_1-\dot{\phi}_{tf1})=0\end{aligned} \quad (4)$$

$$\begin{aligned}&-F_{yr1}.r_1+(r_1-h_{ur1}).m_{ur1}.v(\dot{\beta}_1+\dot{\psi}_1)+k_{tr1}.\phi_{tf1}\\&(r_1-h_{uf1}).m_{ur1}.g.\phi_{tr1}-k_{r1}(\phi_1-\phi_{tr1})-l_{r1}(\dot{\phi}_1-\dot{\phi}_{tr1})=0\end{aligned} \quad (5)$$

$$I_{xz2}.\ddot{\phi}_2-I_{zz2}.\ddot{\psi}_2 = F_{yr2}.dl_{r2}+b'_{f2}.F_C-k_{\psi1}(\psi_1-\psi_2) \quad (6)$$

$$\begin{aligned}&I_{xx2}.\ddot{\phi}_2-I_{xz2}.\ddot{\psi}_2-m_{s2}.a_y.h_{s2}-m_{s2}g.\phi_2.h_{s2}+k_{r2}(\phi_2-\phi_{tr2})\\&+l_{r2}(\dot{\phi}_2-\dot{\phi}_{tr2})+u_{r2}-(h_{af2}-r_2)F_C+k_{\phi1}(\phi_1-\phi_2)=0\end{aligned} \quad (7)$$

$$\begin{aligned}&-F_{yr2}.r_2-(h_{ur2}-r_2).m_{ur2}.v(\dot{\beta}_2+\dot{\psi}_2)-(h_{ur2}-r_2).m_{ur2}.g.\phi_{tr2}\\&-k_{r2}(\phi_2-\phi_{tr2})-l_{r1}(\dot{\phi}_2-\dot{\phi}_{tr2})+k_{tr2}.\phi_{tr2}=0\end{aligned} \quad (8)$$

$$\begin{aligned}&\beta_1-\beta_2-\frac{(r_1-h_{ar1})}{v}\dot{\phi}_1+\frac{(r_2-h_{af2})}{v}\dot{\phi}_2\\&+\frac{b'_{r1}}{v}\dot{\psi}_1-\frac{b'_{f2}}{v}\dot{\psi}_2+\psi_1-\psi_2=0\end{aligned} \quad (9)$$

The lateral tyre forces $F_{y,i}$ in the direction of velocity at the wheel ground connection points are modelled by using linear stiffness coefficients as:

$$F_{yfi}=\mu C_f \alpha_f$$
$$F_{yri}=\mu C_r \alpha_r$$

With the tyre side slip angles:

$$\alpha_{f1}=-\beta_1+\delta_f-\frac{l_{f1}\dot{\psi}_1}{v} \qquad \alpha_{r1}=-\beta_1+\frac{l_{r1}\dot{\psi}_1}{v}$$

$$\alpha_{r2}=-\beta_2+\frac{l_{r2}\dot{\psi}_2}{v}$$

The motion differenial equations from (1) to (9) can be rewritten in the LTI state - space representation as:

$$\begin{cases}\dot{x}=Ax+Bw\\ z=Cx+D\end{cases}$$

Where:

The state vector: $x=[\beta_1\ \dot{\psi}_1\ \phi_1\ \dot{\phi}_1\ \phi_{tf1}\ \phi_{tr1}\ \phi_2\ \dot{\phi}_2\ \beta_2\ \dot{\psi}_2\ \phi_{tr2}]^T$

The exogenous disturbance: $w=[\delta]^T$,

The output vector: $z = x$.

2.3. Criteria evaluate the loss stability of tractor - semi trailer

In order to evaluate the vehicle roll stability of articulated vehicles using the active anti - roll bar system, we would like to minimize the normalized load transfers of the three axles R_i: $|R_i|=\left|\frac{\Delta F_{zi}}{F_{zi}}\right|<1$, where ΔF_{zi} is lateral load transfer and F_{zi} total axle load. If R_i takes the value ±1 then the inner wheel in the bend lifts off, so the rollover occurs and denoted in [9].

3. ROLL STABILITY ANALYSIS

In this part, the simulation results of the yaw - roll model of a tractor - semi trailer are illustrated in the time domain by using Matlab - simulink software. A cornering scenario is used in this paper as the common disturbance for studying the roll stability [9]. The main symbols and parameters of this model are shown in Table 1[8].

Table 1. Tractor - semi trailer parameters

No	Symbol	Parameters	Tractor	Semi trailer	Unit
1	h_s	height of centre of sprung mass, measured upwards from ground	1.058	1.9	m
2	h_u	height of centre of unsprung mass, measured upwards from ground	0.53	0.53	m
3	I_{xx}	roll moment of inertia of sprung mass, measured about sprung centre of mass	2411	20164	kg.m^2
4	I_{xz}	yaw-roll product of inertia of sprung mass, measured about sprung centre of mass	1390	14577	kg.m^2
5	I_{zz}	yaw moment of inertia of sprung mass, measured about sprung centre of mass	11383	223625	kg.m^2
6	k	suspension roll stiffness	380	684	kN.m/rad
7	k_b	vehicle frame torsional stiffness	629	629	kN.m/rad
8	k_t	tyre roll stiffness	2060	1776	kN.m/rad
9	k_ϕ	vehicle coupling roll stiffness	3000	3000	kN.m/rad
10	l	suspension roll damping rate	4.05	23.9	kN.m.s/rad
11	m_s	sprung mass	4819	30821	kg
12	m_u	unsprung mass	706	800	kg
13	r	height of roll axis, measured upwards from ground	0.621	0.1	m
14	F_c	lateral force in vehicle coupling			N
15	F_y	lateral tyre force			N
16	F_z	vertical tyre force			N
17	δ	steer angle			deg
18	ϕ	absolute roll angle of sprung mass			deg
19	ϕ_t	absolute roll angle of unsprung mass			deg
20	ψ	heading angle			deg

Figure 2 shows the time response of the steering angle, the roll angle of sprung mass, the normalized load transfer at two axles of tractor when the vehicle velocity is considered at 60km/h.

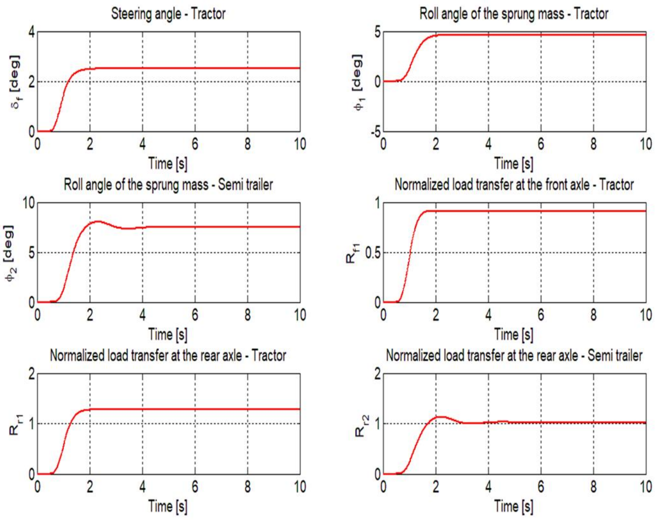

Figure 2. Time responses when vehicle is in a cornering maneuver

We can see that when the velocity is 60km/h, the normalized load transfer of the rear axle of tractor and semi trailer exceed 1, so that the inner wheels lift off and the rollover occurs. In addition, the normalized load transfers at 1.64 seconds in the rear axles of tractor reach 1, this means that the roll stability appears immediately. Of course, these values rely on the steering angle and its velocity.

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Figure 3 shows the time response of the steering angle, the roll angle of sprung mass, the normalized load transfer at two axles of tractor when the vehicle velocity change from 0 to 100km/h.

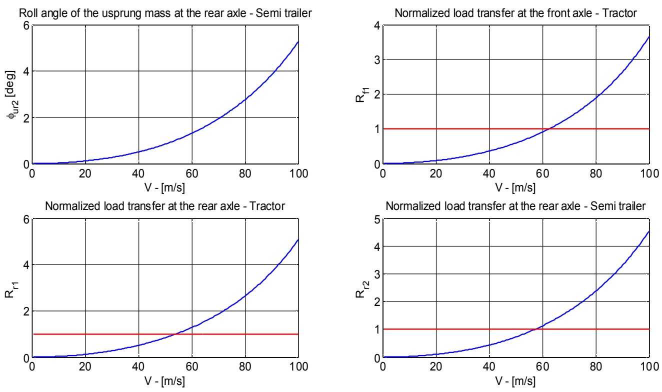

Figure 3. Time responses when vehicle is in a cornering maneuver

We can see that the normalized load transfer equal 1 when the vehicle velocity at front axle of tractor gets value 62.97km/h, while the figure for rear axle of tractor gets 54.62km/h. In addition, when the vehicle velocity at rear axle of semi trailer gets 57.91km/h, the rollover starts occur.

4. CONCLUSIONS

We would like to emphasize that the influence of velocity on the stability of tractor - semi trailer by simulating the model of tractor - semi trailer in two situations: remaining velocity and the change of velocity. From this simulation results, some control methods could be applied in order to improve the stability of this vehicle. The dynamic equations of the tractor - semi trailer in this study are useful for applying the advanced control methods, such as LQR, LVP, Robust control in further studies.

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