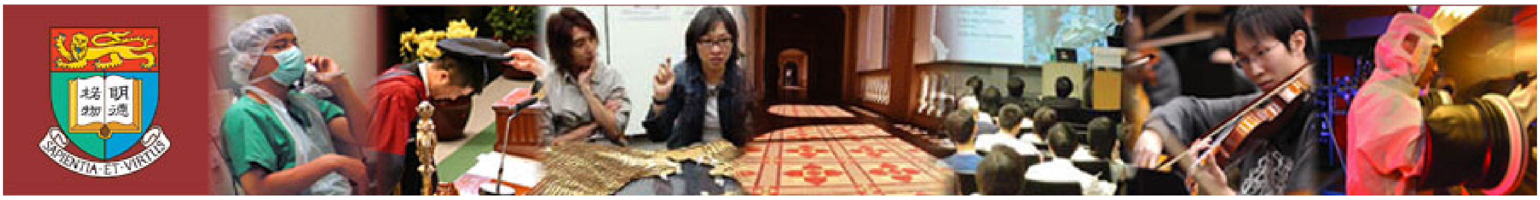

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Analysis and Control of Chaos for Lateral Dynamics of Electric Vehicles

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Abstract — In this paper, the nonlinear dynamic model of the lateral system for electric vehicles (EVs) is proposed. Different from the traditional steering system, a driver's reaction model is introduced and meanwhile the disturbance caused by irregularities of road surface is also considered in this paper. Based on the integrated nonlinear dynamic equations, it shows that the stability of lateral system of EVs is closely related to the heading speed of the vehicle. The lateral system has a Hopf bifurcation when the vehicle heading speed equals a critical value, and then enters into chaos domain along with the increment of the vehicle heading speed. The unstable behaviors may make EVs spin and even turn over, which are quite harmful to the safety of EVs. As for this issue, a control method is proposed and implemented to protect the vehicle from spinning and thus improve the safety of EVs. The computer simulation is utilized in this paper to analyze nonlinear dynamics, as well as to validate the existence of chaotic motions and the feasibility of the control scheme. From the simulation results, it shows that the chaotic motions existing in the EV lateral dynamics can be suppressed by the proposed control method, and thus the corresponding cornering performance and safety are improved.

I. INTRODUCTION

Since the consumption of traditional energies increases greatly and the human living environment becomes worse, studies on electric vehicles (EVs) have been undertaken by different ways [1], such as the management of energy usage [2]-[5], design and control of electric motors (EMs) [6]-[16] and [39]-[42], the type of EVs [17]-[20] and so on, for improving the energy efficiency, driving performance and environment quality. Additionally, nonlinear analysis methods are also applied and exploited for a deep understanding of EV dynamics [27]-[35]. Besides, the safety is also important issue for the development of EVs, which is the prerequisite to put EVs on the market. Being similar to traditional vehicles, a large number of traffic accidents occur when EVs are in the cornering state. Thus, the relationship between the nonlinear behavior of vehicle dynamics and the applied front wheel steering angle becomes a very important issue and thus the study on lateral dynamics of EVs has attracted considerable attentions [21]-[25] as shown in Fig. 1.

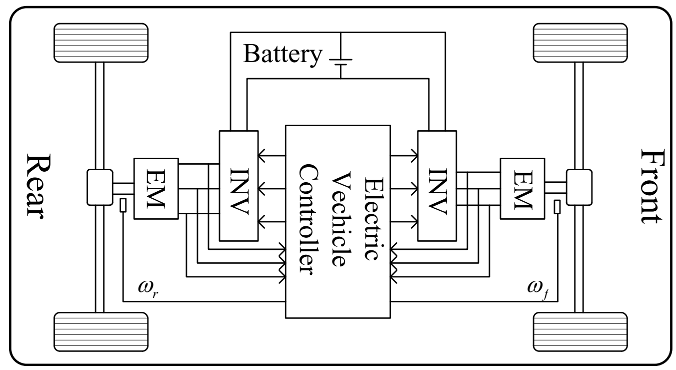

Fig. 1 Overall structure of electric vehicles.

In previous work [26], lateral dynamics are generally studied by establishing mathematical models. By increasing the vehicle heading speed, different dynamical behaviors can be observed. Meanwhile, a bifurcation theory is also applied to analyze complicated dynamical motions and provide detailed explanations on the topology change occurring in solutions of the lateral system mathematical model. By the analysis results, it has shown that the vehicle heading angle will be instable when the heading speed exceeds a critical value. In other words, the stability of lateral dynamics is closely related with the heading velocity of vehicles. When the heading speed beyond the critical value, the vehicle may spin and even turn over. As for this issue, different control methods are proposed and implemented on the steering system to make vehicles escape from unstable domain so as to protect vehicles from spinning and to improve the safety.

However, the influence of driver's operations is not considered in previous work. For example, the driver's reaction time has an important impact on stability properties of vehicles. In order to take into account complicated behaviors occurring in the cornering state, the driver's model is introduced to the lateral system of EVs [36]. The integrated mathematical model is proposed in this paper. Additionally, the disturbance driven by road surface irregularity is also considered in this paper.

This paper is organized as follows. In section II, the nonlinear dynamic model of EVs lateral system is firstly recalled and also the driver's reaction is introduced. Besides, the disturbance driven by irregularities of road surface is also considered in this section. The integrated nonlinear differential equations describing lateral dynamics of EVs are proposed in this paper. Additionally, computer simulations are provided in this section to validate the bifurcation and chaotic motions in the integrated lateral dynamics of EVs. In the section III, retarded linear equations are deduced by linearization at the

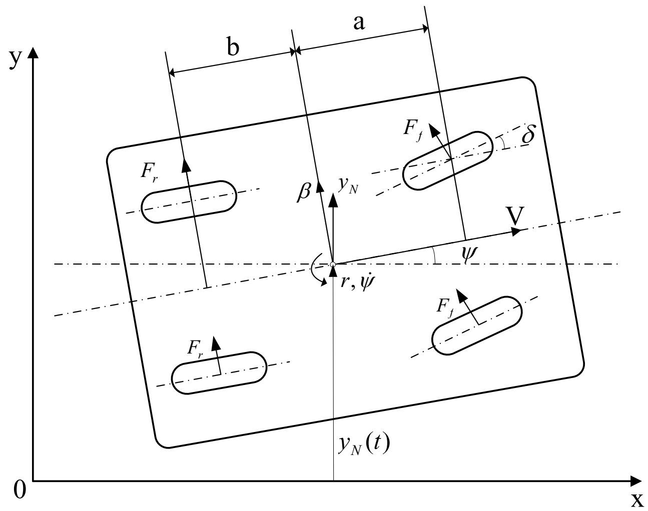

Fig. 2 Lateral system of electric vehicles.

equilibrium point. Based on the linear differential equations, a control method is designed and implemented to suppress chaotic motions and to protect EV from spinning resulted by instability of the lateral system. Meanwhile, simulation results are also given in this section to show the feasibility of the proposed control method. The section IV draws conclusions and discusses about the future research remarks.

II. Nonlinear Lateral Dynamics

In this section, a integrated nonlinear lateral dynamic model of EVs is proposed. In comparison with traditional models, the proposed dynamic model considers the driver's reaction time which will impact the stability of the proposed lateral system of EVs. In the specified driver's reaction time, sub-harmonic, quasi-periodic and chaotic motions will be observed based on different vehicle heading speeds.

A. Mathematical Model

In this paper, we only focus on the lateral dynamics of electric vehicle as shown in Fig. 2, and not consider with the rolling motion resulted by suspension effects. Additionally, we assume that the electric vehicle has a rigid mass m and a forward speed of V along a straight road.

We locate the center of mass of the electric vehicle as the origin of a body-fixed local coordinate system, and thus the equations of motion can be formulated as

$$m(\dot{\beta}+Vr)=2F_f\cos\delta+2F_r, \tag{1}$$

$$I_z\dot{r}=2aF_f\cos\delta-2bF_r, \tag{2}$$

where β is the lateral velocity and r is the yaw velocity of the electric vehicle in the local coordinate system as shown as Fig. 2, I_z is the inertia moment of rotation of the vehicle body with respect to its vertical axis, a and b are the distances between its front and rear axles and the center of gravity of the vehicle, and δ is the resulting steering angle applied on the front wheels. The terms F_f and F_r respectively represent the front and rear lateral forces developed at each wheel of the vehicle by the contact between the tires and the road surface. Using the tire model proposed in [37] and [38], F_f and F_r will be formulated as

$$F_f=-D\sin[C\tan^{-1}\{B(1-E)\alpha_f-E\tan^{-1}(B\alpha_f)\}], \tag{3}$$

$$F_r=-D\sin[C\tan^{-1}\{B(1-E)\alpha_r-E\tan^{-1}(B\alpha_r)\}], \tag{4}$$

where the numerical values of B, C, D and E are obtained experimentally, In this model, α_f and α_r are sideslip angles which can be obtained on the front and rear wheels respectively.

By considering a fixed frame of coordinates, x_N and y_N denote the coordinates of the center of mass G, and ψ is the heading angle of the electric vehicle with respect to the road center line. Then, the following equations are obtained as following

$$\dot{y}_N=\beta\cos\psi+V\sin\psi, \tag{5}$$

$$\dot{\psi}=r. \tag{6}$$

Additionally, the following expressions can be derived from (1) and (2)

$$\dot{\beta}=\frac{2[F_f\cos\delta+F_r]}{m}-v\psi, \tag{7}$$

$$\beta=\frac{(\dot{y}_N-v\sin\psi)}{\cos\psi}, \tag{8}$$

$$\dot{r}=\frac{2[aF_f\cos\delta-bF_r]}{I_z}. \tag{9}$$

By differentiating (5) and (6) with respect to the time t and using relations given in (7), (8) and (9), the equation (10) and (11) can be obtained, which describing the lateral dynamics of the vehicle in the fixed frame of coordinates

$$\ddot{y}_N=\frac{2[F_f\cos\delta+F_r]\cos\psi}{m}-\tan\psi[\dot{y}_N-V\sin\psi]\dot{\psi}, \tag{10}$$

$$\ddot{\psi}=\frac{2[aF_f\cos\delta-bF_r]}{I_z}. \tag{11}$$

With consideration of the driver's reaction time delay and the disturbance resulting from road surface irregularities, we introduce the driver mathematical model as proposed in [36] to replace δ existing in (10) and (11) and then write it in a state variable form as following.

$$\dot{x}_1=x_3, \tag{12}$$

$$\dot{x}_2=x_4, \tag{13}$$

$$\dot{x}_3=\frac{2[F_f\cos\delta(t)+F_r]\cos x_2}{m}-\tan x_2[x_3-V\sin x_2]x_4, \tag{14}$$

$$\dot{x}_4=\frac{2[aF_f\cos\delta(t)-bF_r]}{I_z}, \tag{15}$$

and

$$\delta(t)=-K[x_3(t-T_r)+Lx_1(t-T_r)]+Q\cos(\omega_d t), \tag{16}$$

where y_N is the electric vehicle's lateral displacement with respect to the road center line, and $x=(y_N,\psi,\dot{y}_N,\dot{\psi})^T$ is the state variable vector. In addition, $Q\cos(\omega_d t)$ represents road surface irregularities, in which ω_d represents the disturbance

TABLE I

PARAMETERS OF THE LATERAL SYSTEM MODEL

Symbol and description	Values
m : Mass of the electric vehicle	1640 kg
I_z : Inertia moment of the electric vehicle body	2900 $kg \cdot m^2$
L : Front visibility of the driver	65 m
T_r : Driver's perceptual delay time	0.2 s
a : Distance from the center of gravity to front axis	1.1 m
b : Distance from the center of gravity to rear axis	1.4 m
K : Loop gain in the driver model	0.009 rad/m
L_d : Wavelength of disturbances in front wheels	45 m
Q : Amplitude of the period disturbance	0.04 rad
B : Stiffness factor of the magic formula tire model	3.2
C : Shape factor of the magic formula tire model	2.0
D : Curvature factor of the magic formula tire model	6000
E : Peak factor of the magic formula tire model	-6.25

frequency as $\omega_d = 2\pi V / L_d$ where L_d is a constant disturbance wavelength. The sideslip angles (α_f and α_r) can be formulated as

$$\alpha_f = \tan^{-1}[\frac{\sec\psi(x_1 - V\sin x_4) + ax_2}{V}] - \delta(t), \quad (17)$$

$$\alpha_r = \tan^{-1}[\frac{\sec\psi(x_1 - V\sin x_4) - bx_2}{V}]. \quad (18)$$

B. Nonlinear Analysis

Since we introduce the driver's reaction model and consider the disturbance driven by road surface irregularities, we will study the lateral dynamics of EVs by using equations from (12) to (16) instead of (1) and (2). In addition, coefficients of tire force model in equation (3) and (4) and other corresponding parameters of the proposed lateral model can be referred in TABLE I.

To understand nonlinear characteristics of the EV lateral model, we make computer simulations by MATLAB software. As shown in Fig. 3, we can see that the vehicles heading angle keep periodic oscillations driven by road surface irregularities when the heading velocity $V < V_c$ (around 25 m/s). From the time response as in Fig. 4, it has also shown that the heading angle oscillates with a fixed period when the heading speed $V = 22$ m/s. The result can be also validated by the phase portrait as shown in Fig. 5. However, along with the increment of the heading speed, the vehicle lateral system exhibits some 'complicated' motions (revealed by the dense parts in the bifurcation diagram), such as the limit cycle, sub-harmonic, quasi-periodic and chaotic motions which can be observed when $V > V_c$. From Fig.6, Fig. 7, Fig. 8 and Fig. 9, we can see that the heading angle oscillates with two fixed periods and multi periods when $V = 29$ m/s and $V = 40$ m/s respectively. Therefore, the lateral system enters into instable domain when heading speed exceeds the critical value, and the EV will spin and even roll over. The 'complicated' motions are very harmful for EVs' safety.

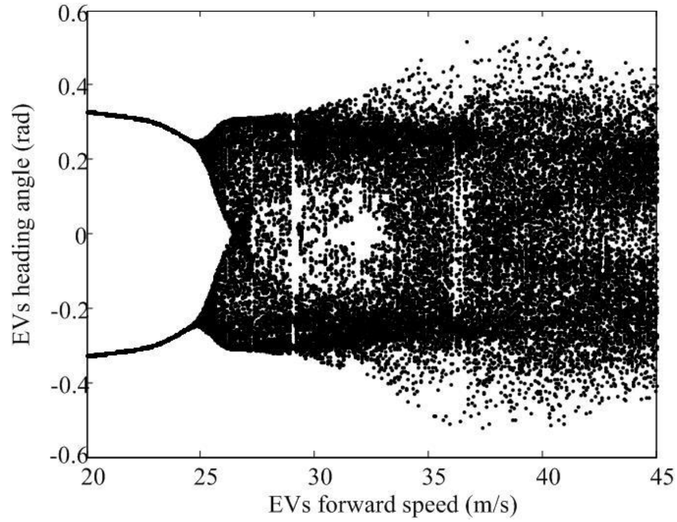

Fig. 3 Bifurcation Diagram.

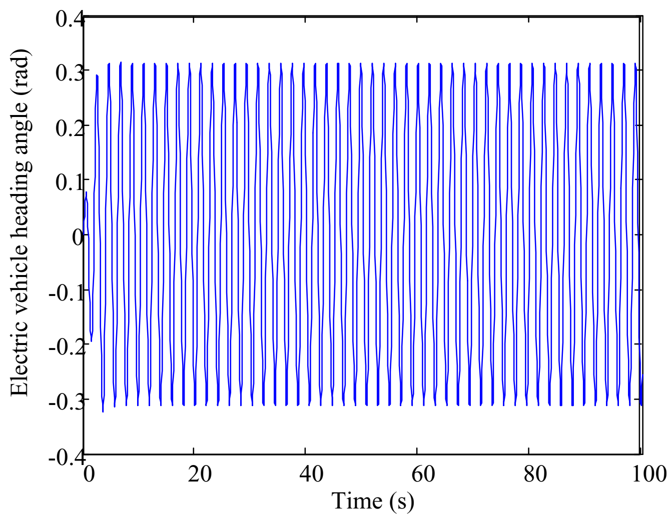

Fig. 4 Time response for V=22 m/s.

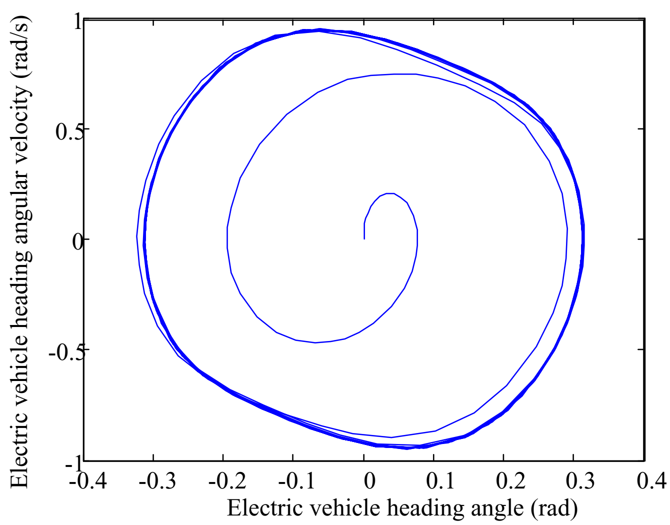

Fig. 5 Phase portrait for V=22 m/s.

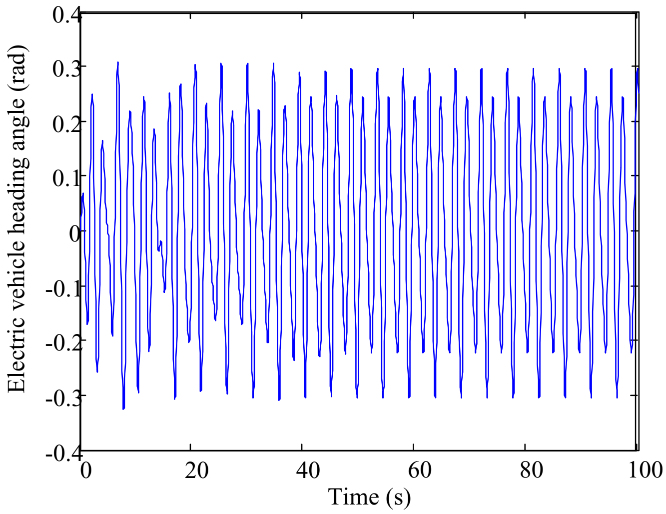

Fig. 6 Time response for V=29 m/s.

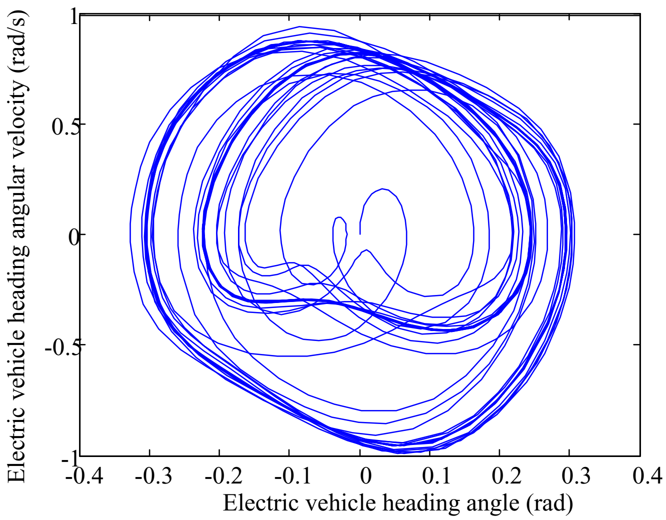

Fig. 7 Phase portrait for V=29 m/s.

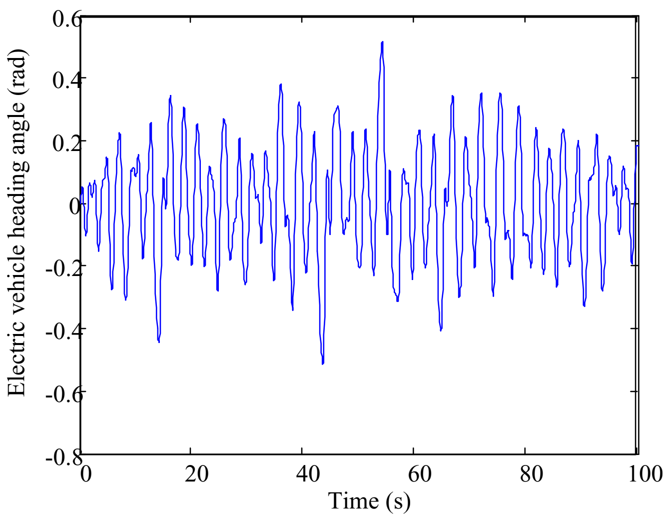

Fig. 8 Time response for V=40 m/s.

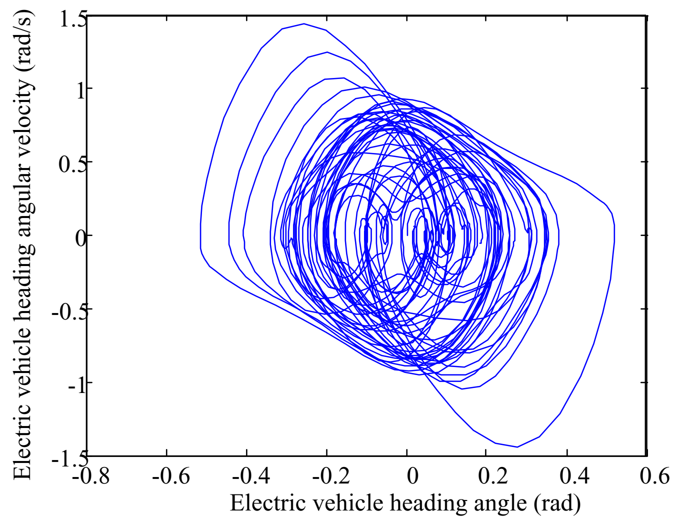

Fig. 9 Phase portrait for V=40 m/s.

III. Control of Chaotic Dynamics

In this section, the lateral system model of EVs will be simplified for the purpose of controller design. The mathematical model, including from (12) to (16) will be linearized around the equilibrium point $[0, 0, 0, 0]^T$. Then, a feedback controller will be implemented to the linearized lateral system in order to suppress the chaotic behaviors when the vehicle heading speed exceeds the critical value.

The linearization model of equations from (12) to (16) can be described in the state-space form as

$$\frac{dx}{dt} = A_0 x + A_1 x(t - T_r), \tag{19}$$

where A_0 and A_1 are the Jacobian matrices of the nonlinear functions as in (6) with respect to variable $x(t)$ and to variable $x(t-T_r)$ respectively, such as

$$A_0 = \frac{\partial f}{\partial x(t)} \text{ and } A_1 = \frac{\partial f}{\partial x(t - T_r)}. \tag{20}$$

The expressions can be obtained for these matrices with respect to the equilibrium point $[0, 0, 0, 0]^T$ as following

$$A_0 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{4DCB}{m} & -\frac{4DCB}{mV} & \frac{2DCB(b-a)}{I_z V} \\ 0 & \frac{2DCB(a-b)}{m} & \frac{2DCB(b-a)}{I_z V} & -\frac{2DCB(a^2+b^2)}{I_z V} \end{bmatrix} \tag{21}$$

and

$$A_1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -\frac{2DCBK}{m} & 0 & -\frac{2DCBKL}{mV} & 0 \\ -\frac{2DCBKa}{I_z} & 0 & -\frac{2DCBaKL}{I_z V} & 0 \end{bmatrix}. \tag{22}$$

In this paper, we applied a simple feedback controller to output control signals based on difference between real value and expected reference value, in order to make the vehicle

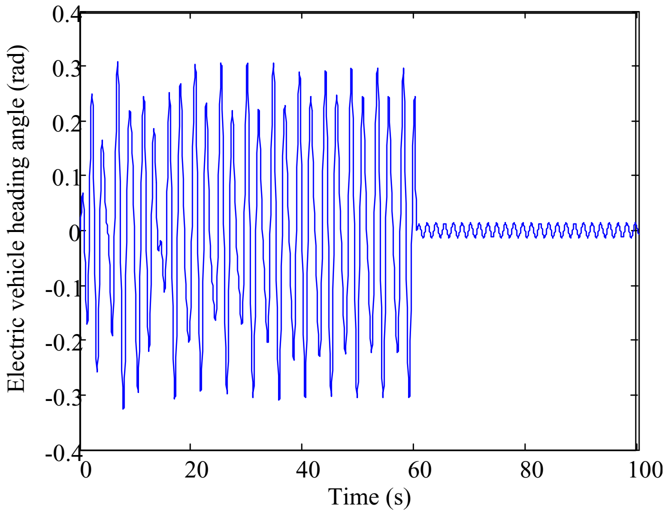

Fig. 10 Time response with feedback control after 60s for V=29 m/s

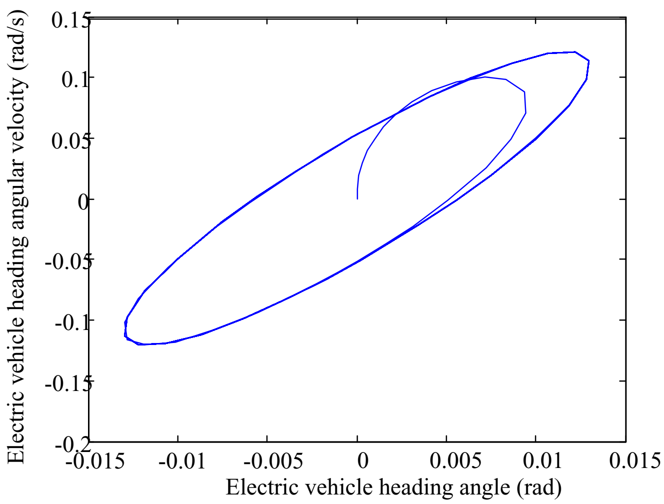

Fig. 11 Phase portrait with feedback control after 60s for V=40 m/s

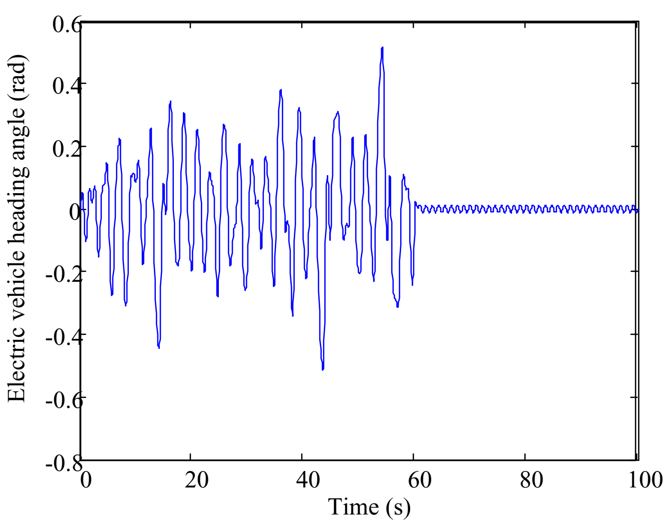

Fig. 12 Time response with feedback control after 60s for V=40 m/s

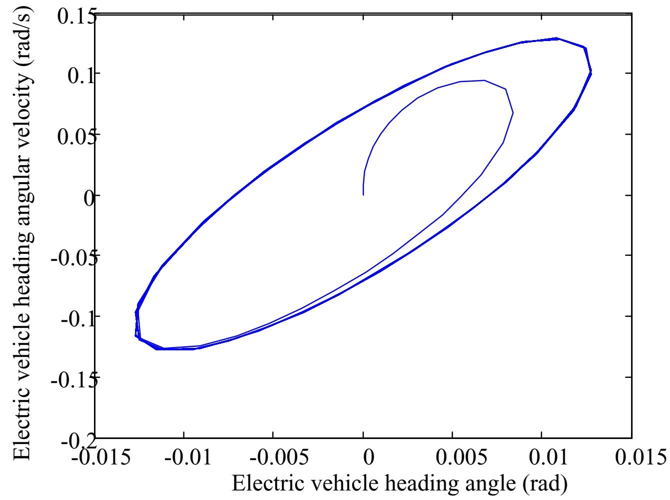

Fig. 13 Phase portrait with feedback control after 60s for V=40 m/s

lateral system escape from chaotic domain and to drive the linearized lateral system to period oscillations.

To validate the feasibility of the control method, we make the computer simulation on MATLAB software by choosing the feedback gain $G = -8.3$ and employing the controller after $t = 60s$. Additionally, we also observe the state of heading angle when vehicle speed equals to 29m/s and 40m/s. As shown in Fig. 10 and Fig. 12, the heading angle of EVs comes back the period oscillations from chaotic behaviors when the feedback controller is applied. Besides, the oscillation peaks caused by the road surface irregularities are also weakened greatly. From phase portraits as shown in Fig. 11 and Fig. 13, it has also indicated that the proposed control method can suppress the chaotic behaviors effectively.

IV. CONCLUSION

This paper works on the lateral system of electric vehicles, and meanwhile the human reaction time and the irregular disturbance due to the road surface are also considered. By nonlinear analysis methods, such as the bifurcation diagram, phase portraits, time responses diagrams and so on, it has shown that the lateral dynamics exhibits ‘complicated’ motions when the forward speed V of EVs exceeds the critical value. The limit cycle, sub-harmonic, quasi-periodic and even chaotic motions can be observed along with the increment of the forward speed V. These instable complicated motions are very dangerous and even make EVs roll over, by which the safety of EVs will be impacted seriously.

In this paper, the feedback control method is applied to the lateral system, aiming to protect EVs from the instability and spinning. By the implementation of this control scheme, it has shown that these ‘complicated’ motions disappear even if the forward speed exceeds the critical value. By comparison of phase portraits and time response diagram at different specified forward speed values, we can also see that lateral dynamics of EVs enter into stable domain and chaotic motions are successfully suppressed. Additionally, computer simulation results also prove the feasibility of the proposed control method. It has shown that the safety performance of EVs has been improved greatly.

ACKNOWLEDGMENT

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