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Complexity and Suppressing Chaos in Automotive Electronic Throttle System

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Keywords：throttle, period-doubling bifurcation, chaos, Lyapunov exponent, state feedback, dither

ABSTRACT

The main objective of this study is to explore the complex nonlinear dynamics and chaos control of an automotive electronic throttle system. The effects of varying the parameter values of an electronic throttle system can be observed in bifurcation diagrams. Various periodic solutions and nonlinear phenomena can be expressed using various numerical methods, such as time responses, phase portraits, Poincaré maps, and frequency spectra. It is shown that electronic throttle systems can undergo a cascade of period-doubling bifurcations prior to the onset of chaos. Estimates of the largest Lyapunov exponent based on synchronization properties reveal the occurrence of chatter vibrations, which is indicative of chaotic motion. In addition, state feedback control and dither signal control are applied to suppress the chaotic behavior of electronic throttle systems. Numerical simulation results demonstrate the effectiveness of these proposed control approaches.

INTRODUCTION

An electronic throttle system adjusts the air inflow into the combustion chamber of the engine, which is a DC-motor-driven valve. Throttle control is an important aspect of engine control. The engine’s power dynamic response is achieved by adjusting the intake air volume. Throttle control is the main method used to adjust engine air intake. Therefore, precise throttle control is vital for improving power dynamics, fuel efficiency, and comfort, as well as reducing emissions (Humaidi and Hameed, 2019); Sun and Jiao, 2020).

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The synthesis of a satisfactory electronic throttle control system is difficult owing to its nonlinear characteristics, such as the strong nonlinear effects of stick-slip friction, springs, and gear backlash (Bai et al., 2016; Yu et al., 2007; Pan et al., 2008). The most important issue in electronic throttle system operation is the improvement in vehicle drivability, fuel economy, and emissions. Nonlinear control in electronic throttle system has been investigated extensively (Zeng and Wan, 2011; Al-samarraie and Abbas, 2012; Bai and Tong, 2014; Wan et al., 2016). An electronic throttle system is typically described by a nonlinear dynamical system of equations, including system parameters. Altering one of these parameters changes the electronic throttle system dynamics that exhibit chaotic, resulting in an unstable engine system. However, the chaotic motion in an electronic throttle system may cause destabilization, thereby resulting in misfires or the incomplete combustion of the engine system. Modern nonlinear theories of bifurcation and chaos are widely adopted in studies of nonlinear systems, and chaos dynamics in electronic throttle systems have been widely investigated (Jin et al., 2008; Bernardo et al., 2009; Yuan et al., 2011; Yang et al., 2012; Jiao et al., 2019; Zhai and Wu, 2020; Ren et al., 2021).

In this study, a variety of numerical methods is applied, including bifurcation diagrams, phase portraits, Poincaré maps, and frequency spectra to explain the rich nonlinear dynamics in an automotive electronic throttle system. Among various parameters, the Lyapunov exponent is the most effective for measuring the sensitivity of a dynamic system, as it pertains to the initial conditions. It can be used to determine whether a system is susceptible to chaotic motion. The algorithms used to compute Lyapunov exponents associated with smooth dynamic systems are well-established (Shimada and Nagashima, 1979; Wolf et al., 1985; Benettin et al., 1980). However, a number of non-smooth dynamic systems possess discontinuities, such as those associated with dry friction, backlash, and saturation; hence, the abovementioned algorithms are not applicable to these systems. Methods for calculating Lyapunov exponents associated with non-smooth dynamic systems have been proposed in several studies (Zhang et al., 2020; Baumann and Leine, 2017; Stefanski, 2000). In this study, we adopted the method developed by Stefanski (2000) to estimate the largest Lyapunov exponent in an electronic throttle system.

Chaotic behaviors in electronic throttle systems are considered undesirable because of the restrictions imposed on the operating ranges of electrical and mechanical devices. In addition, the dynamics of an electronic throttle system become unstable when chaotic motions are exhibited. If instability is not controlled effectively, the engine's operating efficiency will be affected, and the engine system performance will be deteriorated (Yuan et al., 2011; Yang et al., 2012; Jiao et al., 2019; Zhai and Wu, 2020; Ren et al., 2021). Hence, in many engineering applications, control approaches have been developed to convert chaotic motions into periodic orbits or steady states. Since the pioneering work of Ott et al. (1990) pertaining to chaos control, many modified methods and other approaches have been proposed (Ditto et al., 1990; Hunt, 1991; Cai et al., 2002a; Chang and Lue, 2020; Costa and Savi, 2018; Tooranjipour and Vatankhah, 2018; Tacha et al., 2016; Tutsoy and Brown, 2016; Chang, 2020). Additionally, various control algorithms have been presented to control the chaos of electronic throttle systems (Ren et al., 2021; Yuan et al., 2011). Herein, we propose converting chaotic behaviors into periodic motions to improve the performance of system dynamics with electronic throttle system chaotic behaviors. In this study, chaotic motions in an electronic throttle system were inhibited using state feedback control (Cai et al., 2002a; Cai et al., 2002b) and dither signal control (Fun and Tung, 1989; Liaw and Tung, 1998), and simulations were performed to confirm the feasibility and efficacy of the proposed control approaches.

PROBLEM DESCRIPTION AND MODELING OF ELECTRONIC THROTTLE SYSTEM

Based on reference (Zeng and Wan, 2011), a schematic illustration of an electronic throttle control system is shown in Fig. 1, which is a mechatronic device consisting of a DC motor, reduction gears, a return spring, and a throttle valve. The DC motor is an acuter that transmits torque to the throttle shaft to drive the throttle valve for air flow control. In this system, a shaped body duct regulates the relationship between the angular position of the throttle valve and the incoming air flow into the manifold.

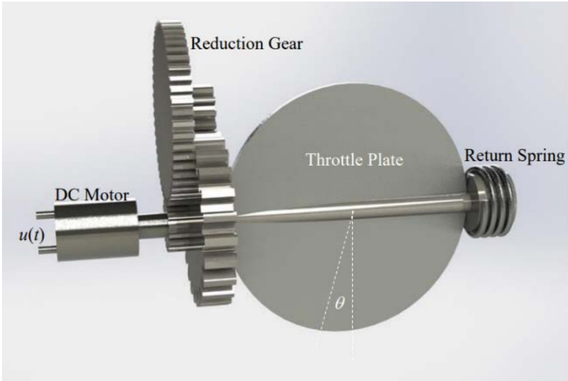

Fig. 1. Schematic of electronic throttle system.

The motor drive torque T_m is proportional to the current and can be expressed as

$$T_m = k_m i(t), \tag{1}$$

where k_m is the motor torque coefficient.

The electrical device is modeled by an induction L, a resistance R, and an electromotive force $E = k_v\omega_m$ induced by the rotation of the motor angle, where k_v is the motor counter electromotive coefficient, and ω_m is the angular velocity of the motor rotor. The equation that expresses the DC armature circuit is as follows:

$$L\frac{di}{dt} + Ri = u(t) - k_v\omega_m(t), \tag{2}$$

where $u(t)$ is the applied voltage.

The spring torque changes with the throttle valve opening. The nonlinear torque of the return spring can be expressed as follows:

$$T_s = k_s(\theta - \theta_0) + D\text{sgn}(\theta - \theta_0), \tag{3}$$

where k_s is the spring coefficient; D is the spring compensation coefficient; θ is the throttle angle; θ_0 is the throttle initial position, which is also known as the limp-home position.

Many types of friction are involved in the motion of the throttle plate, such as viscous and Coulomb friction. The nonlinear friction torque is expressed as

$$T_f = k_d\omega(t) + k_f\text{sgn}(\omega(t)), \tag{4}$$

where k_d is the viscous friction coefficient, k_f is the Coulomb friction coefficient, and ω is the throttle valve angular velocity.

Assuming that the total inertia is J, based on Eqs. (1)-(4), the dynamic equation for the electronic throttle system is expressed as

$$\begin{aligned} J\frac{d\omega}{dt} &= T_m - T_s - T_f \\ &= k_m i - k_s(\theta - \theta_0) - D\text{sgn}(\theta - \theta_0) - \\ &\quad k_d\omega(t) - K_f\text{sgn}(\omega(t)), \end{aligned} \tag{5a}$$

$$\frac{d\theta}{dt} = \omega(t) = N\omega_m(t). \tag{5b}$$

Considering Eqs. (2)-(5) and by introducing state variables $x_1 = \theta - \theta_0$, $x_2 = \omega$, and $x_3 = i$, the state equations for the electronic throttle can be written as follows:

$$\dot{x_1} = x_2, \tag{6a}$$
$$\dot{x_2} = a_{21}x_1 + a_{22}x_2 + a_{23}x_3 - \alpha_1 \mathrm{sgn}(x_1) - \alpha_2 \mathrm{sgn}(x_2), \tag{6b}$$
$$\dot{x_3} = a_{32}x_2 + a_{33}x_3 + b_3 u(t), \tag{6c}$$

where
$a_{21} = -\frac{k_s}{J}$, $a_{22} = -\frac{k_d}{J}$, $a_{23} = \frac{k_m}{J}$, $\alpha_1 = \frac{D}{J}$, $\alpha_2 = \frac{k_f}{J}$, $a_{32} = -\frac{k_v}{NL}$, $a_{33} = -\frac{R}{L}$,
$b_3 = \frac{1}{L}$, $u = A_0 \sin\tilde{\omega}t$

For convenience, we first set $\omega_n = \sqrt{-a_{21}}$, $\Omega = \frac{\tilde{\omega}}{\omega_n}$, and $\tau = \omega_n t$, and then normalize Eqs. (6a-6c) to the following form:

$$\frac{dx_1}{d\tau} = x_2, \tag{7a}$$
$$\frac{dx_2}{d\tau} = x_1 + \frac{a_{22}}{\omega_n}x_2 + \frac{a_{23}}{\omega_n^2}x_3 - \frac{\alpha_1}{\omega_n^2}\mathrm{sgn}(x_1) - \frac{\alpha_2}{\omega_n^2}\mathrm{sgn}(x_2), \tag{7b}$$
$$\frac{dx_3}{d\tau} = \frac{a_{32}}{\omega_n}x_2 + \frac{a_{33}}{\omega_n}x_3 + \frac{b_3}{\omega_n}A_0 \sin(\Omega\tau). \tag{7c}$$

Table 1 (Pan et al., 2008) lists the numerical values for all the parameters used in Eq. (7).

Table 1. Physical parameters of electronic throttle system.

Symbol	Parameter values
a_{21}	-1.6801×10^3
a_{22}	-32.9820
a_{23}	4.2941×10^3
a_{32}	-11.6039
a_{33}	-5.2087×10^2
α_1	4.6139×10^3
α_2	2.1073×10^3
b_3	4.7438×10^2
A_0	3.0

OVERALL CHARACTERISTICS OF ELECTRONIC THROTTLE SYSTEM: SIMULATIONS RESULTS AND DISCUSSIONS

Numerical simulations were performed based on Eq. (7) to clearly understand the overall characteristics of the electronic throttle system. The commercial package DIVPRK of IMSL in FORTRAN subroutines was utilized for mathematical applications to solve ordinary differential equation problems (IMSL, Inc., 1989). Figure 2 presents the resulting bifurcation diagram, which shows that the first period-doubling bifurcation occurred approximately $\Omega = 1.619$ and that a chaotic motion appeared approximately below $\Omega = 1.582$. Figures 3-7 show the various responses exhibited by this system, where each type of response was characterized comprehensively using a phase portrait, a Poincaré map, and a frequency spectrum. The equilibrium point indicated in Eq. (7) was stable at $\Omega > 1.619$, indicating that no chatter vibration occurred. Figures 3(a-c) show period-1 motions. In addition, Figs. 4(a-c) show a cascade of period-doubling bifurcations with new frequency components at $\Omega/2$, $3\Omega/2$, $5\Omega/2$…, which resulted in a series of subharmonic components. Figures 5(a-c) show the first period-four bifurcation, which occurred when Ω was less than 1.588. Subsequently, a cascade of chaos-inducing period-doubling bifurcations appeared as Ω continued to decrease, as shown in Fig. 2, resulting in chatter vibrations that could cause unstable behaviors; consequently, the combustion of the engine would be incomplete and the engine system performance would be deteriorated. In other words, the chaos in an electronic throttle system may cause instability, thereby resulting in misfires or the incomplete combustion of the engine. Two descriptors, the Poincaré map and frequency spectrum, can be utilized to characterize chaotic behavior. The Poincaré map includes an infinite set of points known as strange attractors. Meanwhile, the frequency spectrum of a chaotic motion is a continuous broad spectrum. These two main features, i.e., strange attractors and continuous Fourier spectra are strong indicators of chaos. Figures 6 and 7 show the chaotic behavior in detail.

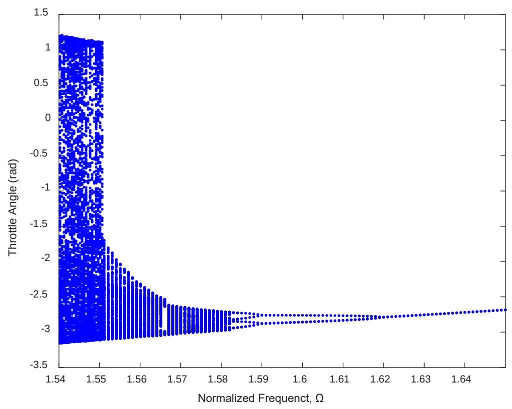

Fig. 2. Bifurcation diagram of throttle valve angle vs. Ω.

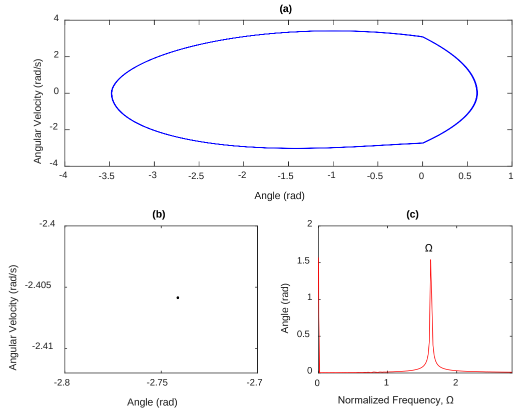

Fig. 3. Period-1 orbit of numerical simulation results for $\Omega = 1.63$:
(a) Phase portrait; (b) Poincaré map; (c) Frequency spectrum.

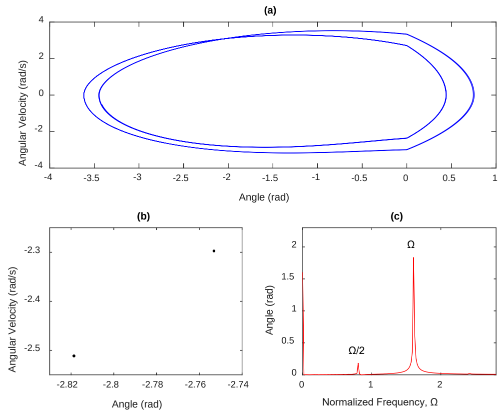

Fig. 4. Period-2 orbit of numerical simulation results for $\Omega = 1.61$:
(a) Phase portrait; (b) Poincaré map; (c) Frequency spectrum.

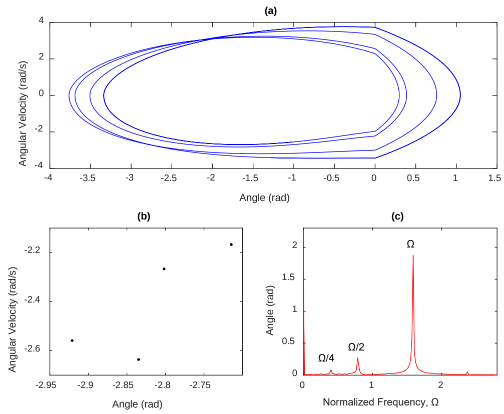

Fig. 5. Period-4 orbit of numerical simulation results $\Omega = 1.584$:
(a) Phase portrait; (b) Poincaré map; (c) Frequency spectrum.

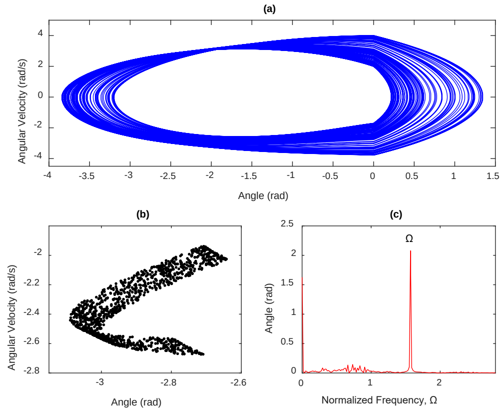

Fig. 6. Chaotic motion of numerical simulation results for $\Omega = 1.57$:
(a) Phase portrait; (b) Poincaré map; (c) Frequency spectrum.

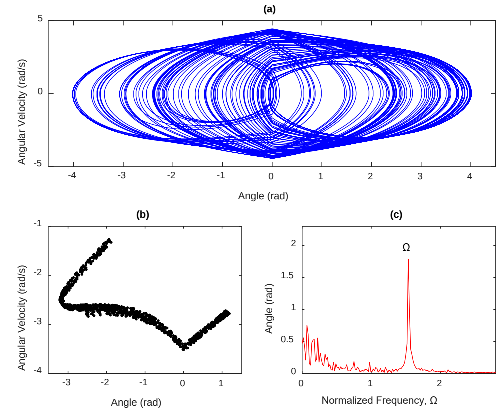

Fig. 7. Chaotic motion of numerical simulation results for $\Omega = 1.542$:
(a) Phase portrait; (b) Poincaré map; (c) Frequency spectrum.

ESTIMATION OF LARGEST LYAPUNOV EXPONENT FOR ANALYZING CHAOS

The largest Lyapunov exponent is a useful indicator for the analysis of chaotic systems. Every dynamic system possesses a spectrum of Lyapunov exponents (λ), which determine the length, area, and volume changes in the phase space. In other words, Lyapunov exponents measure the rate of divergence (or convergence) between two adjacent orbits. Chaos can be identified calculating the largest Lyapunov exponent, which allows one to determine whether nearby trajectories will diverge ($\lambda > 0$) or converge ($\lambda < 0$). Any bounded motion in a system containing at least one positive Lyapunov exponent is defined as chaotic, whereas non-positive Lyapunov exponents indicate periodic motions. Several well-established algorithms can be used to compute the Lyapunov spectrum of smooth dynamic systems (Shimada and Nagashima, 1979; Wolf et al., 1985;

Benettin et al., 1980). However, non-smooth dynamic systems with discontinuities, such as dry friction, backlash, and saturation, do not allow the direct application of such algorithms (Zhang et al., 2020; Baumann and Leine, 2017; Stefanski, 2000). In this study, we estimated the largest Lyapunov exponent to identify the onset of chaotic motion in an electronic throttle system. Stefanski (2000) proposed a simple method for estimating the largest Lyapunov exponent based on properties associated with synchronization. Synchronization controls the response system by accessing the output of the drive system such that the output of the response system asymptotically follows the output of the drive system. This method is described briefly below.

The dynamic system is decomposed into the following two subsystems:

a drive system expressed as

$$\dot{x} = f(x), \tag{8}$$

and a response system expressed as

$$\dot{y} = f(y). \tag{9}$$

Consider a dynamic system comprising two identical *n*-dimensional subsystems, where the response system (9) is combined with the coupling coefficient d, and the drive system (8) remains the same. The first-order differential equation used to describe such a system is as follows:

$$\begin{aligned}\dot{x} &= f(x),\\ \dot{y} &= f(y) + d(x - y).\end{aligned} \tag{10}$$

The condition of synchronization is provided by the following inequality:

$$d > \lambda_{max}. \tag{11}$$

The smallest value of the coupling coefficient d in synchronization d_s is assumed to be equal to the largest Lyapunov exponent, as follows:

$$d_s = \lambda_{max}. \tag{12}$$

Eq. (10) provides an augmented system based on Eq. (7), as follows:

$$\frac{dx_1}{d\tau} = x_2, \tag{13a}$$

$$\frac{dx_2}{d\tau} = x_1 + \frac{a_{22}}{\omega_n} x_2 + \frac{a_{23}}{{\omega_n}^2} x_3 - \frac{\alpha_1}{{\omega_n}^2}\operatorname{sgn}(x_1) - \frac{\alpha_2}{{\omega_n}^2}\operatorname{sgn}(x_2), \tag{13b}$$

$$\frac{dx_3}{d\tau} = \frac{a_{32}}{\omega_n} x_2 + \frac{a_{33}}{\omega_n} x_3 + \frac{b_3}{\omega_n} A_0 \sin(\Omega\tau). \tag{13c}$$

$$\frac{dy_1}{d\tau} = y_2 + d(x_1 - y_1), \tag{13d}$$

$$\frac{dy_2}{d\tau} = y_1 + \frac{a_{22}}{\omega_n} y_2 + \frac{a_{23}}{{\omega_n}^2} y_3 - \frac{\alpha_1}{{\omega_n}^2}\operatorname{sgn}(y_1) - \frac{\alpha_2}{{\omega_n}^2}\operatorname{sgn}(y_2) + d(x_2 - y_2), \tag{13e}$$

$$\frac{dy_3}{d\tau} = \frac{a_{32}}{\omega_n} y_2 + \frac{a_{33}}{\omega_n} y_3 + \frac{b_3}{\omega_n} A_0 \sin(\Omega\tau) + d(x_3 - y_3). \tag{13f}$$

Next, we estimate the largest Lyapunov exponent for the selected parametric values using the method described above. Figure 8 presents the results of the numerical calculations, which show the estimated largest Lyapunov exponents obtained using the synchronization method. At point **P₃**, the sign of the largest Lyapunov exponent changed from negative to positive as the forcing frequency Ω decreased gradually. At points **P₁₋₂**, the largest Lyapunov exponents approached zero, beyond which the system might undergo bifurcation. Nonetheless, the Lyapunov exponent at that point does not indicate the type of bifurcation involved, thereby necessitating the application of the bifurcation diagram shown in Fig. 2. By comparing of Figs. 8 and 2, the occurrences of period-two bifurcation at **P₁** and period-four bifurcation at **P₂** are indicated. All of the largest Lyapunov exponents were positive with regard to the forcing frequency ($\Omega < 1.582$), indicating that the system exhibited chaotic motion. These results provide a better understanding of chatter vibrations in an electronic throttle system.

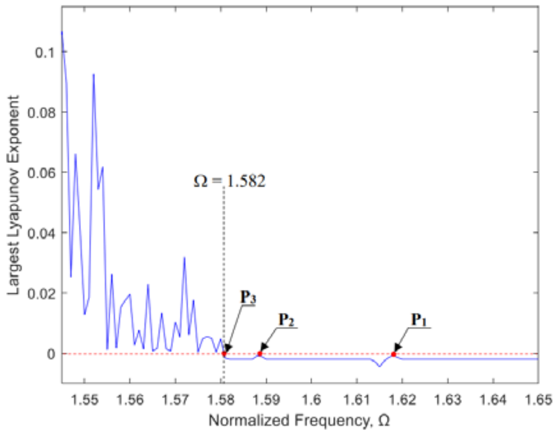

Fig. 8. Evolutions of largest Lyapunov exponent versus Ω.

SUPPRESSING CHAOS IN ELECTRONIC THROTTLE SYSTEM

Analyzing and predicting the behaviors of chaotic systems is beneficial; however, the system must be controlled to maximize its benefits. Improving the performance of a dynamic system or avoiding chaotic motions necessitate periodic motions, which are crucial when specific conditions are involved. This section presents two control methods, i.e., state feedback control (Cai et al., 2002a; Cai et al., 2002b) and dither control (Fun and Tung, 1997; Liaw and Tung, 1998), to suppress chaos in the electronic throttle system used in this study.

State Feedback Control

Cai et al. (2002a; 2002b) proposed a simple and effective method for converting chaos into periodic motions at a steady state using the linear-state feedback of an available system variable. For an *n*-dimensional dynamic system, this method can be expressed as follows:

$$\dot{x} = f(x, t), \tag{14}$$

where $x(t) \in R^n$ is the state vector; $f = (f_1, \ldots, f_i, \ldots, f_n)$, where f_i is a linear or nonlinear function, and f includes at least one nonlinear function. If $f_k(x, t)$ is the key nonlinear function that results in chaotic motion in Eq. (14), then only one term of the state feedback of an available system variable x_m will be added to an equation that includes $f_k(x, t)$, as follows:

$$\dot{x}_k = f_k(x, t) + Kx_m, \quad k, m\{1, 2, \ldots, n\}, \tag{15}$$

where K is the feedback gain, and the other functions maintain their original forms.

State feedback control can be incorporated to Eq. (7) and rewritten as follows:

$$\frac{dx_1}{d\tau} = x_2, \tag{16a}$$

$$\frac{dx_2}{d\tau} = x_1 + \frac{a_{22}}{\omega_n} x_2 + \frac{a_{23}}{{\omega_n}^2} x_3 - \frac{\alpha_1}{{\omega_n}^2} \operatorname{sgn}(x_1) - \frac{\alpha_2}{{\omega_n}^2} \operatorname{sgn}(x_2) + Kx_2, \tag{16b}$$

$$\frac{dx_3}{d\tau} = \frac{a_{32}}{\omega_n} x_2 + \frac{a_{33}}{\omega_n} x_3 + \frac{b_3}{\omega_n} A_0 \sin(\Omega\tau) + Kx_3. \tag{16c}$$

Without state feedback control, Eq. (7) exhibits chaotic behavior under the parameter Ω = 1.542. Considering that the effect of the state feedback control was added to the right-hand side of Eq. (7), by decreasing the feedback gain K from 0 to –0.3, the chaotic behavior disappeared at certain feedback gains. Figure 9 presents the resulting bifurcation diagram, which comprehensively illustrates the dynamic behavior of the controlled electronic throttle system over a range of feedback gains. Chaotic motion appeared when Ω ≥ –0.064, and a stable periodic motion appeared when Ω decreased beyond –0.064. Period-doubling bifurcations appeared when Ω decreased to approximately –0.128 and –0.065. A further decrease in Ω beyond –0.128 resulted in a period-1 motion. The efficacy of the proposed system in controlling chaos was demonstrated by applying a control signal after 60 s, as shown in Fig. 10. Therefore, to suppress the occurrence of chaos, the simple state feedback of an available system variable can be used to disrupt the balance of dynamic behaviors in a chaotic system.

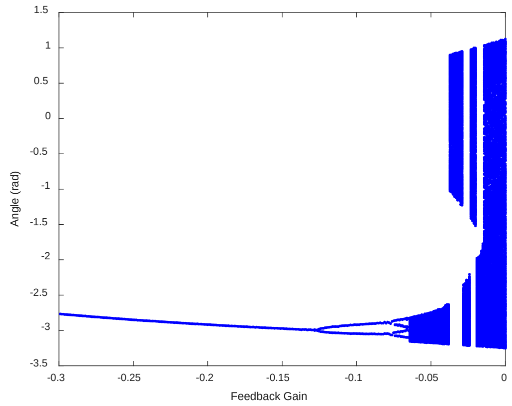

Fig. 9. Bifurcation diagram of throttle valve angle against K for electronic throttle system with state feedback control, where K indicates feedback gain.

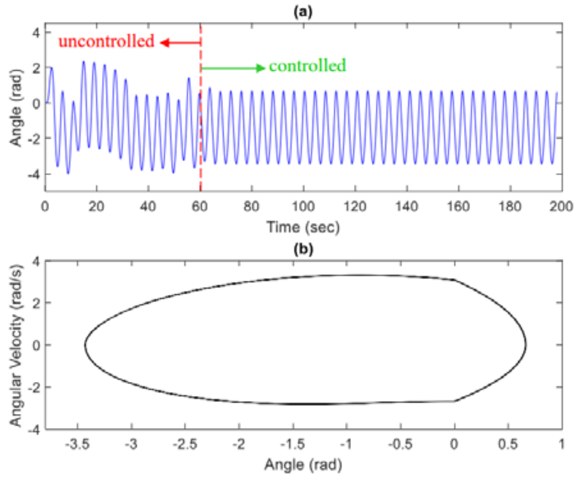

Fig. 10. Transformation of chaotic motion into period-1 orbit for K = –0.2 and Ω =1.542: (a) time responses of controlled system; (b) phase portrait of controlled system. State feedback control signal was introduced after 60 s.

Dither Control

This section describes the process to control motion in a chaotic system by injecting another external input dither signal to modify only the nonlinear terms. A dither signal averages nonlinearity owing to its high frequency and periodic nature. Researchers have developed dither smoothing methods (Fun and Tung, 1997; Liaw and Tung, 1998) to stabilize chaotic systems, and popular dither signals were proposed in Ref. (Cook, 1994). The simplest type of dither signal is the square-wave signal, as shown in Fig. 11; the dither signal assumes constant values W and $-W$ alternately, and each value is maintained for a half-period of $T/2$, where T is much smaller than the time constant of the system. The amplitude W is applied in front of the nonlinearity, $f(.)$. Hence, the effective value of $\bar{n}$ (the output of the nonlinear element) can be written as (Fun and Tung, 1997)

$$\bar{n} = \frac{1}{2}[f(y+W) + f(y-W)]. \tag{17}$$

Consequently, the system equation can be expressed as

$$\dot{y} = \bar{n}. \tag{18}$$

Considering the effect of the dither signal control added to system (7) under the parameter $\Omega = 1.542$, by increasing the amplitude of the square-wave dither signal from $W = 0$ to $W = 0.325$, the dynamics changed from chaotic to periodic motion. Figure 12 shows the evolution of the bifurcation diagram. Next, we considered an electronic throttle system with a coefficient form of friction $\bar{n}$, which is the original nonlinearity f described in Eqs. (3) and (4). Subsequently, we set $W = 0.312$ and plotted the effective nonlinearity $\bar{n}$ and original nonlinearity f, as shown in Figs. 13 and 14, respectively. Figure 15(a) shows the time response of the angle with the amplitude of the square-wave dither signal, $W = 0.315$, injected after 60 s. The chaotic behavior system was transformed into a period-3 orbit. Figure 15(b) illustrates the phase portrait of the controlled system. As shown, the system exhibited chaotic behavior before the dither was introduced, but exhibited a periodic motion subsequently.

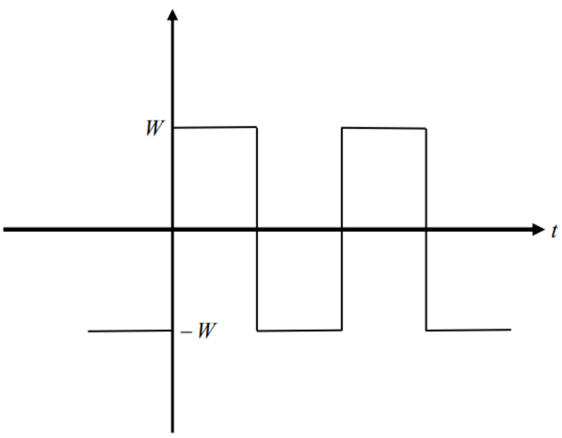

Fig. 11. Square-wave dither signal.

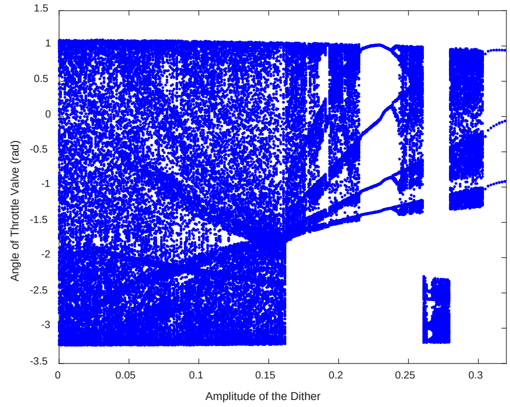

Fig. 12. Bifurcation diagram of throttle valve angle against W for electronic throttle system with square-wave dither, where W represents dither amplitude.

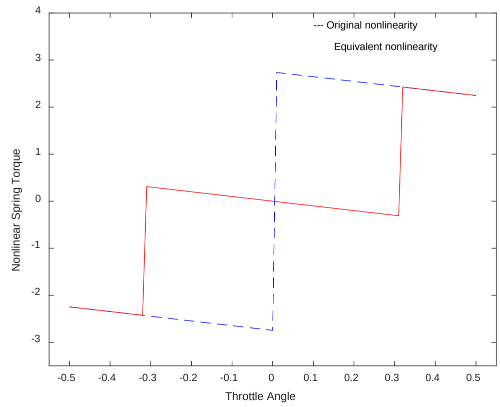

Fig. 13. Equivalent nonlinearity $\bar{n}$ (solid line) expressed in Eq. (17). Original nonlinearity T_s (dashed line) expressed in Eq. (3).

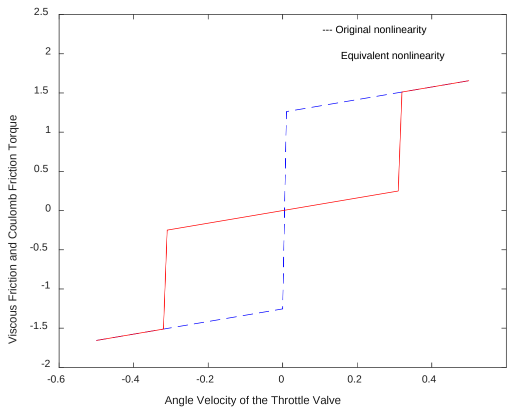

Fig. 14. Equivalent nonlinearity $\bar{n}$ (solid line) expressed in Eq. (17). Original nonlinearity T_f (dashed line) expressed in Eq. (4).

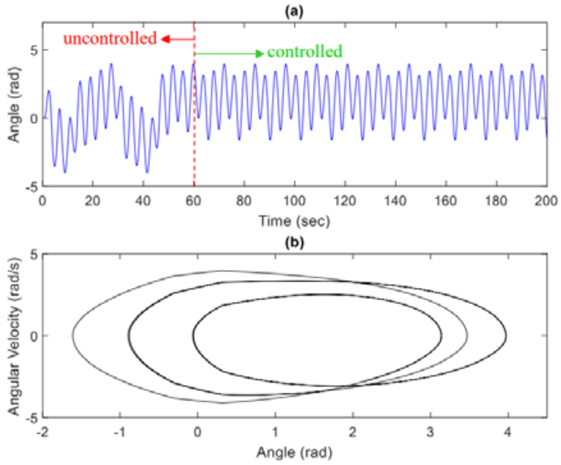

Fig. 15. Square-wave dither signal was injected to control chaotic motion of electronic throttle system for $W = 0.315$ and $\Omega = 1.542$: (a) time responses of controlled system; (b) phase portrait of controlled system. Square dither signal was introduced after 60 s.

CONCLUSIONS

The rich nonlinear dynamics and chaos control of an electronic throttle system were presented herein. The resulting bifurcation diagram showed many nonlinear behaviors, indicating that the electronic throttle system exhibited chaotic motion at a lower Ω; this implies that the system can undergo a cascade of period-doubling bifurcations prior to the onset of chaos. Numerical approaches, including phase portraits, Poincaré maps, and frequency spectra, have been employed to investigate the dynamics of electronic throttle systems. The most effective approach to determine whether an electronic throttle system is in chaotic motion is to use the Lyapunov exponent. The method for estimating the largest Lyapunov exponent of an electronic throttle system involves the use of synchronization properties. The presence of chaotic behavior is generic for certain nonlinearities, parameter ranges, and external forces, and it may need to be avoided or controlled to improve the performance of the electronic throttle system. The state feedback control scheme is simple and effective for chaos suppression, and it can be implemented by adding the feedback of suitable variables to the original system with sufficient control gain to prevent chaos development. Additionally, the square wave of the dither signal can be applied to efficiently convert a chaotic motion into a periodic orbit by injecting a dither signal in front of the nonlinearity of the electronic throttle system. These findings indicate that the proposed system is applicable across a wide range of functions for the design of intelligent vehicles.

Other numerous methods for chaos control have been devised, such as synchronization control, time-delayed feedback control, neuro-fuzzy control, adaptive control and bang-bang control. In this study, state feedback control and dither signal control to control the chaotic behavior of an electronic throttle system. The effectiveness of these proposed chaos control strategies was illustrated through numerical simulations. Overall, it was found that compared with other chaos control methods, the state feedback control and dither signal control techniques are simple and can be easily implemented in chaos suppression. We believe that an in-depth understanding of the dynamics and chaos control of an electronic throttle system will help to advance the development of smart-engine vehicles.

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汽車電子節氣門系統的複雜性和抑制渾沌運動

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摘 要

本文旨在研究探討汽車電子節氣門系統的複雜非線性動態及渾沌控制。因此，利用數值模擬方法，例如：分歧圖、相圖、龐克映相圖、頻譜圖及李亞譜諾指數來探討各種非線性動態行為。研究中發現汽車電子節氣門是經由週期-2 的分歧現象的途徑進入渾沌運動。利用同步性質來估算最大的李亞譜諾指數來驗證系統是否有存在渾沌行為。最後，利用狀態回授及抖振訊號控制法來控制渾沌運動，並經由數值模擬結果來驗證，所提出的控制方式皆能有效地控制汽車電子節氣門系統渾沌行為。