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Controller design by using non-linear control methods for satellite chaotic system

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Abstract In this study, the chaos controllers are improved for the control of satellite attitude motion of the sliding mode control and passive control methods. Sliding mode control has three controller inputs, whereas passive control has only one controller input. The control structure of satellite attitude motion chaotic system was theoretically calculated, and then applied to numerical examples. Both the sliding mode and passive control methods reached to an equilibrium point, but the results of the simulations sliding mode control were better performed than the passive control method. The results show that the method of sliding mode compares very favorable with the passive control method.

Keywords Chaos · Satellite · Sliding mode control (SMC) · Passive control · Equilibrium point

1 Introduction

As space technology progresses, the need for improved satellite systems by better understanding of satellite dynamics has continuously kept attention [1]. Satellite attitude dynamics as nonlinear systems are high dimension [2]. Satellite has got nonlinear attitude dynamics and chaotic behaviors. Since chaotic systems have a non-linear structure, it is difficult to perform control of these systems. Chaotic satellite attitude control problem is also an important procedure [3]. A real satellite attitude control problem subject to chaotic perturbation has been studied using a variety of adaptive control techniques [2].

Any spacecraft in orbit is under the action of several kinds of external disturbance torques as the solar radiation pressure, the gravity gradient torque, the magnetic torque caused by his Earth's magnetic field. These external torques can be considered as perturbations with undesirable effects on the attitude motion of the spacecraft as they may generate chaotic behaviors. The gravity gradient torque is related to one of the most interesting aspects in the attitude dynamics of a spacecraft: the so-called pitch motion [4]. An asymmetric satellite in a closed orbit around the Earth tends to ride with its longest axis vertical due to the effect of the gravity gradient torque [4].

Attitude synchronization is required for modern space mission concepts involving multiple satellites flying information. Disturbances may, however, prevent the satellites from following their reference trajectories precisely. A synchronization control scheme copes with this by controlling the relative errors between the satellites attitudes. The goal is to find control torques that asymptotically drives the satellites attitudes towards the same orientation [5]. On the other hand, stabilizing and synchronization of chaotic orientation motions are two important issues. The synchronization of chaotic satellite systems is handled on the active control approach [1]. Impulsive control was designed to stabilize the chaotic satellite system [6] at the origin [3]. Based on predictive control, two chaotic satellite systems are synchronized [3]. Beletsyk et al. has studied chaotic attitude motion of the satellites in the magnetic field of the earth, in the gravitational field of two centers, or in sunlights flux [7].

Sliding mode control, state feedback control, adaptive control, passive control of nonlinear systems control are most preferred methods. The aim of using a controller is terminated by nonlinear behaviors, and then system variables should be

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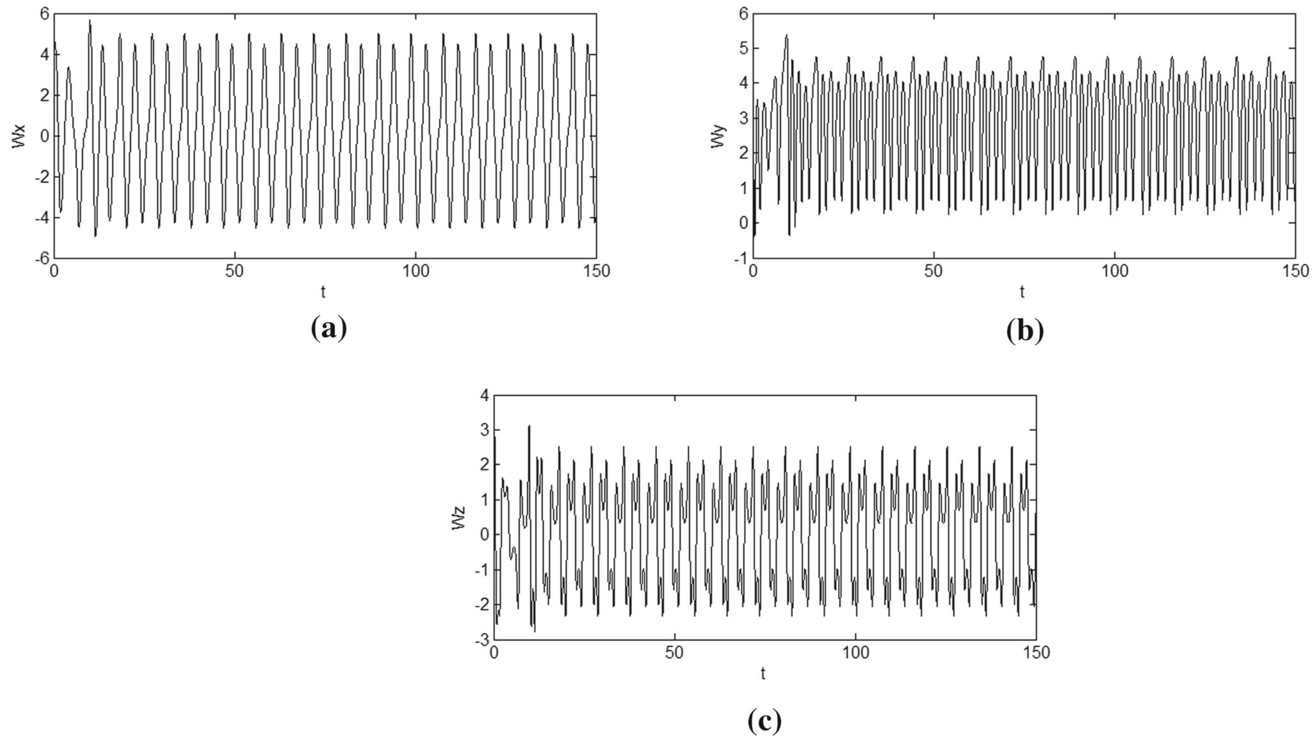


Fig. 1 **a** w_x, **b** w_y and **c** w_z angular velocities in the chaotic satellite system

moved to eigenvalues of zero equilibrium point to stable the system. Sliding mode control method was improved in Russia [8,9] and it has been used for the control of several systems for the last 50 years. One of the application areas of sliding mode control is chaotic systems [10].

Passive controller is another important method used to control the nonlinear systems. Passive control techniques have been applicated to Lorenz [11], Lü [12], Rabinovic [13] and Rucklidge Chaotic Systems [14].

In this study, stabilizing and synchronization of the chaotic orientation motion of the satellite chaotic system are studied with sliding mode control and passive control methods.

This paper is organized as follows: first, a brief definition of a satellited chaos system is given in part 2. Then, the design of the sliding mode controller is given in Sect. 3. Afterward, the design of passive control method is given in Sect. 4, numerical simulation for chaos control by sliding mode control and passive control methods are given. Finally, the conclusion is given in Sect. 5.

2 Chaotic dynamics in satellite attitude

The chaotic dynamic behavior in satellite attitude is defined as in Eq. (1) by Alban and Antonia in 2000 [2,3].

$$\left.\begin{aligned} \dot{w}_x &= I_x^{-1}(I_y - I_z)w_y w_z + I_x^{-1}H_x \\ \dot{w}_y &= I_y^{-1}(I_z - I_x)w_x w_z + I_y^{-1}H_y \\ \dot{w}_z &= I_z^{-1}(I_x - I_y)w_x w_y + I_z^{-1}H_z \end{aligned}\right\} \quad (1)$$

where I_x, I_y and I_z are the principal moments of inertia with respect to the body axes; and, H_x, H_y, H_z is the perturbing torques which can be chosen so as to force the satellite into chaotic motion. The Eq. (1) modified as chosen $I_x = 3$, $I_y = 2$ and $I_z = 1$.

$$\left.\begin{aligned} \dot{w}_x &= \tfrac{1}{3}w_y w_z + \tfrac{1}{3}H_x \\ \dot{w}_y &= -w_x w_z + \tfrac{1}{2}H_y \\ \dot{w}_z &= w_x w_y + H_z \end{aligned}\right\} \quad (2)$$

Using a MATLAB/Simulink model, the time series of the satellite chaotic system of the w_x, w_y, w_z and H_x, H_y, H_z; $w_x w_y$, $w_x w_z$, $w_y w_z$ and $w_x w_y w_z$ and $H_x H_y H_z$ phase portraits were obtained as shown in Figs. 1, 2, 3 and 4 for $w_{x0} = 2$, $w_{y0} = 4.1$, $w_{z0} = 3$, $H_{x0} = H_{y0} = H_{z0} = 0$ and integration time step size 0.01 [2,3].

3 The design of sliding mode controller for satellite chaotic system

Sliding mode controller can be applied to satellite chaotic systems. Stability of satellite chaotic systems was developed using u_x, u_y and u_z controller. The system can be presented with the Eq. (3) given below;

$$\left.\begin{aligned} \dot{w}_x &= \tfrac{1}{3}w_y w_z + \tfrac{1}{3}H_x + u_x \\ \dot{w}_y &= -w_x w_z + \tfrac{1}{2}H_y + u_y \\ \dot{w}_z &= w_x w_y + H_z + u_z \end{aligned}\right\} \quad (3)$$

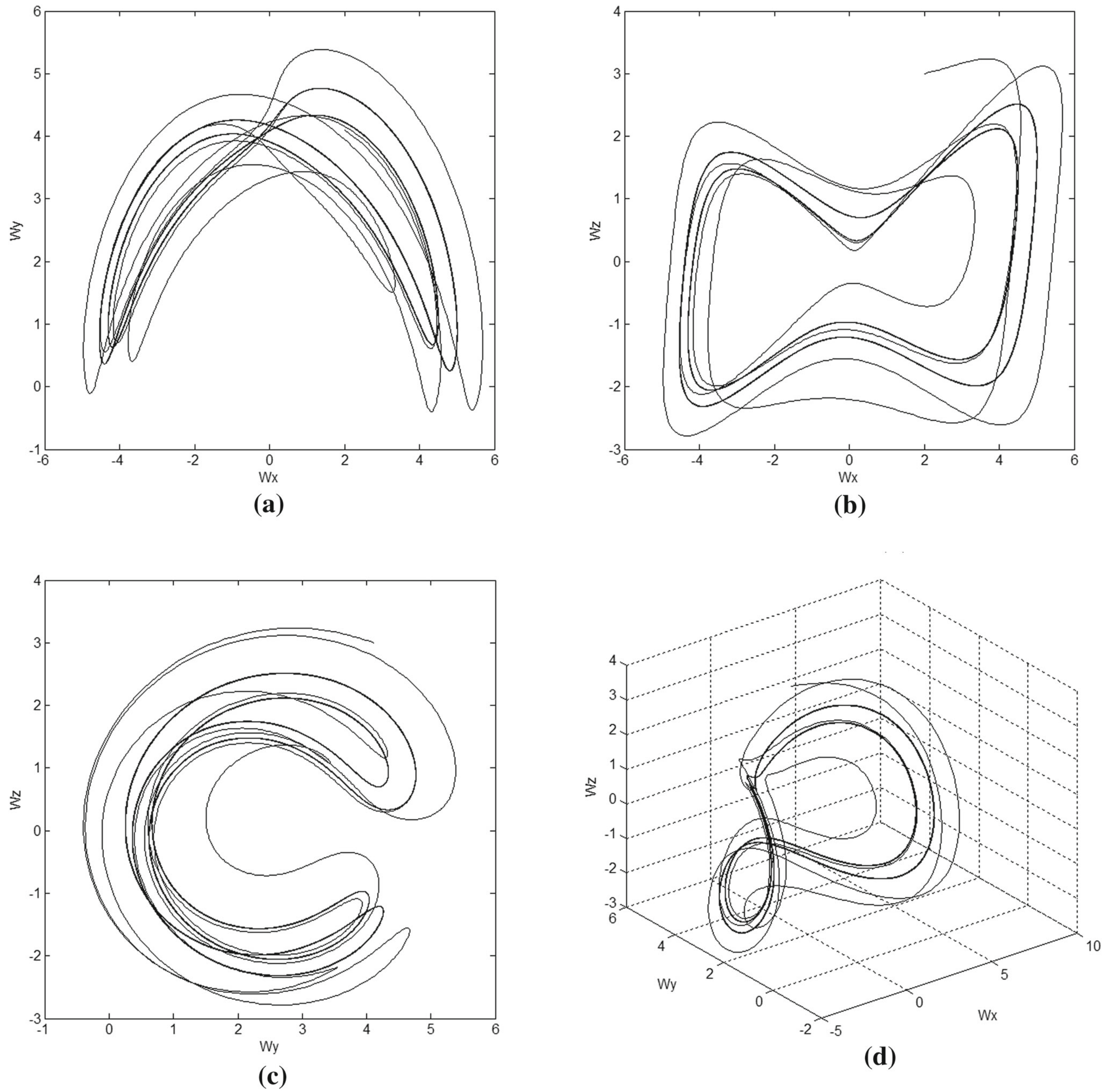


Fig. 2 Phase portraits of the angular velocities in the chaotic satellite system

where u_x, u_y and u_z are the controller inputs.

The choice of reaching and sliding surface is important for the design of sliding mode control. After the selection of a sliding surface from Eq. (4), following equations can be written:

$$s = \dot{e} + \lambda e \tag{4}$$

$$\dot{s} = \ddot{e} + \lambda \dot{e} \tag{5}$$

The trajectory error state could be chosen as $e_x = w_{x_r} - w_x$, $e_y = w_{y_r} - w_y$ and $e_z = w_{z_r} - w_z$, where w_{x_r}, w_{y_r} and w_{z_r} are constants, so $\dot{w}_{x_r} = \dot{w}_{y_r} = \dot{w}_{z_r} = \ddot{w}_{x_r} = \ddot{w}_{y_r} = \ddot{w}_{z_r} = 0$.

$\dot{w}_{x_r}$ and $\ddot{w}_{x_r}$ are obtained as, $\dot{e}_x = \dot{w}_{x_r} - \dot{w}_x = 0 - \dot{w}_x = -\dot{w}_x$ and $\ddot{e}_x = \ddot{w}_{x_r} - \ddot{w}_x = 0 - \ddot{w}_x = -\ddot{w}_x$.

$\dot{w}_{y_r}$ and $\ddot{w}_{y_r}$ are obtained as, $\dot{e}_y = \dot{w}_{y_r} - \dot{w}_y = 0 - \dot{w}_y = -\dot{w}_y$ and $\ddot{e}_y = \ddot{w}_{y_r} - \ddot{w}_y = 0 - \ddot{w}_y = -\ddot{w}_y$.

$\dot{w}_{z_r}$ and $\ddot{w}_{z_r}$ are obtained as, $\dot{e}_z = \dot{w}_{z_r} - \dot{w}_z = 0 - \dot{w}_z = -\dot{w}_z$ and $\ddot{e}_z = \ddot{w}_{z_r} - \ddot{w}_z = 0 - \ddot{w}_z = -\ddot{w}_z$.

$$\text{sign(s)} = \begin{cases} 1, & \text{s} > 0 \\ 0, & \text{s} = 0 \\ -1, & \text{s} < 0 \end{cases} \tag{6}$$

$$\dot{s} = -\rho.\text{sign(s)} \tag{7}$$

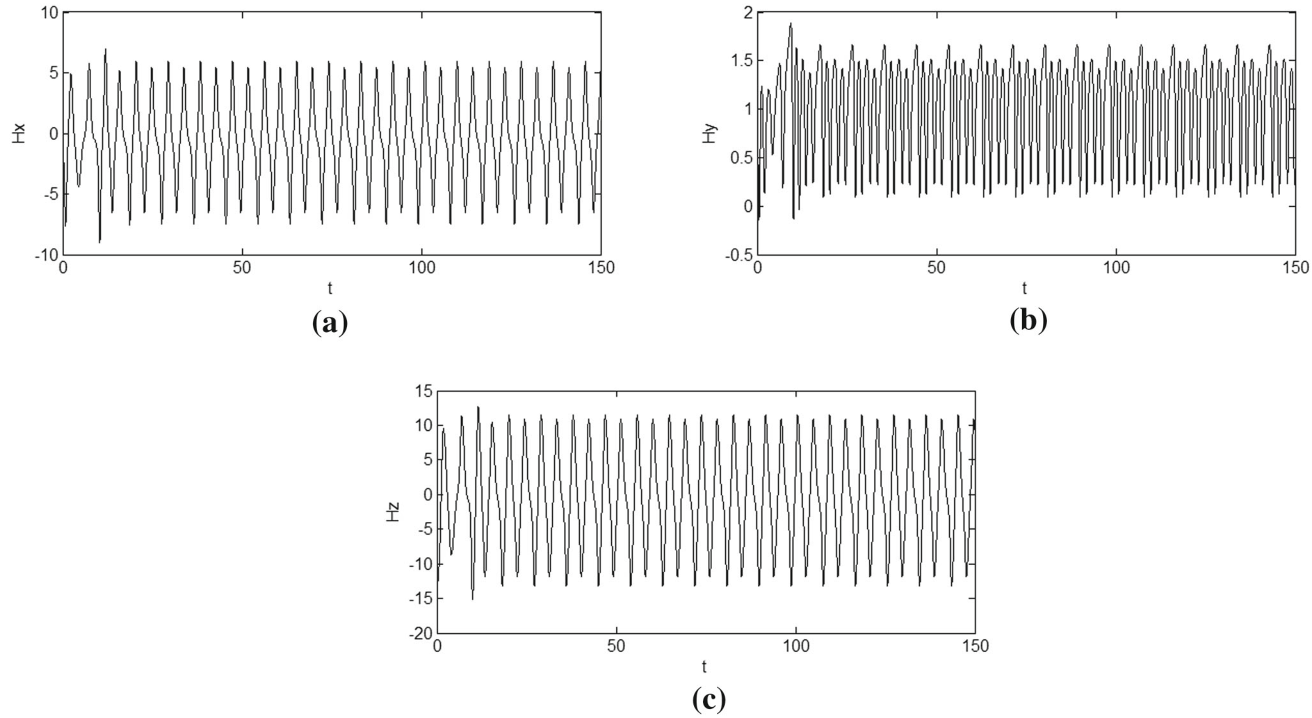


Fig. 3 **a** H_x, **b** H_y and **c** H_z the perturbing torques in the chaotic satellite system

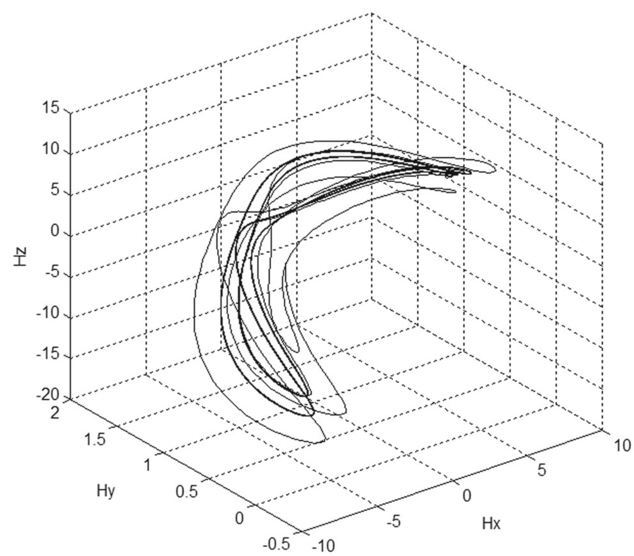


Fig. 4 Phase portrait of the perturbing torques

After a proportional reachability rule like Eq. (7) is chosen, following equations can be written.

$$\left.\begin{aligned} &\dot{s} = \ddot{e} + \lambda\dot{e} = \ddot{w}_{y_r} - \ddot{w}_y + \lambda\left(\dot{w}_{y_r} - \dot{w}_y\right) = -\rho.\,\text{sign(s)} \\ &-\ddot{w}_y - \lambda\dot{w}_y = -\rho.\text{sign(s)} \\ &\dot{w}_{y_{new}} = \dot{w}_y + u_y \\ &-\ddot{w}_y - \lambda\dot{w}_y - \lambda u_y = -\rho.\text{sign(s)} \end{aligned}\right\} \tag{8}$$

The control input signal is obtained as Eq. (9) given below:

$$u_y = -\frac{\ddot{w}_y}{\lambda} - \dot{w}_y + \frac{\rho.\text{sign(s)}}{\lambda} \tag{9}$$

The other control input signals are obtained as Eqs. (10) and (11), given below:

$$u_x = -\frac{\ddot{w}_x}{\lambda} - \dot{w}_x + \frac{\rho.\text{sign(s)}}{\lambda} \tag{10}$$

$$u_z = -\frac{\ddot{w}_z}{\lambda} - \dot{w}_z + \frac{\rho.\text{sign(s)}}{\lambda} \tag{11}$$

In control procedures, stability analysis is important to evaluate the design of nonlinear controller [15]. By using the Lyapunov 2nd method, it is possible to investigate the stability of linear or non-linear systems without knowing the solution in the time domain. Such as, n to be constant, if $\lim_{t\to\infty} y(t) = n$ is provided then the systems is said to be stable [16].

4 Passive control method

Passive control techniques have been quite important techniques in the modern control. Nonlinear system was illustrated by Eq. (12). $u(t)$ and $y(t)$ are the input and output vectors, respectively. $f(x)$ and $g(x)$ are smooth vector fields. Moreover, $h(x)$ is a smooth mapping. Nonlinear system can

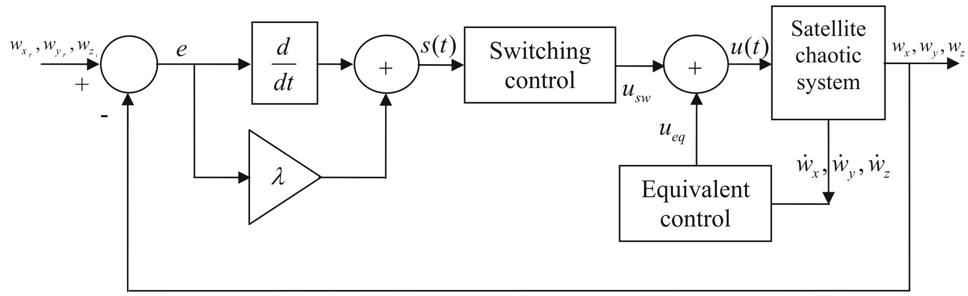


Fig. 5 The sliding mode control model for satellite chaos system

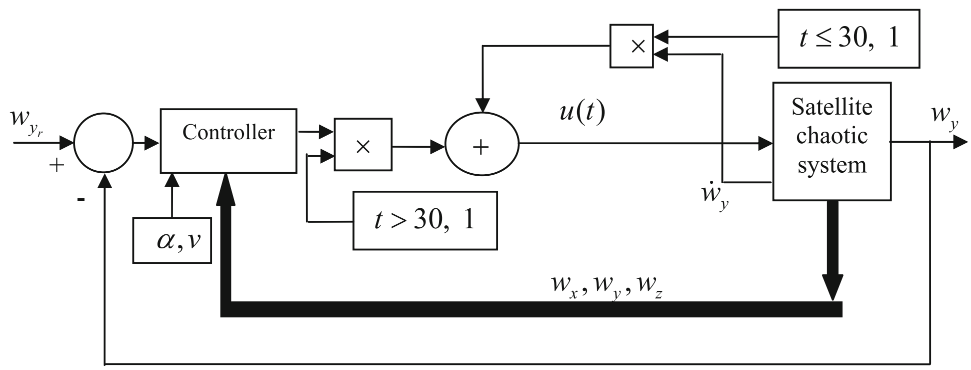


Fig. 6 The passive control model developed for satellite chaotic system

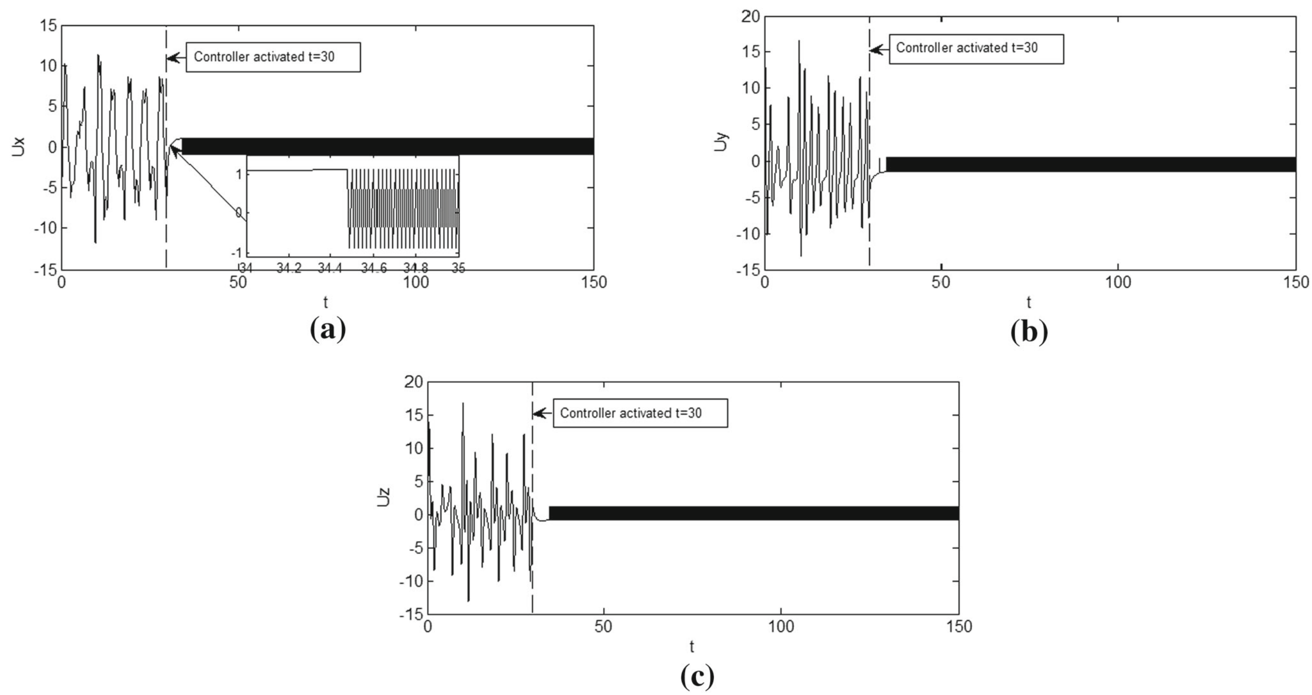


Fig. 7 Control input signals, **a** u_x, **b** u_y and **c** u_z for sliding mode control

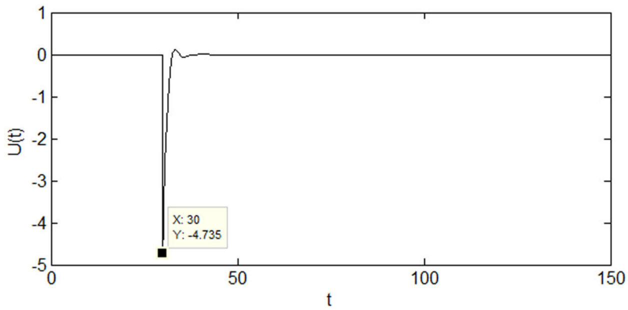


Fig. 8 Control input signal for passive control

be described as [13];

$$\left.\begin{aligned} \dot{x} &= f(x) + g(x) \cdot u(t) \\ y &= h(x) \end{aligned}\right\} \tag{12}$$

Equation (12) modifies the system equation to:

$$\left.\begin{aligned} \dot{z} &= f_0(z) + p(z, y) \cdot y(t) \\ \dot{y} &= b(z, y) + a(z, y) \cdot u(t) \end{aligned}\right\} \tag{13}$$

where $a(z, y)$ is nonsingular matrix for any (z, y) [13]. Let a system state function $V(x)$ called storage function for Eq. (14) and $W(x)$ called Lyapunov function [17]. According to the passive control method, the controlled system (given Eq. 13) can be equivalent to a passive system and globally asymptotically stabilized at its zero equilibrium point. Therefore, passive controller is obtained as follows [14]:

$$u(t) = a(z, y)^{-1} \cdot \times \left[-b^T(z, y) - \frac{\partial W(z)}{\partial z} \cdot p(z, y) - \alpha \cdot y + v \right] \tag{14}$$

5 Numerical simulation

Sliding mode controller gains have been selected $\lambda = 3$, $\rho = 0.01$ with the initial conditions $w_{x0} = 2$, $w_{y0} = 4.1$ and $w_{z0} = 3$, and $H_{x0} = H_{y0} = H_{z0} = 0$. The controllers are activated $t = 30$ s in all simulations [2,3]. The principal moments of inertia have taken $I_x = 3$, $I_y = 2$ and $I_z = 1$, and (ϕ, θ, φ) are estimated to be $\{-0.0077, -0.0077, -0/7509\}$ [2,3], and the perturbing torques are defined by;

$$\left.\begin{aligned} H_x &= (-1.2) \cdot w_x + \tfrac{\sqrt{6}}{2} \cdot w_z + \cos\theta \sin\varphi \\ H_y &= (0.35) \cdot w_y + \cos\phi \sin\theta \\ H_z &= -\sqrt{6} \cdot w_x - 0.4 \cdot w_z + \cos\varphi \sin\phi \end{aligned}\right\} \tag{15}$$

These torques are chosen to be sufficiently large to induce the satellite into chaotic motion [2,3]. $\ddot{w}_x$, $\ddot{w}_y$ and $\ddot{w}_z$ are calculated as $\ddot{w}_x = -0.4$, $\ddot{w}_y = 0.175$ and $\ddot{w}_z = -0.4$ using Eqs. (2) and (15) combined. Controller input signals

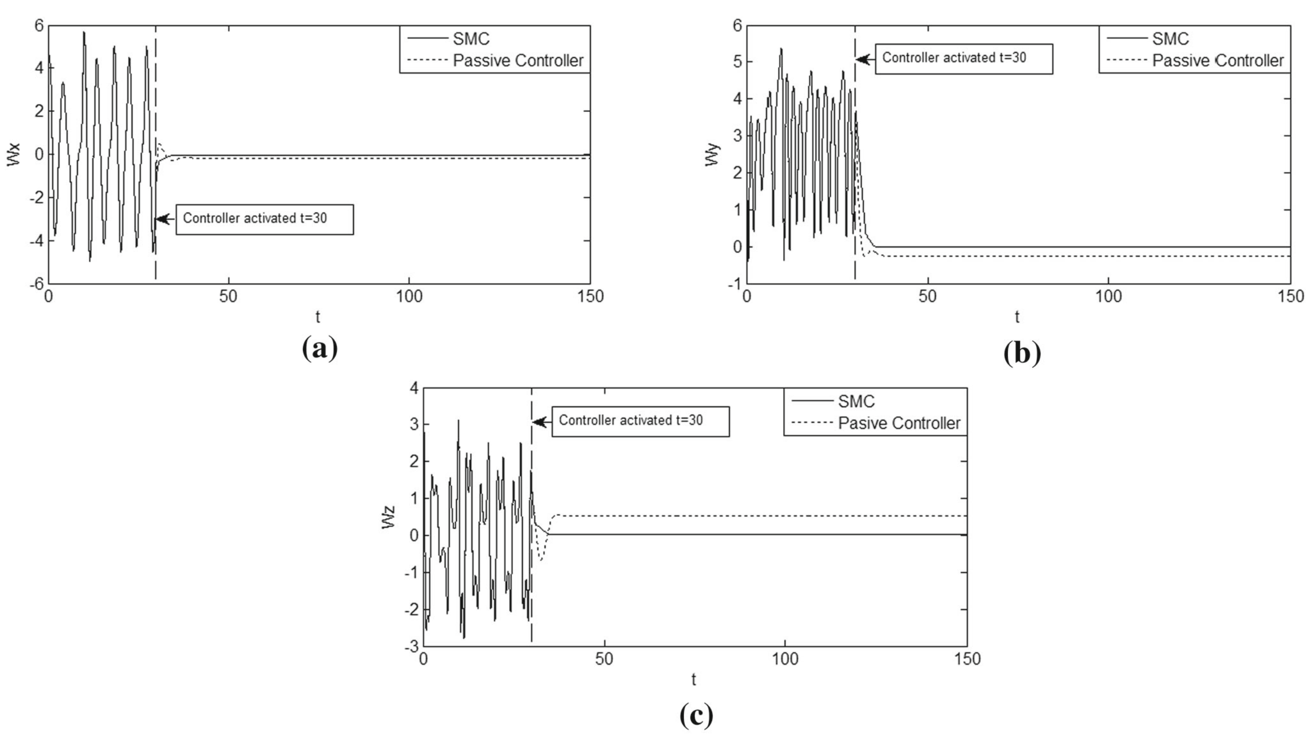


Fig. 9 Time trace of w_x, w_y and w_z controller activated $t = 30$

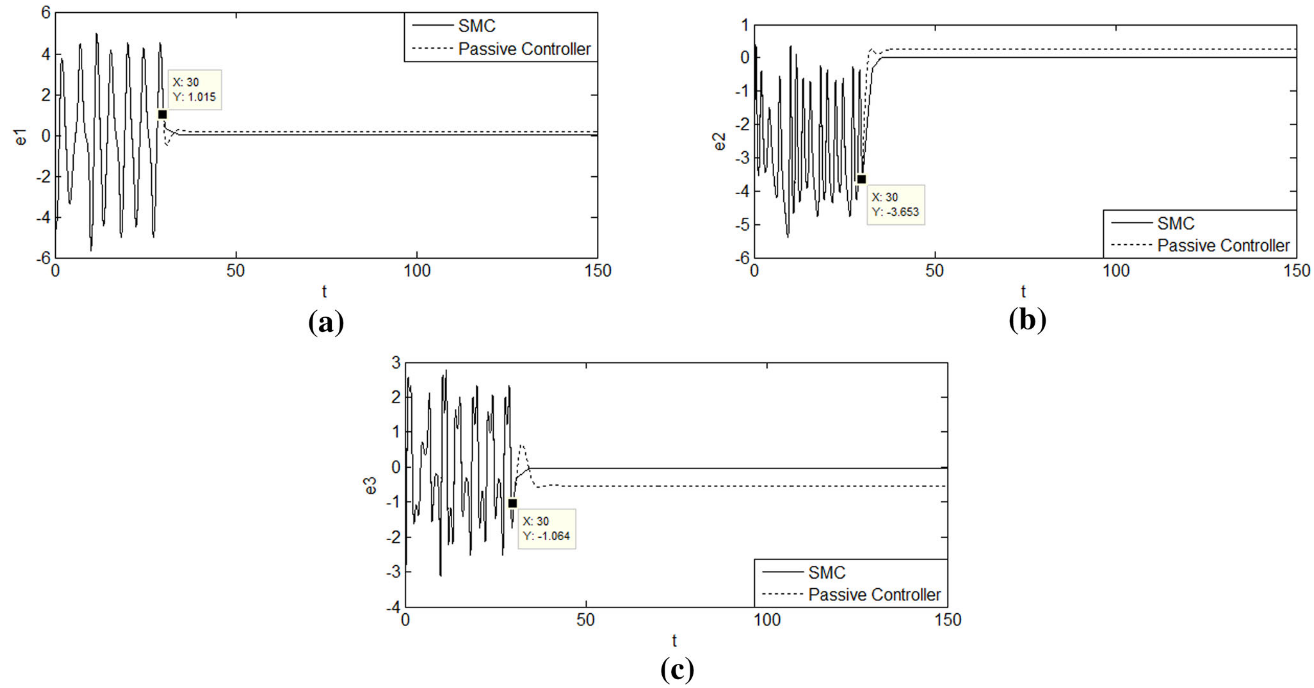


Fig. 10 Synchronization errors of the satellites; **a** e_1, **b** e_2 and **c** e_3 time trace of w_x, w_y and w_z controller activated $t = 30$

Table 1 Performance indices of the controllers

Applied controllers (run time 5s)		**IAE** IAE $= \int \lvert e(t)\rvert \mathrm{d}t$	**ISE** ISE $= \int e^2(t)\mathrm{d}t$	**ITEA** ITEA $= \int t\lvert e(t)\rvert \mathrm{d}t$	**ISCI** ISCI $= \int u^2(t)\mathrm{d}t$
Sliding mode control	w_x	1.050	0.459	32.71	7.550
	w_y	5.729	13.18	178.3	15.71
	w_z	1.096	0.506	34.14	4.371
Passive control	w_x	1.254	0.483	40.40	–
	w_y	2.810	4.925	87.15	10.03
	w_z	2.067	1.154	66.16	–

are defined by;

$$\left.\begin{array}{l} u_x = \frac{0.4}{\lambda} - \frac{1}{3} \cdot (w_y \cdot w_z + H_x) + \frac{\rho.\mathrm{sign(s)}}{\lambda} \\ u_y = -\frac{0.175}{\lambda} + w_x \cdot w_z - \frac{1}{2} \cdot H_y + \frac{\rho.\mathrm{sign(s)}}{\lambda} \\ u_z = \frac{0.4}{\lambda} - w_x \cdot w_y - H_z + \frac{\rho.\mathrm{sign(s)}}{\lambda} \end{array}\right\} \tag{16}$$

A proposed control model for the satellite chaos system is shown in Fig. 5. The control law comprises two parts, the equivalent control $u_{\mathrm{eq}}(t)$ and switching control $u_{\mathrm{sw}}(t)$, as shown in this equation:

$$u(t) = u_{\mathrm{eq}}(t) + u_{\mathrm{sw}}(t) \tag{17}$$

The control of the satellite chaotic system was developed using passive control theory. The control model given by,

$$\left.\begin{array}{l} \dot{w}_x = \frac{1}{3} \cdot w_y \cdot w_z + \frac{1}{3} \cdot H_x \\ \dot{w}_y = -w_x \cdot w_z + \frac{1}{2} H_y + u \\ \dot{w}_z = w_x \cdot w_y + H_z \end{array}\right\} \tag{18}$$

where u is the controller to be designed, suppose that $z_1 = w_x$, $z_2 = w_z$ and w_y is to be output of the system. The system can be expressed by,

$$\left.\begin{array}{l} \dot{z}_1 = \frac{1}{3} y \cdot z_2 + \frac{1}{3} \cdot (-1.2) \cdot z_1 + \frac{1}{3} \cdot \frac{\sqrt{6}}{2} \cdot z_2 + \frac{1}{3} \cdot \cos(\theta) \cdot \sin(\varphi) \\ \dot{z}_2 = z_1 \cdot y - \sqrt{6} \cdot z_1 \text{-} 0.4 \cdot z_2 + \frac{1}{3} \cdot \cos(\varphi) \cdot \sin(\phi) \\ \dot{y} = -z_1 \cdot z_2 + \frac{1}{2} \cdot (0.35) \cdot y + \frac{1}{2} \cdot \cos(\phi) \cdot \sin(\theta) \ + u \end{array}\right\} \tag{19}$$

Equation (19) is a modified form direction of Eq. (14)

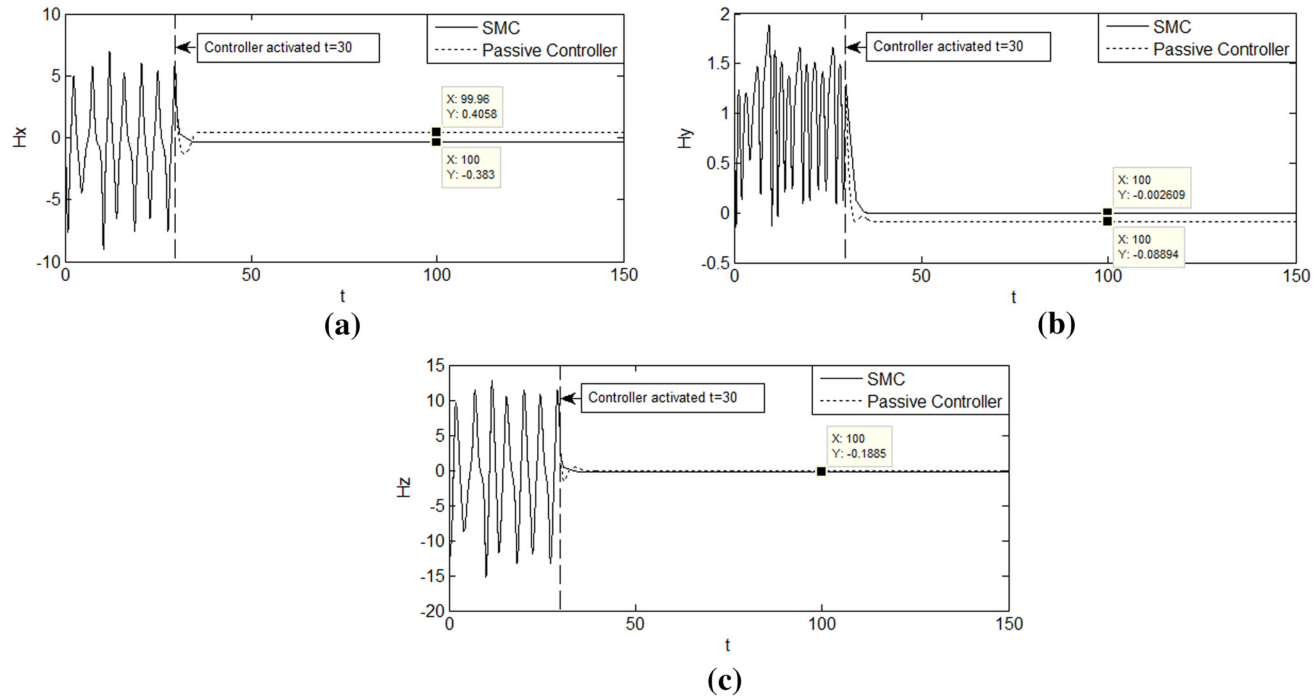


Fig. 11 Time trace of **a** H_x, **b** H_y and **c** H_z controller activated $t = 30$

$$
\left.\begin{aligned}
\dot{z} &= \begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} -0.4 & \frac{\sqrt{6}}{6} \\ -\sqrt{6} & -0.4 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}}_{f_0(z)} + \underbrace{\begin{bmatrix} \frac{1}{3} \cdot z_2 \\ z_1 \end{bmatrix}}_{p(z,y)} \cdot y \\
\dot{y} &= \underbrace{-z_1 \cdot z_2 + 0.175 \cdot y}_{b(z,y)} + \underbrace{u}_{a(z,y)}
\end{aligned}\right\} \tag{20}
$$

Choose the following storage function,

$$
v(z, y) = W(z) + \frac{1}{2} y^2 \tag{21}
$$

where

$$
W(z) = \frac{1}{2}(z_1^2 + z_2^2) \tag{22}
$$

is the Lyapunov function of $f_0(z)$, and $W(0) = 0$. According to Eq. (22) derivative of $W(z)$,

$$
\left.\begin{aligned}
\dot{W}(z) &= \tfrac{\partial W(z)}{dt} = \tfrac{\partial W(z)}{dz} f_0(z) = \begin{bmatrix} z_1 & z_2 \end{bmatrix} \begin{bmatrix} -0.4 & \frac{\sqrt{6}}{6} \\ -\sqrt{6} & -0.4 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \\
&= -0.4 \cdot z_1^2 - \sqrt{6} \cdot z_1 \cdot z_2 + \tfrac{\sqrt{6}}{6} \cdot z_1 \cdot z_2 - 0.4 \cdot z_2^2
\end{aligned}\right\} \tag{23}
$$

According to Eq. (12), the output of the passive control system is $u(t)$ by,

$$
u(t) = z_1 \cdot z_1 - \frac{1}{2} \cdot H_y - z_1 - \alpha \cdot y + v \tag{24}
$$

According to $z_1 = w_x,\ z_2 = w_z$ and $y = w_y$ the system is,

$$
u(t) = w_x \cdot w_z - \frac{1}{2} \cdot (0.35 \cdot w_y + \cos(\phi) \cdot \sin(\theta)) - w_x - \alpha \cdot w_y + v \tag{25}
$$

A control model has been developed for satellite chaotic system using passive control method as seen in Fig. 6. Where $\alpha = 1$ and $v = 0$.

The results of simulations for sliding mode control and passive controller method are illustrated in Figs. 7, 8, 9 and 10.

The comparison of results was given in Table 1 using the performance index for error check such as the integral of the absolute error (IAE), integral of square error (ISE), the integral of the time multiplied by the absolute value of the error (ITAE), and the integral of the squared control input (ISCI) [18]. After the controller was activated, performance values were obtained in 5 s. In the Table 1, SMC has been more successful than passive control method in accordance with the results of error based on the performance index.

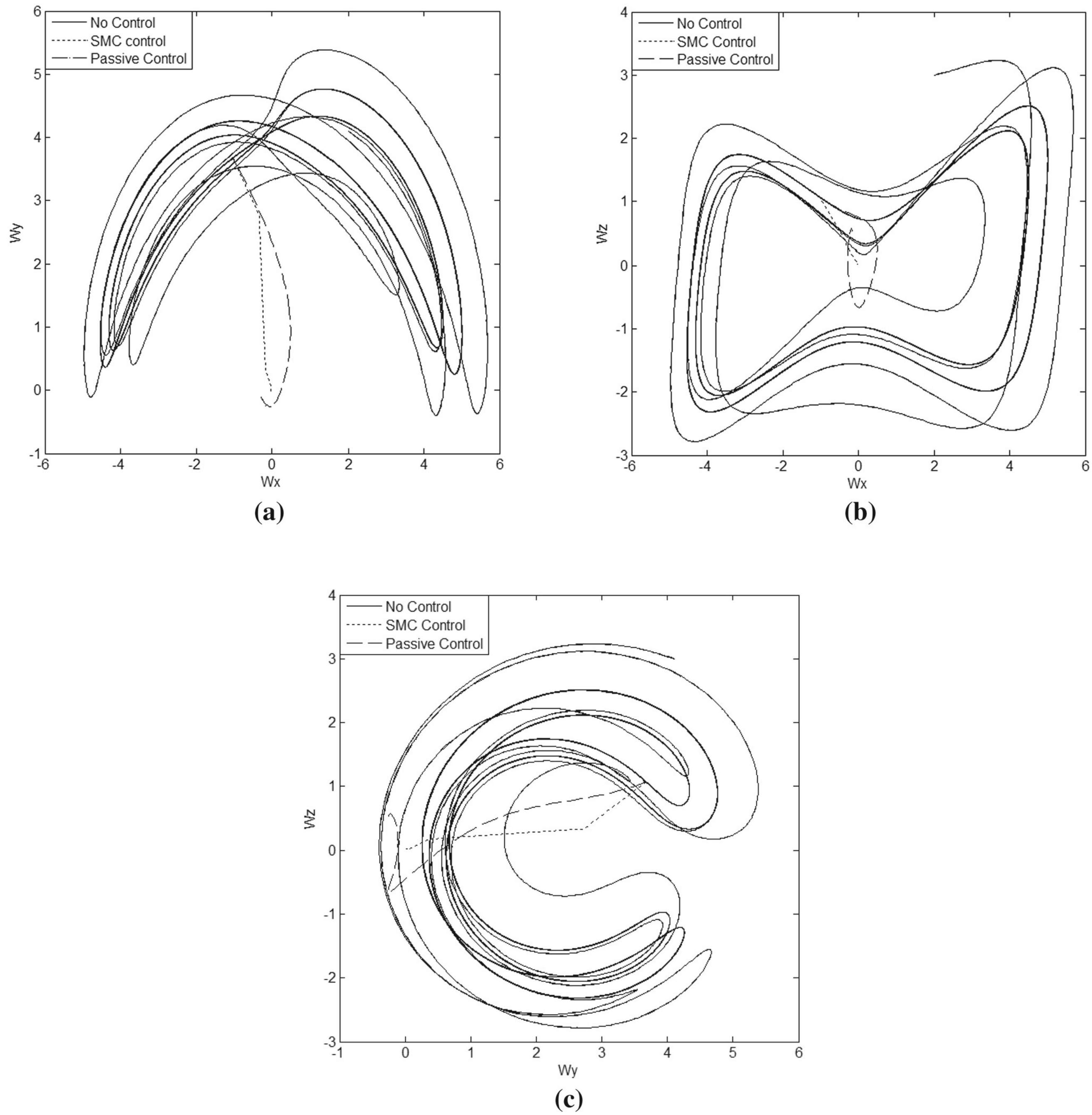
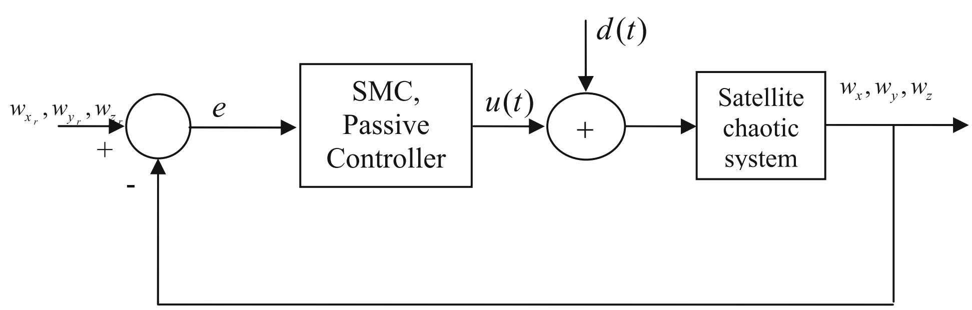


Fig. 12 Phase portraits of the angular velocities in the chaotic satellite system **a** $w_x w_y$, **b** $w_x w_z$ and **c** $w_y w_z$ controller activated $t = 30$

Fig. 13 Satellite chaotic system including external disturbance



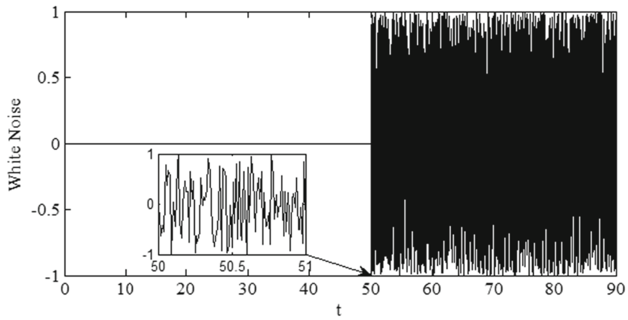


Fig. 14 External disturbance signals

SMC was showed better behavior in terms of the minimum deviation of the tracking error.

I have chosen the angular velocity as control variables w_x, w_y, and w_z. The state variables can reach an equilibrium point $E_0(0,0,0)$ as the controller activates the system at 30th second as given in Fig. 9. By using sliding mode control, state variables reach a fixed point very quickly, whereas they reach a fixed point very slowly with passive control. This phenomenon is seen most clearly from the phase portraits as seen in Fig. 12. On the other hand, sliding mode control response can achieve perfect synchronization more than passive control method. Synchronization errors of the satellites are shown in Fig. 10. Figure 11 shows the perturbing torques H_x, H_y and H_z acting on the satellite during the sliding mode and passive control. The control torques required to achieve stabilization are much larger. In our earlier attempts these varied in the range from -10 to $+8$ for H_x, from -0.2 to $+2$ for H_y and from -15 to $+15$ for H_z torques [2].

The satellite control system used for testing robustness and disturbance performance was added to the external disturbance. This situation is shown in Fig. 13. Figure 14 shows the external disturbance signals ($\mathrm{d}(t)$). The responses of the controller against the disruptive detail illustration shown in Fig. 15 graphically. The sliding mode control shows the robustness against disturbances, however, passive control is remained insufficient.

6 Conclusion

In this study, control problem have been improved by two different control methods to solve the chaotic satellite motion system. Numerical simulations of the sliding mode control technique were more effective than passive control method. While the sliding mode control method reached zero point, passive control method reached zero point with greater error. It was shown that the perfect synchronization of the sliding mode control system was realized, and trajectory of error converged to zero. When the chaotic behavior of the system was terminated, the system reached the equilibrium point. According to the Lyapunov stability analyses of the chaotic satellite motion system, it shows the unstable and nonlinear behavior between 0 and 30 s. Meantime, the sliding mode control shows the robustness against disturbances, but, the passive control is remained insufficient.

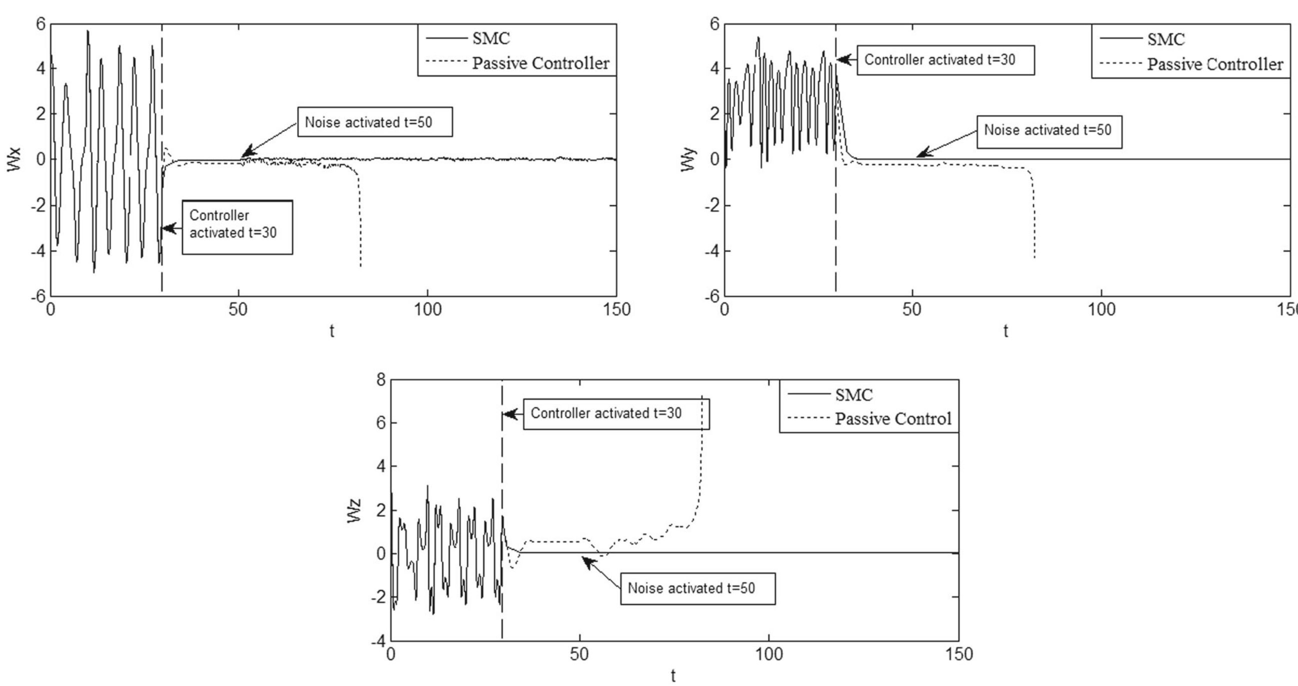


Fig. 15 Time trace of w_x, w_y and w_z controller activated $t = 30$, and noise activated $t = 50$

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