International Journal of ChemTech Research
CODEN (USA): IJCRGG ISSN: 0974-4290
Vol.8, No.6, pp 818-827, 2015

Synchronization of Tokamak Systems with Symmetric and Magnetically Confined Plasma via Adaptive Control

Sundarapandian Vaidyanathan

R & D Centre, Vel Tech University, Avadi, Chennai, Tamil Nadu, INDIA

Abstract: One of the most developed of the modern magnetic fusion concepts is the Tokamak. In respect of their symmetry properties, toroidal magnetically confined plasmas have much in common with the Taylor-Couette flow. This research work discusses the dynamics and properties of the Tokamak system with symmetric and magnetically confined plasma studied by Arter (2009). Then this work discusses the global chaos synchronization of the Tokamak chaotic systems with unknown system parameters via adaptive control method. The main control result is established using Lyapunov stability theory. MATLAB plots have been shown to illustrate all the main results discussed on the Tokamak chaotic system with symmetric and magnetically confined plasma.
Keywords: Tokamak, magnetic fusion, plasma, chaos, chaotic system, synchronization, adaptive control, etc.

1. Introduction

One of the most developed modern magnetic fusion concepts is the Tokamak [1]. After 40 years of research, a great amount is known about Tokamak behaviour. However, a complete understanding of some of the most prominent phenomena has not yet been achieved. For example, diagnosing the behaviour of some aspects of extremely hot plasma is still a very challenging problem for the experimenter. The most intensively studied configuration most analogous to toroidal plasma devices is the Taylor-Couette experiment [2]. In this work, we analyze the dynamics of the Tokamak system with rotationally symmetric and magnetically confined plasma studied by Arter [1].

A dynamical system is called *chaotic,* the system variables should contain some nonlinear terms and the system must satisfy three properties: boundedness, infinite recurrence and sensitive dependence on initial conditions [3-4]. The first known chaotic system was discovered by Lorenz in 1963 [5]. Subsequently, Rössler discovered a 3-D chaotic chemical reaction system in 1976 [6].

The classical chaotic systems were followed by the finding of many 3-D chaotic systems such as Arneodo system [7], Sprott systems [8], Chen system [9], Lü-Chen system [10], Cai system [11], Tigan system [12], etc. Many new chaotic systems have been also discovered in the recent years such as Sampath system [13], Sundarapandian systems [14-15], Vaidyanathan systems [16-38], Pehlivan system [39], Pham system [40], etc.

Chaos theory has important applications in many fields of science and engineering such as lasers [41-42], biology [43-44], chemical reactions [45-47], robotics [48-49], circuits [50], memristors [51-53], etc.

This paper describes the modelling and properties of the Tokamak chaotic system with rotationally symmetric and magnetically confined plasma [1]. This paper also derives new results of adaptive feedback controller design for the Tokamak chaotic system using Lyapunov stability theory [54].

In control theory, active control method is used when the system parameters are available for measurement [55-70]. Adaptive control is a popular control technique used for stabilizing systems when the system parameters are unknown [71-84]. There are also other popular methods available for control and synchronization of systems such as backstepping control method [85-90], sliding mode control method [91-102], etc.

2. Tokamak system with symmetric and magnetically confined plasma:

The mathematical model for the Tokamak system with rotationally symmetric and magnetically confined plasma [1] is given the 3-D dynamics

$$\begin{cases} \dot{x} = y \\ \dot{y} = x - x^3 \\ \dot{z} = a - bz^2 - x^2 \end{cases} \tag{1}$$

In (1), x, y, z are the states of the Tokamak system and a, b are constant system parameters.

In [1], Arter (2009) showed that the Tokamak system (1) shows dissipative chaotic behaviour, when we take the system parameter values as

$$a = 1, \quad b = 0.001 \tag{2}$$

For numerical simulations, we take the initial conditions as $x(0) = 0.01,\ y(0) = 0.01$ and $z(0) = 0.01$.

For the parameter values (2) and the chosen initial conditions, the Lyapunov exponents of the Tokamak system (1) are numerically determined as

$$L_1 = 0.0228, \quad L_2 \ \ 0, \quad L_3 \ \ -0.0701. \tag{3}$$

Also, the Lyapunov dimension of the Tokamak chaotic system (1) is determined as

$$D_L = 2 + \frac{L_1 + L_2}{|L_3|} \quad 2 + \frac{0.0228 + 0}{0.0701} \quad 2.3252 \tag{4}$$

Figure 1 shows the 3-D phase portrait of the strange chaotic attractor of the Tokamak system (1).

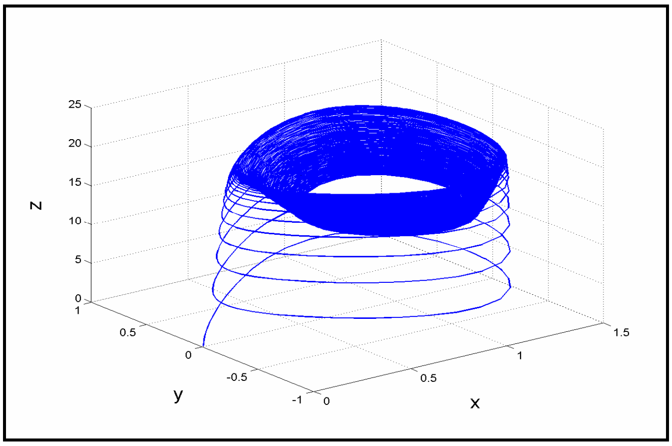

Figure 1. Strange chaotic attractor of the Tokamak system

3. Adaptive synchronization of the identical Tokamak chaotic systems

In this section, we use adaptive control method to design an adaptive feedback control law for globally synchronizing the identical Tokamak chaotic systems with symmetric and magnetically confined plasma.

As the master system, we consider the Tokamak chaotic system given by the 3-D dynamics

$$\begin{cases} \dot{x}_1 = y_1 \\ \dot{y}_1 = x_1 - x_1^3 \\ \dot{z}_1 = a - bz_1^2 - x_1^2 \end{cases} \tag{5}$$

In (5), x_1, y_1, z_1 are the states and a, b are unknown parameters of the system.

As the slave system, we consider the Tokamak chaotic system given by the 3-D dynamics

$$\begin{cases} \dot{x}_2 = y_2 + u_x \\ \dot{y}_2 = x_2 - x_2^3 + u_y \\ \dot{z}_2 = a - bz_2^2 - x_2^2 + u_z \end{cases} \tag{6}$$

In (6), x_2, y_2, z_2 are the states and u_x, u_y, u_z are the adaptive controls to be designed.

The chaos synchronization error is defined by

$$\begin{cases} e_x = x_2 - x_1 \\ e_y = y_2 - y_1 \\ e_z = z_2 - z_1 \end{cases} \tag{7}$$

The error dynamics is obtained as

$$\begin{cases} \dot{e}_x = e_y + u_x \\ \dot{e}_y = e_x - x_2^3 + x_1^3 + u_y \\ \dot{e}_z = -b\left(z_2^2 - z_1^2\right) - x_2^2 + x_1^2 + u_z \end{cases} \tag{8}$$

We consider the adaptive control defined by

$$\begin{cases} u_x = -e_y - k_x e_x \\ u_y = -e_x + x_2^3 - x_1^3 - k_y e_y \\ u_z = \hat{b}(t)\left(z_2^2 - z_1^2\right) + x_2^2 - x_1^2 - k_z e_z \end{cases} \tag{9}$$

Substituting (9) into (8), we get the closed-loop error dynamics given by

$$\begin{cases} \dot{e}_x = -k_x e_x \\ \dot{e}_y = -k_y e_y \\ \dot{e}_z = -[b - \hat{b}(t)]\left(z_2^2 - z_1^2\right) - k_z e_z \end{cases} \tag{10}$$

We define the parameter estimation error as

$$e_b(t) = b - \hat{b}(t) \tag{11}$$

Using (11), we can simplify the closed-loop error dynamics (10) as

$$\begin{cases} \dot{e}_x = -k_x e_x \\ \dot{e}_y = -k_y e_y \\ \dot{e}_z = -e_b\left(z_2^2 - z_1^2\right) - k_z e_z \end{cases} \tag{12}$$

Differentiating the parameter estimation error (11) with respect to time, we get

$$\dot{e}_b(t) = -\dot{\hat{b}}(t) \tag{13}$$

Next, we consider the candidate Lyapunov function given by

$$V(e_x, e_y, e_z, e_b) = \frac{1}{2}\left(e_x^2 + e_y^2 + e_z^2 + e_b^2\right) \tag{14}$$

Differentiating V along the trajectories of (12) and (13), we obtain

$$\dot{V} = -k_x e_x^2 - k_y e_y^2 - k_z e_z^2 + e_b[-e_z(z_2^2 - z_1^2) - \dot{\hat{b}}(t)] \tag{15}$$

In view of (15), we take the parameter estimates as follows:

$$\dot{\hat{b}} = -e_z\left(z_2^2 - z_1^2\right) \tag{16}$$

Theorem 1. *The Tokamak chaotic systems (5) and (6) with symmetric and magnetically confined plasma are globally and exponentially synchronized for all initial values by the adaptive control law (9) and* *parameter update law (16), where* k_x, k_y, k_z *are positive gain constants.*

Proof. The quadratic Lyapunov function V defined by Eq. (14) is a positive definite function on R^4.

Substituting the parameter update law (16) into (15), the time-derivative of V is obtained as

$$\dot{V} = -k_x e_x^2 - k_y e_y^2 - k_z e_z^2 \tag{17}$$

which is a negative semi-definite function on R^4.

Thus, by Lyapunov stability theory [54], we conclude that $\left[e_x(t), e_y(t), e_z(t)\right] \to 0$ exponentially as $t \to \infty$ for all initial conditions $e(0) \in R^3$.

Hence, we have proved that the Tokamak chaotic systems (5) and (6) with symmetric and magnetically confined plasma are globally and exponentially synchronized for all initial values by the adaptive control law (9) and parameter update law (16).

This completes the proof. ■

Numerical Simulations

We use classical fourth-order Runge-Kutta method in MATLAB with step-size $h = 10^{-8}$ for solving the systems of differential equations given by (5), (6) and (16), when the adaptive control law (9) is implemented.

We take the gain constants as $k_x = k_y = k_z = 6$.

We take the initial conditions of the Tokamak system (5) as

$x_1(0) = 2.5, \;\; y_1(0) = 4.9, \;\; z_1(0) = 8.4.$

We take the initial conditions of the Tokamak system (6) as

$x_2(0) = 9.4, \;\; y_2(0) = 2.1, \;\; z_2(0) = 3.7.$

We take the system parameters as in the chaotic case, *i.e.*

$a = 1$ and $b = 0.001$.

Also, we take the initial conditions of the parameter estimate as $\hat{b}(0) = 10.6$.

Figures 2-4 show the synchronization of the states of the Tokomak systems (5) and (6). Figure 5 shows the time-history of the synchronization errors e_x, e_y, e_z. From Figure 5, it is clear that the synchronization errors $e_x(t), e_y(t), e_z(t)$ converge to zero in two seconds.

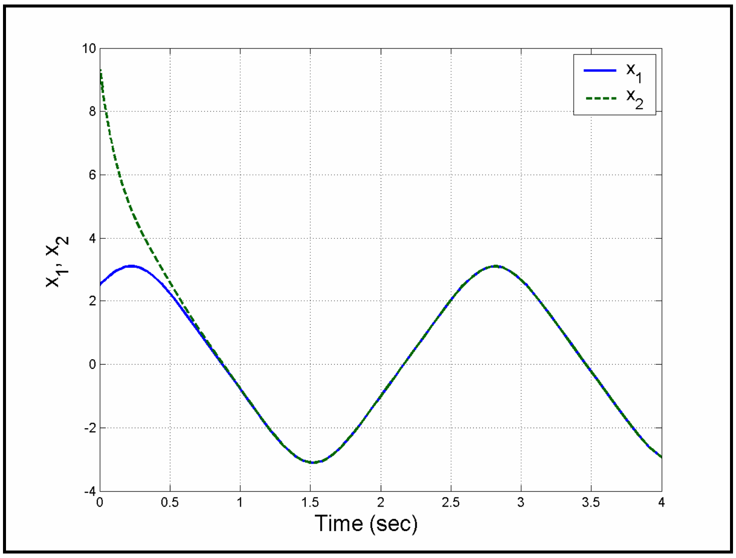

Figure 2. Synchronization of the states $x_1(t)$ and $x_2(t)$

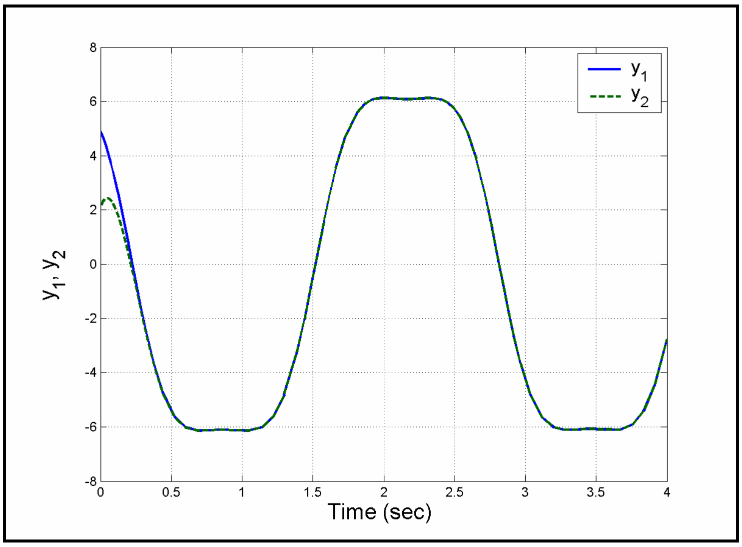

Figure 3. Synchronization of the states $y_1(t)$ and $y_2(t)$

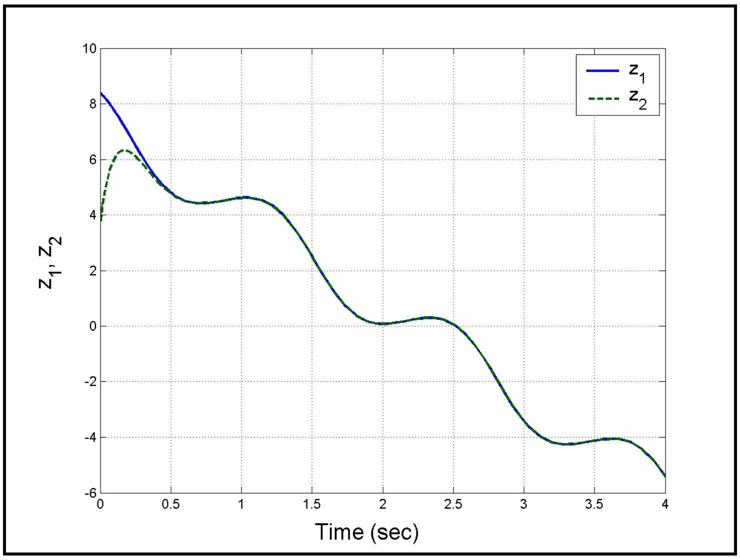

Figure 4. Synchronization of the states $z_1(t)$ and $z_2(t)$

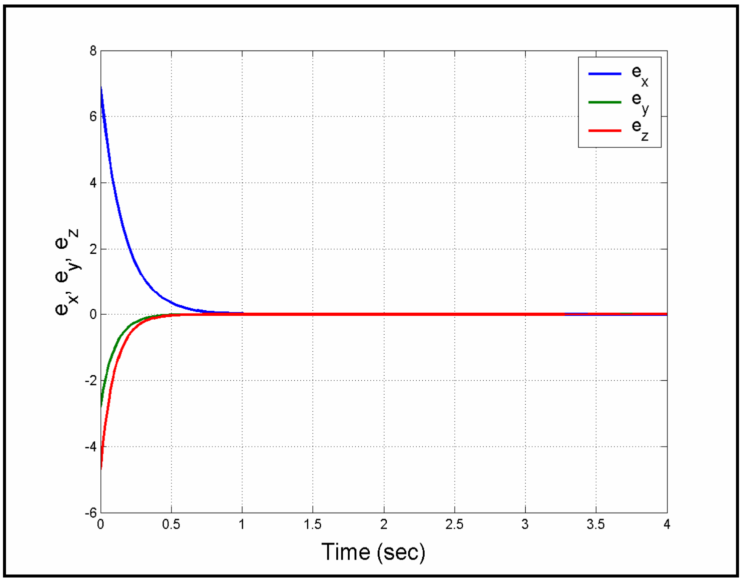

Figure 5. Time-history of the synchronization errors e_x, e_y, e_z

Conclusions

In this paper, new results have been derived for the analysis and adaptive synchronization of the Tokamak chaotic systems with rotationally symmetric and magnetically confined plasma. We analyzed the dynamics and qualitative properites of the Tokamak system with symmetric and magnetically confined plasma studied by Arter (2009). Then we derived new results for the adaptive synchronization of the identical Tokamak chaotic systems with unknown system parameters. The main result was established using Lyapunov stability theory. MATLAB plots were depicted to illustrate all the main results discussed on the Tokamak chaotic system with symmetric and magnetically confined plasma.

References

1. Arter, W., Symmetry constraints on the dynamics of magnetically confined plasma, Physical Review Letters, 2009, 102, 195004.
2. Wesson, J. A., Tokamaks, Clarendon Press, Oxford, U.K., 2003.
3. Azar, A. T., and Vaidyanathan, S., Chaos Modeling and Control Systems Design, Studies in Computational Intelligence, Vol. 581, Springer, New York, USA, 2015.
4. Azar, A. T., and Vaidyanathan, S., Computational Intelligence Applications in Modeling and Control, Studies in Computational Intelligence, Vol. 575, Springer, New York, USA, 2015.
5. Lorenz, E. N., Deterministic nonperiodic flow, Journal of the Atmospheric Sciences, 1963, 20, 130-141.
6. Rössler, O. E., An equation for continuous chaos, Physics Letters A, 1976, 57, 397-398.
7. Arneodo, A., Coullet, P., and Tresser, C., Possible new strange attractors with spiral structure, Communications in Mathematical Physics, 1981, 79, 573-579.
8. Sprott, J. C., Some simple chaotic flows, Physical Review E, 1994, 50, 647-650.
9. Chen, G., and Ueta, T., Yet another chaotic attractor, International Journal of Bifurcation and Chaos, 1999, 9, 1465-1466.
10. Lü, J., and Chen, G., A new chaotic attractor coined, International Journal of Bifurcation and Chaos, 2002, 12, 659-661.
11. Cai, G., and Tan, Z., Chaos synchronization of a new chaotic system via nonlinear control, Journal of Uncertain Systems, 2007, 1, 235-240.
12. Tigan, G., and Opris, D., Analysis of a 3D chaotic system, Chaos, Solitons and Fractals, 2008, 36, 1315-1319.
13. Sampath, S., Vaidyanathan, S., Volos, Ch. K., and Pham, V.-T., An eight-term novel four-scroll chaotic system with cubic nonlinearity and its circuit simulation, Journal of Engineering Science and Technology Review, 2015, 8, 1-6.
14. Sundarapandian, V., and Pehlivan, I., Analysis, control, synchronization and circuit design of a novel chaotic system, Mathematical and Computer Modelling, 2012, 55, 1904-1915.
15. Sundarapandian, V., Analysis and anti-synchronization of a novel chaotic system via active and adaptive controllers, Journal of Engineering Science and Technology Review, 2013, 6, 45-52.
16. Vaidyanathan, S., A new six-term 3-D chaotic system with an exponential nonlinearity, Far East Journal of Mathematical Sciences, 2013, 79, 135-143.
17. Vaidyanathan, S., Analysis and adaptive synchronization of two novel chaotic systems with hyperbolic sinusoidal and cosinusoidal nonlinearity and unknown parameters, Journal of Engineering Science and Technology Review, 2013, 6, 53-65.
18. Vaidyanathan, S., A new eight-term 3-D polynomial chaotic system with three quadratic nonlinearities, Far East Journal of Mathematical Sciences, 2014, 84, 219-226.
19. Vaidyanathan, S., Analysis, control and synchronisation of a six-term novel chaotic system with three quadratic nonlinearities, International Journal of Modelling, Identification and Control, 2014, 22, 41-53.
20. Vaidyanathan, S., and Madhavan, K., Analysis, adaptive control and synchronization of a seven-term novel 3-D chaotic system, International Journal of Control Theory and Applications, 2013, 6, 121-137.
21. Vaidyanathan, S., Analysis and adaptive synchronization of eight-term 3-D polynomial chaotic systems with three quadratic nonlinearities, European Physical Journal: Special Topics, 2014, 223, 1519-1529.
22. Vaidyanathan, S., Volos, C., Pham, V. T., Madhavan, K., and Idowu, B. A., Adaptive backstepping control, synchronization and circuit simulation of a 3-D novel jerk chaotic system with two hyperbolic sinusoidal nonlinearities, Archives of Control Sciences, 2014, 24, 257-285.
23. Vaidyanathan, S., Generalised projective synchronisation of novel 3-D chaotic systems with an exponential non-linearity via active and adaptive control, International Journal of Modelling, Identification and Control, 2014, 22, 207-217.

24. Vaidyanathan, S., Analysis, properties and control of an eight-term 3-D chaotic system with an exponential nonlinearity, International Journal of Modelling, Identification and Control, 2015, 23, 164-172.
25. Vaidyanathan, S., Azar, A. T., Rajagopal, K., and Alexander, P., Design and SPICE implementation of a 12-term novel hyperchaotic system and its synchronisation via active control, International Journal of Modelling, Identification and Control, 2015, 23, 267-277.
26. Vaidyanathan, S., Qualitative analysis, adaptive control and synchronization of a seven-term novel 3-D chaotic system with a quartic nonlinearity, 2014, 7, 1-20.
27. Vaidyanathan, S., Qualitative analysis and control of an eleven-term novel 4-D hyperchaotic system with two quadratic nonlinearities, 2014, 7, 35-47.
28. Vaidyanathan, S., Volos, C., and Pham, V.-T., Hyperchaos, adaptive control and synchronization of a novel 5-D hyperchaotic system with three positive Lyapunov exponents and its SPICE implementation, Archives of Control Sciences, 2014, 24, 409-446.
29. Vaidyanathan, S., Volos, C., Pham, V.-T., and Madhavan, K., Analysis, adaptive control and synchronization of a novel 4-D hyperchaotic hyperjerk system and its SPICE implementation, Archives of Control Sciences, 2015, 25, 135-158.
30. Vaidyanathan, S., Volos, Ch. K., and Pham, V.-T., Analysis, control and synchronization and SPICE implementation of a novel 4-D hyperchaotic Rikitake dynamo system without equilibrium, Journal of Engineering Science and Technology Review, 2015, 8, 232-244.
31. Vaidyanathan, S., A 3-D novel highly chaotic system with four quadratic nonlinearities, its adaptive control and anti-synchronization with unknown parameters, Journal of Engineering Science and Technology Review, 2015, 8, 106-115.
32. Vaidyanathan, S., Rajagopal, K., Volos, Ch. K., Kyprianidis, I. M., and Stouboulos, I. N., Analysis, adaptive control and synchronization of a seven-term novel 3-D chaotic system with three quadratic nonlinearities and its digital implementation in LabVIEW, Journal of Engineering Science and Technology Review, 2015, 8, 130-141.
33. Vaidyanathan, S., and Pakiriswamy, S., A 3-D novel conservative chaotic system and its generalized projective synchronization via adaptive control, Journal of Engineering Science and Technology Review, 2015, 8, 52-60.
34. Vaidyanathan, S., Volos, Ch. K., Kyprianidis, I. M., Stouboulos, I. N., and Pham, V.-T., Analysis, adaptive control and anti-synchronization of a six-term novel jerk chaotic system with two exponential nonlinearities and its circuit simulation, Journal of Engineering Science and Technology Review, 2015, 8, 24-36.
35. Vaidyanathan, S., Volos, Ch. K., and Pham, V.-T., Analysis, adaptive control and adaptive synchronization of a nine-term novel 3-D chaotic system with four quadratic nonlinearities and its circuit simulation, Journal of Engineering Science and Technology Review, 2015, 8, 174-184.
36. Vaidyanathan, S., Pham, V.-T., and Volos, C. K., A 5-D hyperchaotic Rikitake dynamo system with hidden attractors, European Physical Journal: Special Topics, 2015, 224, 1575-1592.
37. Pham, V.-T., Vaidyanathan, S., Volos, C. K., and Jafari, S., Hidden attractors in a chaotic system with an exponential nonlinear term, European Physical Journal: Special Topics, 2015, 224, 1507-1517.
38. Vaidyanathan, S., Hyperchaos, qualitative analysis, control and synchronisation of a ten-term 4-D hyperchaotic system with an exponential nonlinearity and three quadratic nonlinearities, International Journal of Modelling, Identification and Control, 2015, 23, 380-392.
39. Pehlivan, I., Moroz, I. M., and Vaidyanathan, S., Analysis, synchronization and circuit design of a novel butterfly attractor, Journal of Sound and Vibration, 2014, 333, 5077-5096.
40. Pham, V. T., Volos, C., Jafari, S., Wang, X., and Vaidyanathan, S., Hidden hyperchaotic attractor in a novel simple memristic neural network, Optoelectronics and Advanced Materials – Rapid Communications, 2014, 8, 1157-1163.
41. Behnia, S., Afrang, S., Akhshani, A., and Mabhouti, Kh., A novel method for controlling chaos in external cavity semiconductor laser, Optik-International Journal for Light and Electron Optics, 2013, 124, 757-764.
42. Yuan, G., Zhang, X., and Wang, Z., Generation and synchronization of feedback-induced chaos in semiconductor ring lasers by injection-locking, Optik-International Journal for Light and Electron Optics, 2014, 125, 1950-1953.
43. Kyriazis, M., Applications of chaos theory to the molecular biology of aging, Experimental Gerontology, 1991, 26, 569-572.
44. Vaidyanathan, S., Adaptive backstepping control of enzymes-substrates system with ferroelectric behaviour in brain waves, International Journal of PharmTech Research, 2015, 8, 256-261.

45. Gaspard, P., Microscopic chaos and chemical reactions, Physica A: Statistical Mechanics and Its Applications, 1999, 263, 315-328.
46. Vaidyanathan, S., Adaptive control of a chemical chaotic reactor, International Journal of PharmTech Research, 2015, 8, 377-382.
47. Vaidyanathan, S., Adaptive synchronization of chemical chaotic reactors, International Journal of ChemTech Research, 2015, 8, 612-621.
48. Lankalapalli, S., and Ghosal, A., Chaos in robot control equations, International Journal of Bifurcation and Chaos, 1997, 7, 707-720.
49. Nakamura, Y., and Sekiguchi, A., The chaotic mobile robot, IEEE Transactions on Robotics and Automation, 2001, 17, 898-904.
50. Volos, C. K., Pham, V.-T., Vaidyanathan, S., Kyprianidis, I. M., and Stouboulos, I. N., Synchronization phenomena in coupled Colpitts circuits, Journal of Engineering Science and Technology Review, 2015, 8, 142-151.
51. Pham, V.-T., Volos, C. K., Vaidyanathan, S., and Vu, V. Y., A memristor-based hyperchaotic system with hidden attractors: dynamics, synchronization and circuital emulating, Journal of Engineering Science and Technology Review, 2015, 8, 205-214.
52. Volos, C. K., Kyprianidis, I. M., Stouboulos, I. N., Tlelo-Cuautle, E., and Vaidyanathan, S., Memristor: A new concept in synchronization of coupled neuromorphic circuits, Journal of Engineering Science and Technology Review, 2015, 8, 157-173.
53. Pham, V.-T., Volos, C., Jafari, S., Wang, X., and Vaidyanathan, S., Hidden hyperchaotic attractor in a novel simple memristive neural network, Optoelectronics and Advanced Materials, Rapid Communications, 2014, 8, 1157-1163.
54. Khalil, H.K., Nonlinear Systems, Prentice Hall, New Jersey, USA, 2002.
55. Sundarapandian, V., Output regulation of the Lorenz attractor, Far East Journal of Mathematical Sciences, 2010, 42, 289-299.
56. Vaidyanathan, S., and Rajagopal, K., Anti-synchronization of Li and T chaotic systems by active nonlinear control, Communications in Computer and Information Science, 2011, 198, 175-184.
57. Vaidyanathan, S., and Rasappan, S., Global chaos synchronization of hyperchaotic Bao and Xu systems by active nonlinear control, Communications in Computer and Information Science, 2011, 198, 10-17.
58. Vaidyanathan, S., Output regulation of the unified chaotic system, Communications in Computer and Information Science, 2011, 198, 1-9.
59. Vaidyanathan, S., and Rajagopal, K., Global chaos synchronization of hyperchaotic Pang and Wang systems by active nonlinear control, 2011, 198, 84-93.
60. Vaidyanathan, S., Hybrid chaos synchronization of Liu and Lu systems by active nonlinear control, Communications in Computer and Information Science, 2011, 204, 1-10.
61. Sarasu, P., and Sundarapandian, V., Active controller design for generalized projective synchronization of four-scroll chaotic systems, International Journal of Systems Signal Control and Engineering Application, 2011, 4, 26-33.
62. Vaidyanathan, S., and Rasappan, S., Hybrid synchronization of hyperchaotic Qi and Lu systems by nonlinear control, Communications in Computer and Information Science, 2011, 131, 585-593.
63. Vaidyanathan, S., and Rajagopal, K., Hybrid synchronization of hyperchaotic Wang-Chen and hyperchaotic Lorenz systems by active non-linear control, International Journal of Systems Signal Control and Engineering Application, 2011, 4, 55-61.
64. Vaidyanathan, S., Output regulation of Arneodo-Coullet chaotic system, Communications in Computer and Information Science, 2011, 133, 98-107.
65. Sarasu, P., and Sundarapandian, V., The generalized projective synchronization of hyperchaotic Lorenz and hyperchaotic Qi systems via active control, International Journal of Soft Computing, 2011, 6, 216-223.
66. Vaidyanathan, S., and Pakiriswamy, S., The design of active feedback controllers for the generalized projective synchronization of hyperchaotic Qi and hyperchaotic Lorenz systems, Communications in Computer and Information Science, 2011, 245, 231-238.
67. Sundarapandian, V., and Karthikeyan, R., Hybrid synchronization of hyperchaotic Lorenz and hyperchaotic Chen systems via active control, Journal of Engineering and Applied Sciences, 2012, 7, 254-264.
68. Vaidyanathan, S., and Pakiriswamy, S., Generalized projective synchronization of double-scroll chaotic systems using active feedback control, Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, 2012, 84, 111-118.
69. Pakiriswamy, S., and Vaidyanathan, S., Generalized projective synchronization of three-scroll chaotic

systems via active control, Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, 2012, 85, 146-155.

70. Karthikeyan, R., and Sundarapandian, V., Hybrid chaos synchronization of four-scroll systems via active control, Journal of Electrical Engineering, 2014, 65, 97-103.
71. Vaidyanathan, S., Azar, A. T., Rajagopal, K., and Alexander, P., Design and SPICE implementation of a 12-term novel hyperchaotic system and its synchronisation via active control, International Journal of Modelling, Identification and Control, 2015, 23, 267-277.
72. Vaidyanathan, S., and Rajagopal, K., Global chaos synchronization of Lu and Pan systems by adaptive nonlinear control, Communication in Computer and Information Science, 2011, 205, 193-202.
73. Vaidyanathan, S., Adaptive controller and synchronizer design for the Qi-Chen chaotic system, Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunication Engineering, 2012, 85, 124-133.
74. Sundarapandian, V., Adaptive control and synchronization design for the Lu-Xiao chaotic system, Lectures on Electrical Engineering, 2013, 131, 319-327.
75. Vaidyanathan, S., Analysis, control and synchronization of hyperchaotic Zhou system via adaptive control, Advances in Intelligent Systems and Computing, 2013, 177, 1-10.
76. Vaidyanathan, S., and Rajagopal, K., Global chaos synchronization of Lü and Pan systems by adaptive nonlinear control, Communications in Computer and Information Science, 2011, 205, 193-202.
77. Sundarapandian, V., and Karthikeyan, R., Anti-synchronization of Lü and Pan systems by adaptive nonlinear control, European Journal of Scientific Research, 2011, 64, 94-106.
78. Sundarapandian, V., and Karthikeyan, R., Anti-synchronization of hyperchaotic Lorenz and hyperchaotic Chen systems by adaptive control, International Journal of Systems Signal Control and Engineering Application, 2011, 4, 18-25.
79. Sundarapandian, V., and Karthikeyan, R., Adaptive anti-synchronization of uncertain Tigan and Li systems, Journal of Engineering and Applied Sciences, 2012, 7, 45-52.
80. Sarasu, P., and Sundarapandian, V., Generalized projective synchronization of three-scroll chaotic systems via adaptive control, European Journal of Scientific Research, 2012, 72, 504-522.
81. Vaidyanathan, S., and Rajagopal, K., Global chaos synchronization of hyperchaotic Pang and hyperchaotic Wang systems via adaptive control, International Journal of Soft Computing, 2012, 7, 28-37.
82. Sarasu, P., and Sundarapandian, V., Generalized projective synchronization of two-scroll systems via adaptive control, International Journal of Soft Computing, 2012, 7, 146-156.
83. Sarasu, P., and Sundarapandian, V., Adaptive controller design for the generalized projective synchronization of 4-scroll systems, International Journal of Systems Signal Control and Engineering Application, 2012, 5, 21-30.
84. Vaidyanathan, S., Anti-synchronization of Sprott-L and Sprott-M chaotic systems via adaptive control, International Journal of Control Theory and Applications, 2012, 5, 41-59.
85. Vaidyanathan, S., and Pakiriswamy, S., Generalized projective synchronization of six-term Sundarapandian chaotic systems by adaptive control, International Journal of Control Theory and Applications, 2013, 6, 153-163.
86. Rasappan, S., and Vaidyanathan, S., Hybrid synchronization of n-scroll chaotic Chua circuits using adaptive backstepping control design with recursive feedback, Malaysian Journal of Mathematical Sciences, 2013, 7, 219-246.
87. Suresh, R., and Sundarapandian, V., Global chaos synchronization of a family of n-scroll hyperchaotic Chua circuits using backstepping control with recursive feedback, Far East Journal of Mathematical Sciences, 2013, 73, 73-95.
88. Rasappan, S., and Vaidyanathan, S., Global chaos synchronization of WINDMI and Coullet chaotic systems using adaptive backstepping control design, Kyungpook Mathematical Journal, 2014, 54, 293-320.
89. Vaidyanathan, S., and Rasappan, S., Global chaos synchronization of n-scroll Chua circuit and Lur'e system using backstepping control design with recursive feedback, Arabian Journal for Science and Engineering, 2014, 39, 3351-3364.
90. Vaidyanathan, S., Idowu, B. A., and Azar, A. T., Backstepping controller design for the global chaos synchronization of Sprott's jerk systems, Studies in Computational Intelligence, 2015, 581, 39-58.
91. Vaidyanathan, S., Volos, C. K., Rajagopal, K., Kyprianidis, I. M., and Stouboulos, I. N., Adaptive backstepping controller design for the anti-synchronization of identical WINDMI chaotic systems with unknown parameters and its SPICE implementation, Journal of Engineering Science and Technology Review, 2015, 8, 74-82.

92. Vaidyanathan, S., and Sampath, S., Global chaos synchronization of hyperchaotic Lorenz systems by sliding mode control, Communications in Computer and Information Science, 2011, 205, 156-164.
93. Sundarapandian, V., and Sivaperumal, S., Sliding controller design of hybrid synchronization of four-wing chaotic systems, International Journal of Soft Computing, 2011, 6, 224-231.
94. Vaidyanathan, S., and Sampath, S., Anti-synchronization of four-wing chaotic systems via sliding mode control, International Journal of Automation and Computing, 2012, 9, 274-279.
95. Vaidyanathan, S., and Sampath, S., Sliding mode controller design for the global chaos synchronization of Coullet systems, Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, 2012, 84, 103-110.
96. Vaidyanathan, S., and Sampath, S., Hybrid synchronization of hyperchaotic Chen systems via sliding mode control, Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, 2012, 85, 257-266.
97. Vaidyanathan, S., Global chaos control of hyperchaotic Liu system via sliding control method, International Journal of Control Theory and Applications, 2012, 5, 117-123.
98. Vaidyanathan, S., Sliding mode control based global chaos control of Liu-Liu-Liu-Su chaotic system, International Journal of Control Theory and Applications, 2012, 5, 15-20.
99. Vaidyanathan, S., Global chaos synchronisation of identical Li-Wu chaotic systems via sliding mode control, International Journal of Modelling, Identification and Control, 2014, 22, 170-177.
100. Vaidyanathan, S., and Azar, A. T., Anti-synchronization of identical chaotic systems using sliding mode control and an application to Vaidyanathan-Madhavan chaotic systems, Studies in Computational Intelligence, 2015, 576, 527-547.
101. Vaidyanathan, S., and Azar, A. T., Hybrid synchronization of identical chaotic systems using sliding mode control and an application to Vaidyanathan chaotic systems, Studies in Computational Intelligence, 2015, 576, 549-569.
102. Vaidyanathan, S., Sampath, S., and Azar, A. T., Global chaos synchronisation of identical chaotic systems via novel sliding mode control method and its application to Zhu system, International Journal of Modelling, Identification and Control, 2015, 23, 92-100.

*****