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**CHAOTIC BEHAVIOR MONITORING & CONTROL IN FLUIDIZED BED SYSTEMS
USING ARTIFICIAL NEURAL NETWORK**

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Introduction

We have developed techniques to control the chaotic behavior in Fluidized Bed Systems (FBC) systems using recurrent neural networks.^[1,2] For the sake of comparison of the techniques we have developed with the traditional chaotic system control methods, in the past three months we have been investigating the most popular and first known chaotic system control technique known as the OGY method. This method was developed by Edward Ott, Celso Grebogi and James York in 1990. In the past few years this method was further developed and applied by many researchers in the field. It was shown that this method has potential applications to a large cross section of problems in many fields. The only remaining question is whether it will prove possible to move from laboratory demonstrations on model systems to real world situations of engineering importance. We have developed computer programs to compute the OGY parameters from a chaotic time series, to control a chaotic system to a desired periodic orbit, using small perturbations to an accessible system parameter. We have tested those programs on the logistic map and the Henon map. We were able to control the chaotic behavior in such typical chaotic systems to period 1, 2, 3, 5 ..., as shown in some sample results below. In the following sections a brief discussion for the OGY method will be introduced, followed by results for the logistic map and Henon map control.

The OGY Chaotic System Control Method

The OGY method is a feed-back control method that uses the sensitivity to initial conditions property in chaotic systems to stabilize a normally unstable orbit, using small perturbations to an accessible system parameter, to achieve certain system performance.^[3,4, 5] This method is based on the theory that for most periodic orbits there are stable manifolds (directions) from which system states tend to move toward the orbit, and unstable manifolds from which system states tend to move away from the orbit. The actual control process is preceded by a learning process to design the control strategy.^[6,7] The controlled trajectory is usually mapped on a domain that makes it easier to monitor, such as a surface of section, a Poincare map, or a return map.^[3, 8, 9] On such a map, periodic orbits turn into fixed points. First, the precise location of the fixed point, to be controlled, needs to be found. Then, by observing the points that fell within a certain neighborhood of the fixed point, it is possible to build a linear model that describes the movement of the consecutive iterates on the map with respect to the fixed point. This linear map will describe the behavior of the consequent iterates on the surface of section around a fixed point according to the following relationship:

$$\xi_{n+1} - \xi_F = M(\xi_n - \xi_F), \quad (1)$$

Where $\xi_{n+1} = \begin{pmatrix} X_{n+2} \\ X_{n+1} \end{pmatrix}$, $\xi_n = \begin{pmatrix} X_{n+1} \\ X_n \end{pmatrix}$, $\xi_F = \begin{pmatrix} X_F \\ X_F \end{pmatrix}$. Where X_n , X_{n+1} , X_{n+2} are the system iterates at times n , $n+1$, and $n+2$ respectively. ξ_n and ξ_{n+1} are the corresponding points on the chosen surface of section, and ξ_F is a fixed point on the map.

Knowing this linear map, we can extract the stable and unstable eigenvalues, and the corresponding, stable and unstable eigenvectors, that describe the stable and unstable manifolds

of the fixed point. Knowing the maximum allowable perturbation in the control parameter, we can compute the maximum distance from the stable manifold for which control is achievable. Also, the partial derivative of the fixed point location with respect to the control parameter perturbation need to be computed.^[4] This parameter can also be computed from experimental measurements according to the relationship:

$$g = \frac{\partial \xi_F}{\partial P} = \frac{\delta \xi_F}{\delta P}, \quad (2)$$

where P is the control parameter. Knowing these quantities, we can compute the necessary perturbation to move the fixed point such that the current state point is on the stable manifold of the displaced fixed point, and the next iterate is on the stable manifold of the original fixed point. Once the state point is on the stable manifold of the fixed point, it is supposed to move toward the fixed point, using the system's natural forces. Theoretically, once the state point is on a fixed point it never leaves unless perturbed, which means that we can remove the controller without the orbit losing its stability. However, this does not happen in practice, because of noise and modeling errors, and because in practice the operating point comes very near to the fixed point but not exactly on it.^[3, 10] Hence, the actual control strategy is to wait for the state point to fall within the achievable control distance, measure its distance from the fixed point, calculate the necessary control perturbation, and apply the control perturbation such that the next iterate is on the stable manifold of the fixed point. This procedure is repeated at every iterate, to correct for the state point deviation from the fixed point, and to ensure the desired periodic behavior of the system. This method was also adopted to control discrete systems, using the time delay coordinates technique (embedding).^[10, 11]

Controlling the Logistic Map Chaotic Behavior Using the OGY Technique

The logistic map is a simple one equation model that represents the evolution of the population of some species in a closed community, and is described in the following equation:

$$X_{n+1} = X_n \lambda (1 - X_n) \quad (3)$$

For low values of λ the map has a fixed point that bifurcates as λ increases to period one, period two, and so on. For a value of λ near 4, the system behavior turns into chaos. Figure 1 shows the bifurcation diagram of the logistic map. Figure 2 and 3 show the chaotic time behavior and chaotic attractor, for the logistic map, respectively. Figures 4 through 9 show the logistic map behavior when control is applied and then removed, and the corresponding control perturbations for period one, two and five, respectively, using the OGY method.

Controlling the Henon Map Chaotic Behavior Using the OGY Technique

The Henon map is a two equation model as shown below:

$$\begin{aligned} X_{n+1} &= 1 - \alpha X_n^2 + Y_n \\ Y_{n+1} &= \beta X_n \end{aligned} \quad (4)$$

For values of $\alpha=1.4$, and $\beta=0.3$ the Henon map has a chaotic behavior. Figure 1 shows the bifurcation diagram of the logistic map. Figure 10 and 11 show the chaotic time behavior and chaotic attractor, for the Henon map, respectively. Figures 12 through 15 show the logistic map behavior when control is applied and then removed, and the corresponding control perturbations for period one, two, respectively, using the OGY method.

Figure 1. A bifurcation diagram for the logistic map, showing X_n vs λ .

Figure 2. A chaotic time series from the logistic map.

Figure 3. The logistic map chaotic attractor.

Figure 4. Controlling the logistic map to period one.

Figure 5. The control perturbations necessary to achieve the control shown in Figure 4.

Figure 6. Controlling the logistic map to period two.

Figure 7. The control perturbations necessary to achieve the control shown in Figure 6.

Figure 8. Controlling the logistic map to period five.

Figure 9. The control perturbations necessary to achieve the control shown in Figure 8.

Figure 10. A chaotic time series from the Henon map.

Figure 11. The Henon map chaotic attractor.

Figure 12. Controlling the Henon map to period one.

Figure 13. The control perturbations necessary to achieve the control shown in Figure 12.

Figure 14. Controlling the Henon map to period two.

Figure 15. The control perturbations necessary to achieve the control shown in Figure 14.

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Student Involvement:

Mr. Jehad Ababneh, Graduate Student. He is working on his Master Thesis, and is supported by this grant. He is involved on research related to the known OGY (Ott, Grebogi, and York) method to control the chaotic behavior using small perturbations. There are future plans for him to investigate the utilization of neural network techniques to estimate the general parameters for the OGY method.