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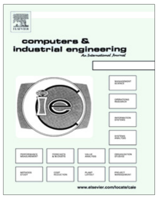

Synchronization and control of chaos in supply chain management

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ABSTRACT

This paper presents the synchronization and control of a chaotic supply chain management system based on its mathematical model. For this purpose, active controllers are applied for the synchronization of two identical chaotic supply chain management systems. Also, linear feedback controllers are designed and added to the nonlinear supply chain management system to achieve the control of the system. In these methods, synchronization and control are established by using Lyapunov stability theory. As a result, the synchronization and control of chaotic supply chain management system are realized numerically. Computer simulations are performed to verify the robustness of proposed synchronization and control methods.

1. Introduction

A chaotic system is a nonlinear dynamical system which sensitively depends on initial conditions. Chaos has been intensively found and investigated in a variety of fields since Lorenz discovered the first chaotic attractor (Lorenz, 1963). Because of the undesired complex behavior of chaos, the synchronization and control of chaotic systems have been one of the major issues in engineering. Hubler was the first to introduce an adaptive control for chaotic systems (Hubler, 1989) and then, Ott, Grebogi and Yorke developed a method called OGY to control chaotic systems (Ott, Grebogi, & York, 1990). Along with these, Pecora and Carroll introduced the idea of synchronizing two identical chaotic systems (Pecora & Carroll, 1990). Since these pioneering studies, various types of chaos control and synchronization methods such as active control, linear feedback control, sliding mode control, impulsive control, passive control and backstepping design have been proposed and applied to the chaotic systems. Among them, the most preferred and effective one for the synchronization is the active control method. It has been used for the synchronization of many chaotic systems such as Lorenz (Bai & Lonngren, 1997; Bai & Lonngren, 2000), Rossler (Agiza & Yassen, 2001), Chen (Agiza & Yassen, 2001), unified (Ucar, Lonngren, & Bai, 2006), Bonhöffer–Van der Pol (Njah & Vincent, 2009), Vilnius (Kocamaz & Uyaroglu, 2014a) and many others. To control chaotic systems, linear feedback control method is widely preferred due to configuration simplicity. It has been successfully applied to control many chaotic systems such as Lorenz (Jianzu & Vincent, 1997), Rossler (Hegazi, Agiza, & El-Dessoky, 2001), Chen (Gambino, Lombardo, & Sammartino, 2006), Liu (Wang & Li, 2010), Rucklidge (Kocamaz & Uyaroglu, 2014b) and many others.

In recent years, many researchers have investigated the topics of supply chain modeling, planning, analysis and management. Hou, Zeng, and Zhao (2009) studied an integrated model of production, inventory and distribution in a two-stage supply chain. Then, Glock (2011) used it together with integrated inventory model. But Amorim, Gunther, and Almada-Lobo (2012) applied it to perishable products. Zhang and Zhou (2012) developed a novel nonlinear complementarity formulation for a supply chain network equilibrium model and some qualitative properties of the model regarding the existence and uniqueness were established under weaker conditions. Yuan and Hwarng (2012) analyzed the impact of customers' behavior and purchasing decisions on stability with a chaos perspective. Kumar and Tiwari (2013) investigated risk pooling effects of safety stock and running inventory in a supply chain system to minimize the cost along with determining facility location and capacity. In number of studies, supply chain management systems have some unpredictable factors in their dynamics and they have resulted in nonlinearity and chaos (Donner, Scholz-Reiter, & Hinrichs, 2008; Fawcett & Waller, 2011; Lu, Tang, & Tang, 2004; Ramirez & Pena, 2011). For instance, inventory system, planning and scheduling system may cause chaotic behaviors in system components and inventory levels under different stages.

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During the supply chain stages, information sharing process between the elements of chain distortions, incorrect inventory policies followed by sub-level suppliers and unsuitable demand forecasting methods based on high level of demand and supply to increase the process variability may cause significant problems for companies. It was firstly expressed by Forrester in 1961 (Towill, Zhou, & Disney, 2007). Then, a negative effect of aforementioned problems was detected by some researchers during the stages with different perspectives when examining the process variability (Burbidge, 1989; Houlihan, 1987). Afterwards, all of these studies have combined and the negative status is named as "Bullwhip Effect" (Lee, Padmanabhan, & Whang, 1997). Many studies have been carried out to measure, control and find the evidence of bullwhip effect in real life business environments, which has great importance both theoretical and empirical purposes. Five major causes of the bullwhip effect are defined as: the usage of demand signal processing, non-zero lead times, order batching, supply shortages and price fluctuations (Hwarng & Xie, 2008; Lee et al., 1997).

Chaos at inventory levels and production strategies causes some undesirable problems which could be controlled. The control and synchronization of nonlinear behaviors in supply chain have great importance from the management point of view to avoid undesirable behaviors such as bullwhip effect. Recently, the control and synchronization of chaos in supply chain have been investigated in some studies. The benefits of sharing information about end-customer demand throughout a multi-level supply chain were shown and a control engineering based measure was proposed to quantify the variance amplification (Dejonckheere, Disney, Lambrecht, & Towill, 2004). The chaos synchronization of bullwhip effect in a supply chain system was implemented by using radial basis function neural networks (Zhang, Li, & Xu, 2006). Then, the bullwhip effect on the supply chain was counteracted by the linear control theory (Wang, Chen, Fu, Li, & Hong, 2006). Afterwards, H-∞ control technique was proposed for the management of a supply chain model linearized with nominal operating conditions (Boccadoro, Martinelli, & Valigi, 2008). A robust-intelligent controller based on sliding mode control theory and radial basis function neural network was presented to reduce the bullwhip effect in supply chain management (Ghane, Zarvandi, & Yousefi, 2010). In recent years, robust control technique has been proposed with the aim of reducing the bullwhip effect in periodic-review inventory systems with variable lead-time (Ignaciuk & Bartoszewicz, 2011). The control of bullwhip effect in a supply chain management system has significant importance due to eliminating undesirable oscillations and decreasing uncertainties. Thus, it increases the effectiveness of the system.

This study carries on further investigations on the synchronization and control of chaotic behavior in supply chain management system. For this purpose, active controllers and linear feedback controllers are employed to achieve the synchronization and control, respectively. Stability analyses of the proposed methods are provided by using the Lyapunov stability theory. Numerical simulations are also given to verify the effectiveness of synchronization and control results.

This paper is organized as follows: In Section 2, the chaotic behavior in supply chain management system is described in detail. Active control method is applied to chaotic supply chain system to achieve the synchronization and the simulation results of synchronization are demonstrated in Section 3. In Section 4, the control of chaos in supply chain system via linear feedback control method is applied and demonstrated. Finally, concluding remarks are given in Section 5.

2. Description of chaotic supply chain system

The chaotic behavior in supply chain is described by a set of three autonomous differential equations as (Zhang et al., 2006):

$$\begin{aligned}\dot{x} &= (m+\delta m)y-(n+1+\delta n)x+d_1,\\ \dot{y} &= (r+\delta r)x-y-xz+d_2,\\ \dot{z} &= xy+(k-1-\delta k)z+d_3\end{aligned} \tag{1}$$

where x, y, z are state variables, m, n, r, k are constant parameters, δm, δn, δr, δk denote linear perturbation of system parameter m, n, r, k respectively when the system is perturbed, and d_1, d_2, d_3 are nonlinear perturbation in three different states which are in general from the system outside.

As seen in Fig. 1, the supply chain system includes three levels: end-customers, distributors and producers. x, y and z represent demand, inventory and produced quantities, respectively. m is delivery efficiency of distributors and n is ratio of customer demand. r and k denote distortion and safety stock coefficients. δm, δn, δr and δk indicate linear distortions and disorders in these three levels. d_1, d_2 and d_3 are nonlinear changes in different levels of the supply chain system. When the parameter values of supply chain system are considered as in Table 1, it exhibits chaotic behavior (Zhang et al., 2006).

Under the initial conditions $x(0) = 0$, $y(0) = -0.11$ and $z(0) = 9$, the time series, 2D phase portraits and 3D phase plane of chaotic supply chain system are shown in Fig. 2, Fig. 3 and Fig. 4, respectively.

3. Synchronization of chaos in supply chain system

3.1. Synchronization

It is assumed that two supply chain systems are taken where the initial positions are different so as to observe the synchronization of chaos in supply chain. The drive system which is denoted by subscript 1 is to control the response system which is denoted by subscript 2. They are defined as follows:

$$\begin{aligned}\dot{x}_1 &= (m+\delta m)y_1-(n+1+\delta n)x_1+0.2\sin(t),\\ \dot{y}_1 &= (r+\delta r)x_1-y_1-x_1z_1+0.1\cos(5t),\\ \dot{z}_1 &= x_1y_1+(k-1-\delta k)z_1+0.3\sin(t)\end{aligned} \tag{2}$$

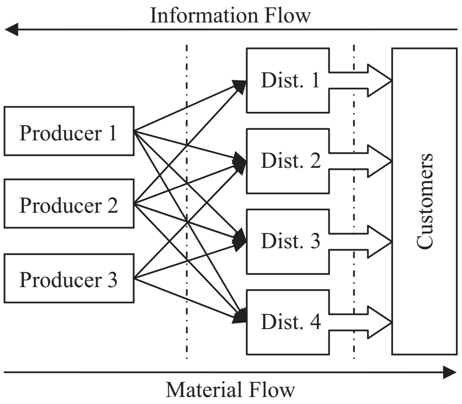

Fig. 1. A model of supply chain system.

Table 1
Values of the chaotic supply chain system parameters.

Parameters	m	n	r	k	δm	δn	δr	δk	d_1	d_2	d_3
Values	10	9	28	−5/3	0.1	0.1	0.2	0.3	0.2sin(t)	0.1cos(5t)	0.3sin(t)