TELKOMNIKA, Vol. 11, No. 2, February 2013, pp. 926~934
ISSN: 2302-4046

Adaptive Control of Rotor-bearing System with Coupling Faults of Pedestal Looseness and Rub-impact

JIA Limin*[1], YAO Dechen[1], LI Xiaofeng[1], QIN Yong[1], CAI Guoqiang[1]
[1]State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University Beijing, China
*Corresponding author, e-mail: shmily137@sina.com

Abstract

Pedestal looseness and rub-impact are two important faults in rotating machinery. Once the Pedestal looseness is developed in a rotor system, the rotor is more likely to make contact with stator under tight clearance conditions. Due to the presence of both Pedestal looseness and rub-impact, the whole system becomes highly nonlinear and instability. The present study is aimed to simulate a chaotic system of the nonlinear rotor system and the system can adaptively be converted to normal working state under the circumstance of the chaotic state occasioned by outside perturbation for the complicated chaotic system. The nonlinear dynamic equations of rotor-bearing system with coupling faults of pedestal looseness and rub-impact force are derived and a multi-parameter adaptive control algorithm is given. As a result, it is found that those systems possess various nonlinear dynamical inherences. The numerical results also show that the parametric adaptive control method is appropriate to those rotor-bearing systems, outside interference under the state of chaos arising from the situation can be adaptive to adjust to normal working condition. It has strongly control capability of stability. The theoretical and practical idea for controlling rotor–bearing systems and optimizing their operation can be more precise.

Keywords: *rotor-bearing system, pedestal looseness, rub-impact force, chaotic system, adaptive control, simulation*

1. Introduction

Rotating machinery is commonly used in our society for a wide range of energy conversion applications, such as electric power, mechanical power, fluid pumping, propulsion, ventilation and cooling, etc [1]. It is well known that the failure of a mechanical system is always accompanied with the changes from linear or weak nonlinear to strong nonlinear dynamics. In rotating machinery in which faults appear, for example, one generally finds evidence of a complicated nonlinear vibrating system. Chaotic motion can be found in rotating machinery with rotor-to-stator rub, loose pedestal, an unstable oil film and a cracked rotor [2–6].

The rotor-to-stator impact causes changes in the system force balance and its dynamic behavior. Many causes may exist for the occurrence of the rub-impact in rotating machinery, which include rotor vibrations due to imbalance, displacements of the rotor centerline due to rotor misalignment, rotor permanent bow, or fluid-related constant radial forces. Therefore a number of articles on this topic have been published to analyze the nonlinear dynamics of rub-impact rotor. Erich [7] studied the effects of chaos and subcritical superharmonic response in a system with rotor to stator contact. Real data of an aero engine were supplied to compare with numerical simulation. Zhang et al. [8] analyzed the rub–impact caused by geometric asymmetry between the rotor and stator, and studied the grazing phenomenon of the single point rubbing in detail. Dai et al. [9] designed an experiment of rotor/stop rubbing, and analyzed its vibration responses. Chu and Zhang [10] investigated the non-linear vibration characteristics of a rub-impact Jeffcott rotor. They also found that when the rotating speed increase, the grazing bifurcation, the quasi-periodic motion and chaotic motion occur after the rub-impact.

Pedestal looseness is one of the common faults that occur in rotating machinery. It is usually caused by the poor quality of installation or long period of vibration of the machine. Under the action of the imbalance force, the rotor system with pedestal looseness will have a periodic beating. This will generally lead to a change in stiffness of the system and the impact effect. Therefore, the system will often show very complicated vibration phenomenon. The

Received September 13, 2012; Revised December 31, 2012; Accepted January 15, 2013

pedestal looseness will occur for long-term vibration of rotating machinery and it will cause piecewise nonlinear characteristic of the pedestal support [11-13]. The rotor systems with loosing foundation were studied by several investigators. Goldman and Muszynska [14] performed experimental, analytical and numerical investigations on the unbalance response of a rotating machine with one loose pedestal. The model was simplified as a vibrating system with bi-linear form. Synchronous and subsynchronous fractional components of the response were found. In a subsequent paper [15], they discussed the chaotic behavior of the system based on the bi-linear model.

As the predictability of chaos, it is very difficult to control the observed error signal during a period of given time to zero by the common method. The statistical prediction technology is taken up to control the chaotic system by Hubler [16]. Ho M. C. [17] studied the generalized synchronization between driving system and respond system by approximately steps, but this method can't estimate all the parameters of driving system. Reference [18] represented a method to control the chaos system, but it is linear synchronization method and can't control the chaos system accurately. Guan xinping [19] achieved the synchronization of Ameodo system by nonlinear state feedback.The references listed above adopted the nonlinear method or adaptive control method, but they did not take account of parameter excitation of the chaos system at the same time.

In this paper, a dynamic model of the rotor-bearing system with coupling faults is set up and a multi-parameter adaptive control algorithm is given. The simulation results show that the methodology is appropriate to the rotor and stator system, outside interference under the state of chaos arising from the situation can be adaptive to adjust to normal working condition. The results are helpful for fault diagnoses, dynamic design, and security running of rotor-bearing systems.

2. Model and Differential Equation of Rotor-Bearing Systems with the Pedestal Looseness and Rub-Impact Force

Model of the rotor-bearing systems with the pedestal looseness and rub-impact force are shown as Figure1.

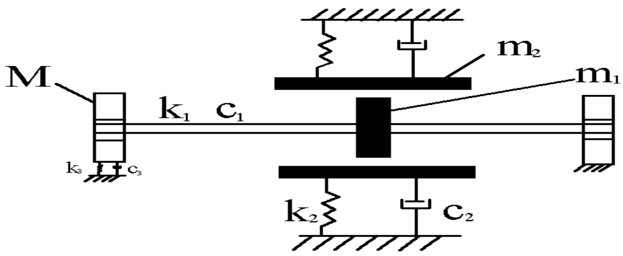

Figure 1. Mechanical Model of Rotor-Bearing Systems with the Pedestal Looseness and Rub-Impact Force

$$\begin{cases} m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 - k_r(1-\frac{\delta}{r})(x_2 - x_1 \\ \quad + \mu(y_1 - y_2)) = m_1e\Omega^2\cos(\Omega t) \\ m_1\ddot{y}_1 + c_1(\dot{y}_1 - \dot{y}_3) + k_1(y_1 - y_3) - k_r(1-\frac{\delta}{r}) \\ \quad (-\mu(x_1 - x_2) + y_2 - y_1) = \\ \quad m_1e\Omega^2\sin(\Omega t) - m_1g \\ m_2\ddot{x}_2 + c_2\dot{x}_2 + k_2x_2 + k_r(1-\frac{\delta}{r})(x_2 - x_1 \\ \quad + \mu(y_1 - y_2)) = 0 \\ m_2\ddot{y}_2 + c_2\dot{y}_2 + k_2y_2 + k_r(1-\frac{\delta}{r}) \\ \quad (-\mu(x_1 - x_2) + y_2 - y_1) = -m_2g \\ M\ddot{y}_3 + c_3\dot{y}_3 + k_3y_3 = c_1(\dot{y}_1 - \dot{y}_3) \\ \quad + k_1(y_1 - y_3) - Mg \end{cases} \qquad \delta < r \qquad (1a)$$

Shaft coupling connects the motor and rotor. The system mass is equivalently concentrated on the center of every disc and bearing support respectively. The torsional vibration and gyro moment are neglected and only the lateral vibration of system is considered. Both ends of rotor are supported by journal bearings with symmetrical structures. The motion differential equation of the rotor-bearing system considering the pedestal looseness and rub-impact force is:

$$\begin{cases} m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1 x_1 = m_1 e\Omega^2\cos(\Omega t) \\ m_1\ddot{y}_1 + c_1(\dot{y}_1 - \dot{y}_3) = \\ \quad m_1 e\Omega^2\sin(\Omega t) - m_1 g \\ m_2\ddot{x}_2 + c_2\dot{x}_2 + k_2 x_2 = 0 \\ m_2\ddot{y}_2 + c_2\dot{y}_2 + k_2 y_2 = -m_2 g \\ M\ddot{y}_3 + c_3\dot{y}_3 + k_3 y_3 = c_1(\dot{y}_1 - \dot{y}_3) \\ \quad + k_1(y_1 - y_3) - Mg \end{cases} \qquad \delta \geq r \qquad (1b)$$

Suppose $\tau = \Omega t$, $\tilde{x}_1 = \frac{x_1}{\delta}$, $\tilde{y}_1 = \frac{y_1}{\delta}$, $\tilde{x}_2 = \frac{x_2}{\delta}$, $\tilde{y}_2 = \frac{y_2}{\delta}$, $\tilde{y}_3 = \frac{y_3}{\delta}$, $\dot{\tilde{x}}_1 = \frac{d\tilde{x}_1}{d\tau}$, $\dot{\tilde{y}}_1 = \frac{d\tilde{y}_1}{d\tau}$, $\dot{\tilde{x}}_2 = \frac{d\tilde{x}_2}{d\tau}$, $\dot{\tilde{y}}_2 = \frac{d\tilde{y}_2}{d\tau}$, $\dot{\tilde{y}}_3 = \frac{d\tilde{y}_3}{d\tau}$, $\ddot{\tilde{x}}_1 = \frac{d^2\tilde{x}_1}{d\tau^2}$, $\ddot{\tilde{y}}_1 = \frac{d^2\tilde{y}_1}{d\tau^2}$, $\ddot{\tilde{x}}_2 = \frac{d^2\tilde{x}_2}{d\tau^2}$, $\ddot{\tilde{y}}_2 = \frac{d^2\tilde{y}_2}{d\tau^2}$, $\ddot{\tilde{y}}_3 = \frac{d^2\tilde{y}_3}{d\tau^2}$, $\xi_1 = \frac{c_1}{m_1\Omega}$, $\xi_2 = \frac{c_2}{m_2\Omega}$, $\alpha_1 = \frac{k_1}{m_1\Omega^2}$, $\alpha_2 = \frac{k_2}{m_2\Omega^2}$, $\beta_1 = \frac{k_r}{m_1\Omega^2}$, $\beta_2 = \frac{k_r}{m_2\Omega^2}$, $\rho = \frac{e}{\delta}$, $G = \frac{g}{\delta\Omega^2}$, $\xi_3 = \frac{c_3}{M\Omega}$, $\alpha_3 = \frac{k_3}{M\Omega}$, $\phi_3 = \frac{k_1}{M\Omega^2}$, the equation (1) may change into:

$$\begin{cases} \ddot{\tilde{x}}_1 + \xi_1\dot{\tilde{x}}_1 + \alpha_1\tilde{x}_1 - \beta_1(1-\frac{1}{\gamma})(\tilde{x}_2 - \tilde{x}_1 \\ \quad + \mu(\tilde{y}_1 - \tilde{y}_2)) = \rho\cos(\tau) \\ \ddot{\tilde{y}}_1 + \xi_1\dot{\tilde{y}}_1 + \alpha_1\tilde{y}_1 - \beta_1(1-\frac{1}{\gamma})(-\mu(\tilde{x}_1 - \tilde{x}_2) \\ \quad + \tilde{y}_2 - \tilde{y}_1) = \rho\sin(\tau) - G \\ \ddot{x}_2 + \xi_2\dot{x}_2 + \alpha_2 x_2 + \beta_2(1-\frac{1}{\gamma}) \\ \quad (\tilde{x}_2 - \tilde{x}_1 + \mu(\tilde{y}_1 - \tilde{y}_2)) = 0 \\ \ddot{y}_2 + \xi_2\dot{y}_2 + \alpha_2 y_2 + \beta_2(1-\frac{1}{\gamma}) \\ \quad (-\mu(\tilde{x}_1 - \tilde{x}_2) + \tilde{y}_2 - \tilde{y}_1) = -G \\ \ddot{\tilde{y}}_3 + \xi_3\dot{\tilde{y}}_3 + \alpha_3\tilde{y}_3 = \zeta_3(\dot{\tilde{y}}_1 - \dot{\tilde{y}}_3) \\ \quad + \phi_3(\tilde{y}_1 - \tilde{y}_3) - G \end{cases} \qquad \delta < r$$

(2a)

$$\begin{cases} \ddot{\tilde{x}}_1 + \xi_1\dot{\tilde{x}}_1 + \alpha_1\tilde{x}_1 = \rho\cos(\tau) \\ \ddot{\tilde{y}}_1 + \xi_1\dot{\tilde{y}}_1 + \alpha_1\tilde{y}_1 = \rho\sin(\tau) - G \\ \ddot{x}_2 + \xi_2\dot{x}_2 + \alpha_2 x_2 = 0 \\ \ddot{y}_2 + \xi_2\dot{y}_2 + \alpha_2 y_2 = -G \\ \ddot{\tilde{y}}_3 + \xi_3\dot{\tilde{y}}_3 + \alpha_3\tilde{y}_3 = \zeta_3(\dot{\tilde{y}}_1 - \dot{\tilde{y}}_3) \\ \quad + \phi_3(\tilde{y}_1 - \tilde{y}_3) - G \end{cases} \qquad \delta \geq r \qquad (2b)$$

3. Parametric Adaptive Control of Multi-Parametric Non-Autonomous Chaotic Systems

Consider the general non-autonomous systems:

$$\frac{\mathrm{d}\boldsymbol{x}}{\mathrm{d}t}=\boldsymbol{F}(\boldsymbol{x},t,\boldsymbol{\mu}) \tag{3}$$

where the system state vector $\boldsymbol{x}\in\boldsymbol{R}^{\mathrm{n}}$, time $t\in\boldsymbol{R}$, parameter $\boldsymbol{\mu}\in\boldsymbol{R}^{\mathrm{m}}$, F: $\boldsymbol{R}^{\mathrm{n}}\times\boldsymbol{R}\times\boldsymbol{R}^{\mathrm{m}}\to\boldsymbol{R}^{\mathrm{n}}$. Suppose parameter $\boldsymbol{\mu}$ is linear with respect to F, then equation (3) can be written as

$$\frac{\mathrm{d}\boldsymbol{x}}{\mathrm{d}t}=\varphi(\boldsymbol{x},t)+\sum_{k=1}^{\mathrm{m}}\boldsymbol{\psi}_k(\boldsymbol{x},t)\mu_k \tag{4}$$

where φ , $\boldsymbol{\psi}_k:\boldsymbol{R}^{\mathrm{n}}\times\boldsymbol{R}\to\boldsymbol{R}^{\mathrm{n}}$, $k=(1,2,\cdots,\mathrm{m})$, $\boldsymbol{\mu}=(\mu_1,\cdots,\mu_{\mathrm{m}})$ is parameter vector, these control parameter determine the asymptotic behavior of the orbits. The objective of control is to adjust the parameter vector to the predicted value. The parameter value variation can be distinguished through the global dynamic system. Namely, depend on deviation relationship between the system variable *x* and reference model variable *y*, the variation of parameter can be controlled [20]. Consider the reference model:

$$\frac{\mathrm{d}\boldsymbol{y}}{\mathrm{d}t}=\boldsymbol{F}_M(\boldsymbol{y},t,\boldsymbol{\mu}_g) \tag{5}$$

Choice of adaptive control law is

$$\frac{\mathrm{d}\boldsymbol{\mu}}{\mathrm{d}t}=\boldsymbol{\beta}(\boldsymbol{x},t)\cdot\boldsymbol{G}(\boldsymbol{e}) \tag{6}$$

where $\boldsymbol{\beta}$: $\boldsymbol{R}^{\mathrm{n}}\times\boldsymbol{R}\to\boldsymbol{R}^{\mathrm{m}}$, $\boldsymbol{G}$: $\boldsymbol{R}^{\mathrm{n}}\to\boldsymbol{R}^{\mathrm{m}\times\mathrm{m}}$ are the continuous function, $\boldsymbol{e}=\boldsymbol{x}-\boldsymbol{y}$. Generally, $\boldsymbol{G}$ is the nonlinear function of derivation of signal errors. The difficult point of the equation (6) lies in how to choose $\boldsymbol{G}$ properly.

For effective controlling the more complicated system, the output variable $\boldsymbol{x}(t)$ in equation (3) is fed back to the system (5). Then, we get the coupled equations from system (3) and system (5):

$$\frac{\mathrm{d}\boldsymbol{y}}{\mathrm{d}t}=\boldsymbol{F}_M(\boldsymbol{x},t,\boldsymbol{\mu}_g) \tag{7}$$

So we can predict the dynamic behavior of $\boldsymbol{y}(t)$ by use of the dynamic feedback of the system to reference model. The convergence of the parametric adaptive control law (6) can be improved. Therefore, the control coupled equations consist of equations (3), (7) and (6), as follows:

$$\frac{\mathrm{d}x_k}{\mathrm{d}t}=F_k(\boldsymbol{x},t,\boldsymbol{\mu}) \qquad (k=1,2,\ldots,\ n) \tag{8a}$$

$$\frac{\mathrm{d}y_k}{\mathrm{d}t}=F_{Mk}(\boldsymbol{x},t,\boldsymbol{\mu}_g) \qquad (k=1,2,\ldots,\ n) \tag{8b}$$

$$\frac{\mathrm{d}\mu_l}{\mathrm{d}t}=\beta_l(\boldsymbol{x},t)\cdot G_l(\dot{\boldsymbol{e}}) \qquad (l=1,2,\ldots,\ m) \tag{8c}$$

where $\dot{\boldsymbol{e}}=\dot{\boldsymbol{x}}-\dot{\boldsymbol{y}}$. For convenience sake, suppose that dynamic model is the same as the dynamic system, namely, $\boldsymbol{F}_{\boldsymbol{M}}=\boldsymbol{F}$, $\boldsymbol{G}$ is defined as

$$G_l(z)=\sum_{k=1}^{n}z_k \qquad (l=1,2,\ldots,\ \ m) \tag{9}$$

where $z=(z_1,\cdots,z_n)^T\in R^n$, Further suppose $F(x,t,\mu)=\varphi(x,t)+\sum_{l=1}^{m}\psi_l(x,t)\cdot\mu_l$ Where φ, ψ_l : $R^n\times R\to R^n$ $\varphi(x,t)=(\varphi_1(x,t),\varphi_2(x,t),\cdots,\varphi_n(x,t))^T$ $\psi_l(x,t)=(\psi_{l1}(x,t),\psi_{l2}(x,t),\cdots,\psi_{ln}(x,t))^T$ (l = 1,2,…, m) $\psi_{lk}(x,t)$ (l = 1,2,…, m, k = 1, 2, …, n) is the real variable function of the continuous time t, Let the control stiffness $\beta_l(x,t)$ be as following equation.

$$\beta_l(x,t)=-\sum_{k=1}^{n}\psi_{lk}(x,t)\quad (l=1,2,\ldots,m) \tag{10}$$

Then the coupled equations of the control system can be represented as

$$\frac{dx_k}{dt}=\varphi_k(x,t)+\sum_{l=1}^{m}\psi_{lk}(x,t)\cdot\mu_l \tag{11a}$$

$$\frac{dy_k}{dt}=\varphi_k(x,t)+\sum_{l=1}^{m}\psi_{lk}(x,t)\cdot\mu_{lg} \tag{11b}$$

$$\frac{d\mu_l}{dt}=-\left(\sum_{k=1}^{n}\psi_{lk}(x,t)\right)\cdot\left(\sum_{p=1}^{m}\sum_{q=1}^{n}\psi_{pq}(x,t)\cdot(\mu_p-\mu_{pq})\right) \tag{11c}$$

4. The Study of Parameter Adaptive Control on Rotor-Bearing Systems With the Pedestal Looseness and Rub-Impact Force

As $\tilde{x}_1=\tilde{z}_1$, $\tilde{y}_1=\tilde{z}_2$, $\dot{\tilde{x}}_1=\tilde{z}_3$, $\dot{\tilde{y}}_1=\tilde{z}_4$, $\tilde{x}_2=\tilde{z}_5$, $\tilde{y}_2=\tilde{z}_6$, $\dot{\tilde{x}}_2=\tilde{z}_7$, $\dot{\tilde{y}}_2=\tilde{z}_8$, $\tilde{y}_3=\tilde{z}_9$, $\dot{\tilde{y}}_3=\tilde{z}_{10}$ the equation (2) may change into:

When $\delta<r$:

$$\frac{d\tilde{x}_1}{d\tau}=\tilde{z}_3 \tag{12a}$$

$$\frac{d\tilde{z}_3}{d\tau}=-\xi_1\tilde{z}_3-\alpha_1\tilde{z}_1+\rho\cos(\tau)+\beta_1(1-\frac{1}{\gamma})[\tilde{z}_5-\tilde{z}_1+\mu(\tilde{z}_2-\tilde{z}_6)] \tag{12b}$$

$$\frac{d\tilde{y}_1}{d\tau}=\tilde{z}_4 \tag{12c}$$

$$\frac{d\tilde{z}_4}{d\tau}=-\xi_1\tilde{z}_4-\alpha_1\tilde{z}_2+\rho\sin(\tau)+\beta_1(1-\frac{1}{\gamma})[\tilde{z}_6-\tilde{z}_2+\mu(\tilde{z}_1-\tilde{z}_5)]-G \tag{12d}$$

$$\frac{d\tilde{x}_2}{d\tau}=\tilde{z}_7 \tag{12e}$$

$$\frac{d\tilde{z}_7}{d\tau}=-\xi_2\tilde{z}_7-\alpha_2\tilde{z}_5-\beta_2(1-\frac{1}{\gamma})[\tilde{z}_5-\tilde{z}_1+\mu(\tilde{z}_2-\tilde{z}_6)] \tag{12f}$$

$$\frac{d\tilde{y}_2}{d\tau}=\tilde{z}_8 \tag{12g}$$

$$\frac{d\tilde{z}_8}{d\tau}=-\xi_2\tilde{z}_8-\alpha_2\tilde{z}_6-\beta_2(1-\frac{1}{\gamma})[\tilde{z}_6-\tilde{z}_2+\mu(\tilde{z}_1-\tilde{z}_5)] \tag{12h}$$

$$\frac{d\tilde{y}_3}{d\tau}=\tilde{z}_{10} \tag{12i}$$

$$\frac{d\tilde{z}_{10}}{d\tau}=-\xi_3\tilde{z}_6-\zeta_3(\tilde{z}_4-\tilde{z}_6)-\alpha_3\tilde{z}_5+\phi_3(\tilde{z}_2-\tilde{z}_5)-G \tag{12j}$$

When $\delta \geq r$

$$\frac{d\tilde{x}_1}{d\tau} = \tilde{z}_3 \quad (13a)$$

$$\frac{d\tilde{z}_3}{d\tau} = -\xi_1\tilde{z}_3 - \alpha_1\tilde{z}_1 + \rho\cos(\tau) \quad (13b)$$

$$\frac{d\tilde{x}_2}{d\tau} = \tilde{z}_4 \quad (13c)$$

$$\frac{d\tilde{z}_4}{d\tau} = -\xi_1\tilde{z}_4 - \alpha_1\tilde{z}_2 + \rho\sin(\tau) - G \quad (13d)$$

$$\frac{d\tilde{x}_5}{d\tau} = \tilde{z}_7 \quad (13e)$$

$$\frac{d\tilde{z}_7}{d\tau} = -\xi_2\tilde{z}_7 - \alpha_2\tilde{z}_5 \quad (13f)$$

$$\frac{d\tilde{x}_6}{d\tau} = \tilde{z}_8 \quad (13g)$$

$$\frac{d\tilde{z}_8}{d\tau} = -\xi_2\tilde{z}_8 - \alpha_2\tilde{z}_6 \quad (13h)$$

$$\frac{d\tilde{y}_3}{d\tau} = \tilde{z}_{10} \quad (13i)$$

$$\frac{d\tilde{z}_{10}}{d\tau} = -\xi_3\tilde{z}_6 - \zeta_3(\tilde{z}_4 - \tilde{z}_6) - \alpha_3\tilde{z}_5 + \phi_3(\tilde{z}_2 - \tilde{z}_5) - G \quad (13j)$$

When $\xi_1 = 0.1110$, $\alpha_1 = 0.0666$, $\rho = 0.5$ the system presents chaos state, as shown in Figure 2.

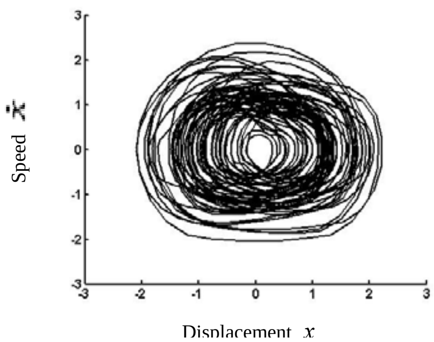

Figure 2. Chaos of the System Before Controlling

Consider the system model (12) and (13), When $\xi_1 = 0.8877$, $\alpha_1 = 0.3996$, $\rho = 2$ the system presents Normal working condition. Supposes system's reference model take as:

When $\delta < r$:

$$\frac{d\tilde{x}_1}{d\tau} = \tilde{z}_3 \quad (14a)$$

$$\frac{d\tilde{z}_3}{d\tau} = -0.8877\tilde{z}_3 - 0.3996\tilde{z}_1 + 2\cos(\tau) + 3.4131(1 - \frac{1}{2.7531})[\tilde{z}_5 - \tilde{z}_1 + 0.06(\tilde{z}_2 - \tilde{z}_6)] \quad (14b)$$

$$\frac{d\tilde{x}_2}{d\tau}=\tilde{z}_4 \quad (14c)$$

$$\frac{d\tilde{z}_4}{d\tau}=-0.8877\tilde{z}_4-0.3996\tilde{z}_2+2\sin(\tau)+3.4131(1-\frac{1}{2.7531})[\tilde{z}_6-\tilde{z}_2+0.06(\tilde{z}_1-\tilde{z}_5)]-0.1632 \quad (14d)$$

$$\frac{d\tilde{x}_5}{d\tau}=\tilde{z}_7 \quad (14e)$$

$$\frac{d\tilde{z}_7}{d\tau}=-0.0555\tilde{z}_7-1.7066\tilde{z}_5-1.7066(1-\frac{1}{2.7531})[\tilde{z}_5-\tilde{z}_1+0.06(\tilde{z}_2-\tilde{z}_6)] \quad (14f)$$

$$\frac{d\tilde{x}_6}{d\tau}=\tilde{z}_8 \quad (14g)$$

$$\frac{d\tilde{z}_8}{d\tau}=-0.0555\tilde{z}_8-1.7066\tilde{z}_6-1.7066(1-\frac{1}{2.7531})[\tilde{z}_6-\tilde{z}_2+0.06(\tilde{z}_1-\tilde{z}_5)] \quad (14h)$$

$$\frac{d\tilde{y}_3}{d\tau}=\tilde{z}_{10} \quad (14i)$$

$$\frac{d\tilde{z}_{10}}{d\tau}=-0.0015\tilde{z}_6-0.0012(\tilde{z}_4-\tilde{z}_6)-0.0222\tilde{z}_5+0.0133(\tilde{z}_2-\tilde{z}_5)-0.1632 \quad (14j)$$

When $\delta \geq r$

$$\frac{d\tilde{x}_1}{d\tau}=\tilde{z}_3 \quad (15a)$$

$$\frac{d\tilde{z}_3}{d\tau}=-0.8877\tilde{z}_3-0.3996\tilde{z}_1+2\cos(\tau) \quad (15b)$$

$$\frac{d\tilde{x}_2}{d\tau}=\tilde{z}_4 \quad (15c)$$

$$\frac{d\tilde{z}_4}{d\tau}=-0.8877\tilde{z}_4-0.3996\tilde{z}_2+2\sin(\tau)-0.1632 \quad (15d)$$

$$\frac{d\tilde{x}_5}{d\tau}=\tilde{z}_7 \quad (15e)$$

$$\frac{d\tilde{z}_7}{d\tau}=-0.0555\tilde{z}_7-1.7066\tilde{z}_5 \quad (15f)$$

$$\frac{d\tilde{x}_6}{d\tau}=\tilde{z}_8 \quad (15g)$$

$$\frac{d\tilde{z}_8}{d\tau}=-0.0555\tilde{z}_8-1.7066\tilde{z}_6 \quad (15h)$$

$$\frac{d\tilde{y}_3}{d\tau}=\tilde{z}_{10} \quad (15i)$$

$$\frac{d\tilde{z}_{10}}{d\tau}=-0.0015\tilde{z}_6-0.0012(\tilde{z}_4-\tilde{z}_6)-0.0222\tilde{z}_5+0.0133(\tilde{z}_2-\tilde{z}_5)-0.1632 \quad (15j)$$

Assume that the parameters ξ_1, α_1, ρ in the system are deviated from the desired values ($\xi_1=0.8877, \alpha_1=0.3996, \rho=2$) while the system is perturbed. Suppose that the parameters are changed to $\xi_1=0.1110, \alpha_1=0.0666, \rho=0.5$, after the perturbation. At this time, the system is in a chaos state. Now we control the parameters in the system (12) and (13) to feed back to the desired values so that the perturbed system in the chaos state is fed back to the normal working state. We obtain the following equations with the adaptive control law:

$$\frac{d\xi_1}{d\tau} = -(-\tilde{z}_3)[-\tilde{z}_3(\xi_1 - 0.8877) - \tilde{z}_1(\alpha_1 - 0.3996) + \cos(\tau)(\rho - 2)] \tag{16a}$$

$$\frac{d\alpha_1}{d\tau} = -(-\tilde{z}_1)[-\tilde{z}_3(\xi_1 - 0.8877) - \tilde{z}_1(\alpha_1 - 0.3996) + \cos(\tau)(\rho - 2)] \tag{16b}$$

$$\frac{d\rho}{d\tau} = -\cos(\tau)[-\tilde{z}_3(\xi_1 - 0.8877) - \tilde{z}_1(\alpha_1 - 0.3996) + \cos(\tau)(\rho - 2)] \tag{16c}$$

Figure 3 is single-cycle state after the adaptive control, Figure 4~ Figure 6 are system entering chaos state by disturbing, after adaptive control, the system enters into normal working state.

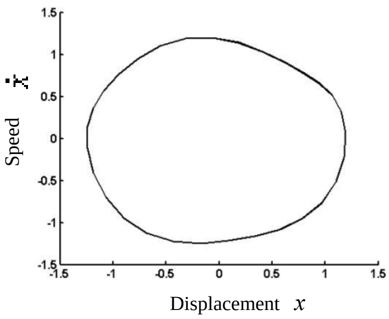

Figure 3. Normal Track of the System After Controlling

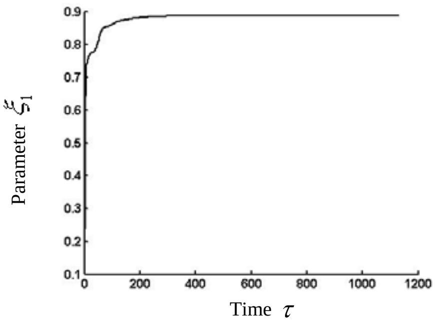

Figure 4. Parameter ξ_1 Reach its Target Value ξ_1=0.8877

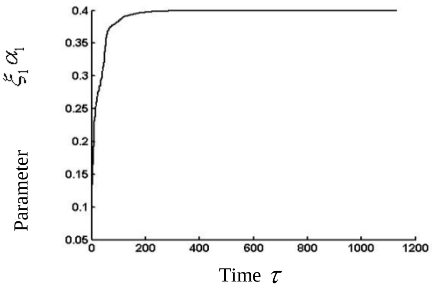

Figure 5. Parameter α_1 Reach its Target Value α_1=0.3996

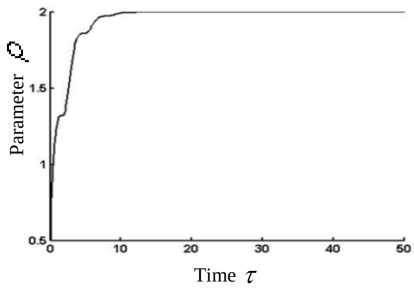

Figure 6. Parameter ρ Reach its Target Value ρ=2

5. Conclusions

From the above computations and analyses, it can be observed that in the rotor system, the nonlinear response will evolve from one type of motion to another under grazing bifurcation. The conclusions drawn from the study can be summarized as follows:

(1) Nonlinear dynamic model of the nonlinear rotor-bearing system with coupling faults of pedestal looseness and rub-impact was set up.

(2) The multi-parametric adaptive control method suggested in the paper is successfully applied to simulate a chaotic system of the nonlinear rubbing rotor system and the system can adaptively be converted to normal working state under the circumstance of the chaos state occasioned by outside perturbation for the multi-parametric non-autonomous complicated chaos system.

(3) The parametric adaptive control law given in the paper has strongly control capability of stability.

References

[1] Wen-Ming Zhang, Guang Meng. Stability, bifurcation and chaos of a high-speedrub-impact rotor system in MEMS. *Sensors and Actuators*. 2006; 127(2): 163-178.
[2] Chen CL, Yao HT. Chaos in the imbalance response of a flexible rotor supported by oil film bearings with nonlinear suspension. Nonlinear Dynamics. 1998; 16(1): 71-90.
[3] Alvaro Vargas-Clara, Sangram Redkar. Dynamics and Control of a Stop Rotor Unmanned Aerial Vehicle. *International Journal of Electrical and Computer Engineering.* 2012; 2(5), 597-608.
[4] Bechar University, Algeria, A Decoupled Parameters Estimators for in Nonlinear Systems Fault diagnosis by ANFIS. *International Journal of Electrical and Computer Engineering*. 2012; 2(2): 166-174.
[5] Chu FL, Zhang Z S. Periodic, quasi-periodic and chaotic vibrations of a rub-impact system supported on oil film bearings. *International Journal of Engineering Science.* 1997; 35(11): 963-973.
[6] Muller PC, Bajkowski J, Soffke D. Chaotic motions and fault detection in a cracked rotor. *Nonlinear Dynamics*. 1994; 5(2): 233–254.
[7] FF Ehrich. High order subharmonic response of high speed rotors in bearing clearance, in Design Transactions of the ASME. *Journal of Vibration, Acoustics, Stress and Reliability*. 1988; 110(1): 8-16.
[8] S Zhang, Q Lu, Q Wang. Analysis of rub–impact events for a rotor eccentric from the case. *Journal of Vibration Engineering*. 1998; 11(4): 492-496.
[9] X Dai, X Zhang, Z Jin. Experiments of partial and full rotor/stop rubbing. *Journal of Aerospace Power*. 2000; 15(4): 405-409.
[10] F Chu, Z Zhang. Bifurcation and chaos in rub-impact jeffcott rotor system. *Journal of Sound and Vibration*. 1998; 210(1): 1-18.
[11] Z Ji, JW Zu. Method of multiple scales for vibration analysis of rotor shaft systems with non-linear bearing pedestal model. *Journal of Sound and Vibration*. 1998; 218(2): 293-305.
[12] F Chu, Z Zhang. Stability and non-linear responses of a rotor bearing system with pedestal looseness. *Journal of Sound and Vibration.* 2001; 241(5): 879-893.
[13] YG Luo, YH Du, XD Liu, et al. Study on dynamics and fault characteristics of two-span rotor-bearing system with pedestal looseness. *Journal of Mechanical Strength.* 2006; 28(3): 327-331.
[14] P Goldman, A Muszynska. Analytical and experimental simulation of loose pedestal dynamic effects on a rotating machine vibrational response, Rotating Machinery and Vehicle Dynamics. *American Society of Mechanical Engineers*. 1991; 35: 11-17.
[15] P Goldman, A Muszynska, Chaotic responses of unbalanced rotor-bearing stator systems with looseness or rubs, Chaos Solitons & Fractals. 1995; 5(9): 1683-1704.
[16] A Hubler. Adaptive Control of Chaotic System. TUM preprint, LR3895, Helv. Phys. Acta. 1989; 62: 343-346.
[17] MC Ho, YC Hung, ZY Liu, IM Jiang: submitted to Phys. Lett. 2006: 32-64.
[18] C Qinzong. Theory and Design of Linear System. Science Press: Beijing. 1998; 56-80.
[19] G Xinping, F Zhengping, C Cailian, H Changchun. Chaos Control and Application in Security Communication. National Defiance Industry Press: Beijing. 2002; 70-95.
[20] Yin Yufeng, Yao Dechen, Li Jie. Adaptive Control of Nonlinear Cracked Rotor Seal Chaotic System. *Transactions of Chinese Society for Agricultural Machinery.* 2009; 40(7): 203-207.