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非线性刚性转子－轴承系统的混沌研究

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摘 要: 以转子动力学和非线性动力学理论为基础, 针对非线性转子－轴承系统的具体特点, 用数值积分和庞加莱映射方法对采用短轴承模型的刚性 Jeffcott 转子轴承系统在较宽参数范围内进行稳定性研究。计算结果表明, 系统存在混沌运动。用数值方法得到系统在某些参数域中的分叉图、响应曲线、频谱图、相图、轴心轨迹、及庞加莱映射图, 直观显示了系统在某些参数域中的运行状态; 同时, 由轴承几何尺寸对系统稳定性的影响进行了分析, 数值分析结果为该类转子－轴承系统的设计和安全运行提供理论参考。

关 键 词: 转子动力学; 非线性转子－轴承系统; 混沌; 稳定性

中图分类号: TH133.3 文献标识码: A

1 引言

转子－轴承系统是各类旋转机械的常见结构, 对于该类系统的描述, 稍微准确一些的方程都是非线性的[1], 人们对非线性转子－轴承系统进行了大量的研究, 文献[2]用打靶法和连续算法, 对经模态降维的转子－轴承系统求解了周期解; 文献[3]用伪不动点追踪法对该类系统多重周期解进行了计算。由于系统中非线性油膜力的存在, 使转子－轴承系统的振动在分叉点附近会产生突变, 给系统带来巨大危害。本文的主要工作是研究一个具有两个自由度的非线性转子－轴承系统稳态周期响应的分叉问题。用数值算法得到了系统的周期解、分叉图、时间波形、轴心轨迹图、频谱图及庞加莱映射图, 直观显示了系统的运动状态和特点, 分析结果为定性控制采用该类轴承的转子－轴承系统的稳定性提供了理论依据。

2 非线性 Jeffcott 转子模型

非线性 Jeffcott 转子－轴承系统的数学模型如图 1 所示。

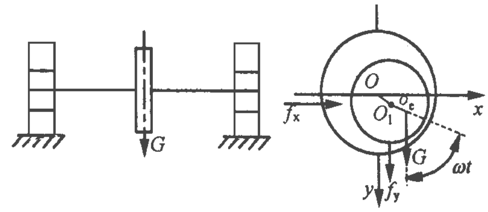

图 1 Jeffcott 转子轴承系统

图 1 $G=\frac{g}{c\omega^2}$－无量纲外载荷, o－轴瓦几何中心, o_1－转子几何中心, o_c－转子质心, ω－转子角速度。在无量纲偏心为 $\rho=e/c$ 时, 系统的状态方程为:

$$\begin{cases}\dfrac{\mathrm{d}x_1}{\mathrm{d}\tau}=x_3\\ \dfrac{\mathrm{d}x_2}{\mathrm{d}\tau}=x_4\\ \dfrac{\mathrm{d}x_3}{\mathrm{d}\tau}=\dfrac{1}{m}f_x+\rho\cos\tau\\ \dfrac{\mathrm{d}x_4}{\mathrm{d}\tau}=\dfrac{1}{m}f_y+\rho\sin\tau-G\end{cases}\tag{1}$$

其中, $\{x_1, x_2, x_3, x_4\}^T=\left\{x, y, \frac{\mathrm{d}x}{\mathrm{d}\tau}, \frac{\mathrm{d}y}{\mathrm{d}\tau}\right\}^T$ 为状态变量, 是轴心的无量纲位移和速度, f_x, f_y 的确定: 其中, 无量纲坐标 $x=\frac{X}{c}$, $y=\frac{Y}{c}$, $f_x=\frac{F_x}{\delta}$, $f_y=\frac{F_y}{\delta}$－无量纲非线性油膜力分量, μ－润滑油粘度, $G=\frac{g}{c\omega^2}$－无量纲外载荷, $\tau=\omega t$－无量纲时间, e－偏心量, c－轴承半径间隙, L－轴承长度, R－轴承半径, P－转子半重, $\delta=\frac{\mu\omega RL}{P}\left(\frac{R}{c}\right)^2\left(\frac{L}{2R}\right)^2$－Sommerfeld 修正数, $m=\frac{\omega^2 c}{g}$, f_x, f_y 由文献[4]确定:

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$$\begin{Bmatrix} f_x \\ f_y \end{Bmatrix} = -\frac{[(x-2y')^2+(y+2x')^2]^{1/2}}{1-x^2-y^2}\begin{Bmatrix} 3xV(x,y,\alpha)-\sin\alpha G(x,y,\alpha)-2\cos\alpha S(x,y,\alpha) \\ 3yV(x,y,\alpha)+\cos\alpha G(x,y,\alpha)-2\sin\alpha S(x,y,\alpha) \end{Bmatrix}$$

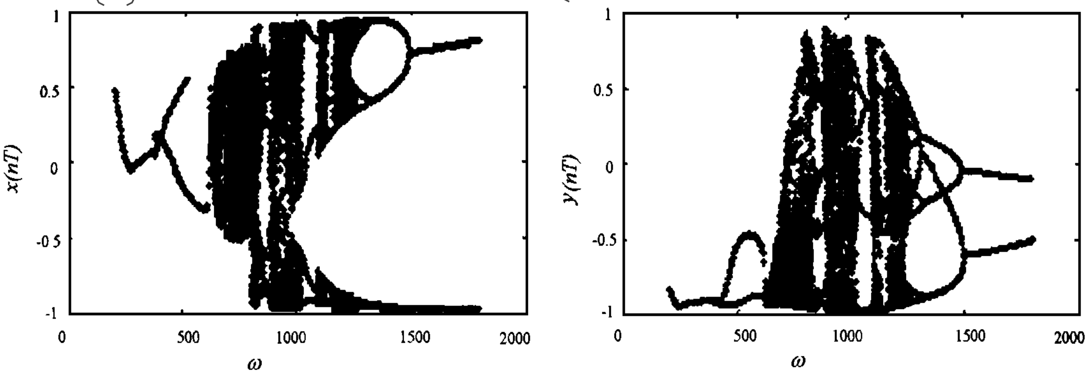

图 2 x, y 随 ω 变化的分叉图

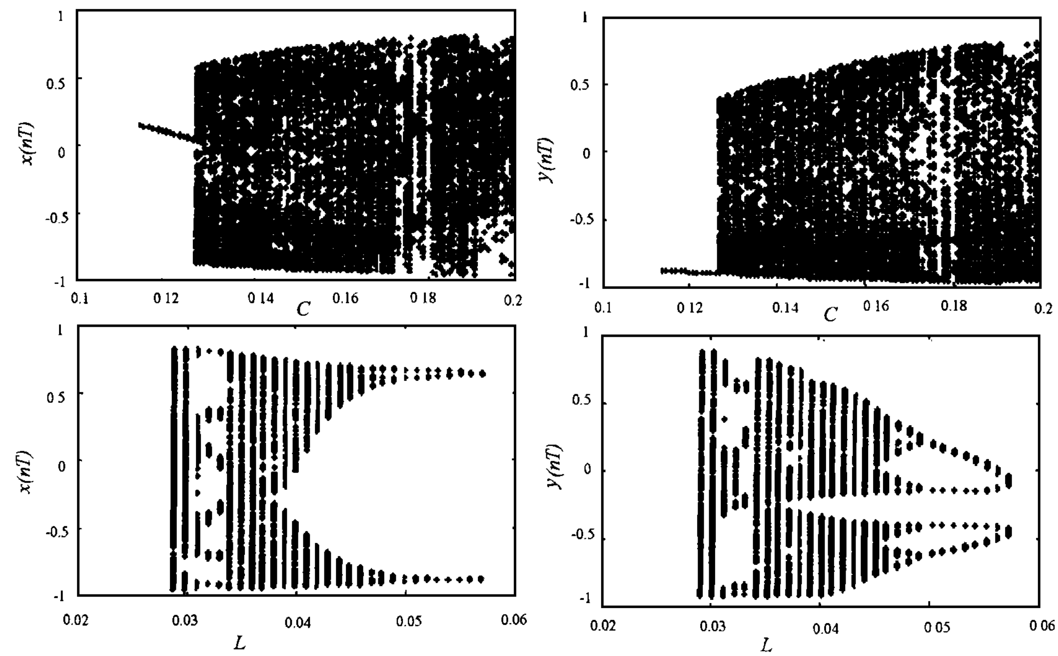

图 3 x, y 随 c, L 变化的分叉图

式中, $V(x, y, \alpha) = \dfrac{2+(y\cos\alpha - x\sin\alpha)G(x, y, \alpha)}{1-x^2-y^2}$,

$$S(x, y, \alpha) = \frac{x\cos\alpha + y\sin\alpha}{1-(x\cos\alpha+y\sin\alpha)^2},$$

$$G(x, y, \alpha) = \frac{2}{(1-x^2-y^2)^{1/2}}\left[\frac{\pi}{2}+arctg\frac{y\cos\alpha - x\sin\alpha}{(1-x^2-y^2)^{1/2}}\right],$$

$$\alpha = arctg\frac{y+2x'}{x-2y'} - \frac{\pi}{2}sign\left(\frac{y+2x'}{x-2y'}\right) - \frac{\pi}{2}sign(y+2x')$$

3 数值积分及结果

由于油膜力的强非线性特征, 因此选用龙格－库塔法。本文选用的时间步长为 π/100, 误差小于 0.001, 所得数据用于频谱、分叉图及庞加莱映射的计算。庞加莱截面是对给定动力系统的流, 在状态空间中的横截超曲面。在非自治系统中, 庞加莱截面上的一个点对应一个连续时间间隔为 T 的时间点序列(T 为激振力的周期)。$X(nT)-Y(nT)$ 平面的庞加莱映射截面被称为动力系统的庞加莱映射。对于周期运动, 如果周期为 nT, 庞加莱映射为 n 个离散的点。对于混沌运动, 庞加莱映射具有几何分形结构。

3.1 分叉图

取 $m_R = 520$(kg); $R = 57$(mm); $c = 0.2$(mm); $L = 28.5$(mm); $\mu = 18\times10^{-3}$Pa · s; ω, e 为参变量。将油膜力公式及各已知数值代入转子运动方程后, 通过跟踪数值积分中 ω 值的变化可以发现转子系统的混沌运动。取 $e = 0.04$ mm, 从图 2 中观察 ω 的变化范围为 200 ～ 1 800 rad/s 区域内位移 x 的不同性质, 可以发现当 ω＞ 806 rad/s 后系统发生混沌运动。

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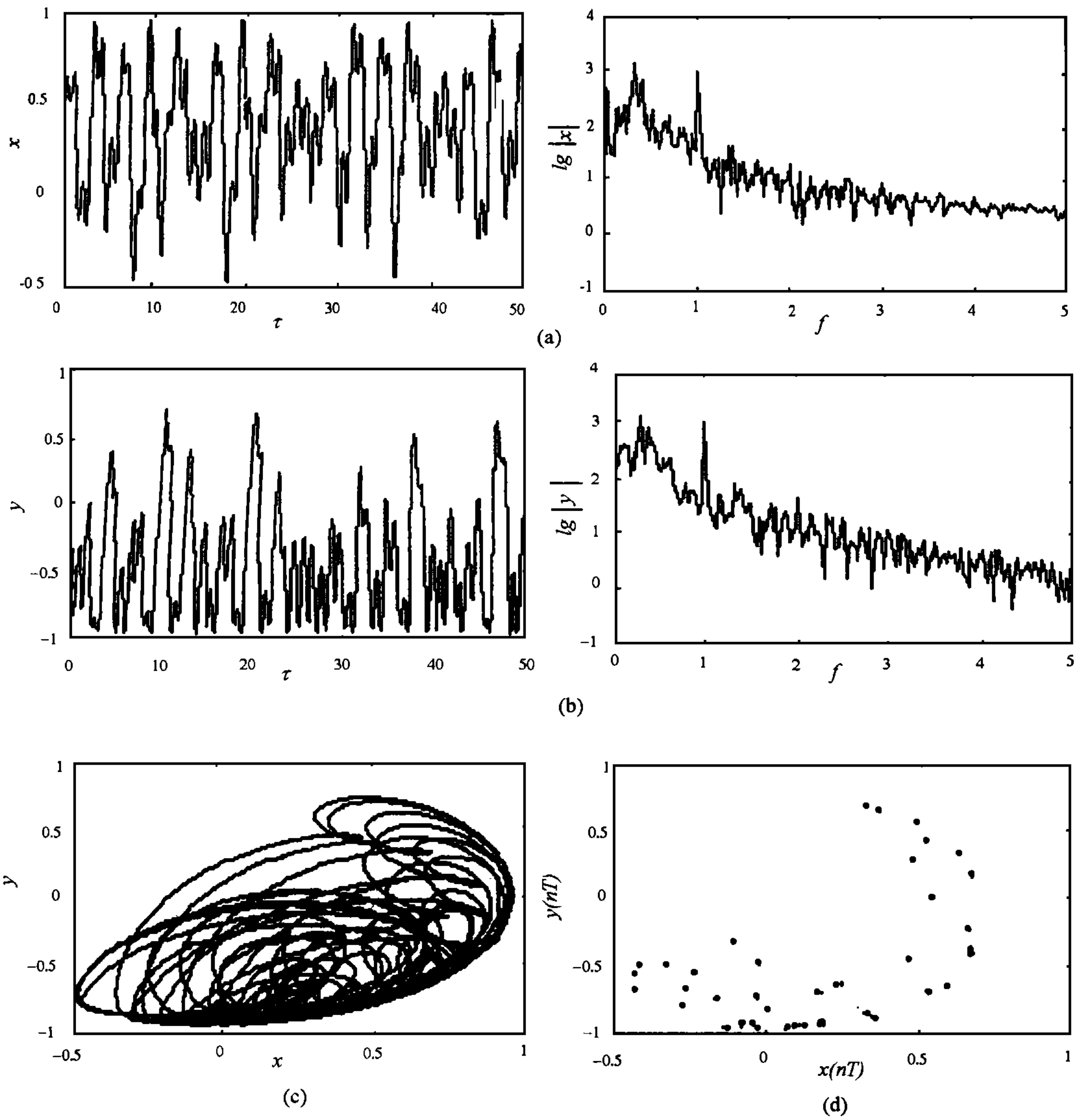

图 4　ω＝806 rad/s, e＝0.04 mm 时的 x 方向时域波形及频谱(a), y 方向的时域波形及频谱(b), 轴心轨迹(c), 庞加莱映射(d)

从图3 可以发现, 当 ω＝806 rad/s 时, 改变轴承半径间隙和轴承长度(即改变长径比)(c 及 L) 可以使运动稳定性发生质的变化, 在本文所选的系统中, 轴承半径间隙的减少和长径比的增加可以使系统稳定性提高。

3.2　其它结果

取 ω＝806 rad/s 处的 x, y 的时间序列, 频谱图, 轴心轨迹, 庞加莱映射, 如图 4 所示。可以发现混沌运动的一些规律。即, 混沌运动具有连续的频谱, 庞加莱映射具有几何分形结构。

4　结论

(1) 当转速增加到超过某一极限后, 系统将发生混沌运动, 使转子系统失稳。

(2) 偏心质量产生的激振力是导致混沌运动的根本原因, 数值计算结果表明转子－轴承系统具有产生复杂运动的潜在可能性。

(3) 轴承几何尺寸的改变, 可以使系统的运动状态发生质的改变。

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Shaanxi, China, Post Code: 710049) // Journal of Engineering for Thermal Energy &Power. — 2000, 15(4). —364 ~366

An analysis was performed of the flow process of a heat exchange tube bank in an ice storage tank, and a physical model featuring the actual flow process has been set up. An analytical solution was obtained through a theoretical deduction. On the basis of the above the authors have provided a theoretical method for the accurate calculation of the flow distribution and system pressure drop of the heat exchange tube bank as well as the design of the latter. **Key words**: ice storage tank, heat exchanger, flow characteristics, flow distribution, pressure drop

非线性刚性转子—轴承系统的混沌研究= **A Study on the Chaotic Motions Existing in a Nonlinear and Rigid Rotor-bearing System** [刊, 汉] /ZHANG Xin-jiang, WU Xin-hua, HAN Wan-jin (College of Energy Science and Engineering under the Harbin Institute of Technology), LI Jian-zhao (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy &Power. — 2000, 15(4). —367 ~369

In connection with the specific features of a nonlinear rotor-bearing system and under a relatively wide range of parameters a study has been conducted of the stability of a rigid Jeffcott rotor-bearing system using a short bearing model. The study was performed on the basis of the rotor dynamics and nonlinear dynamics theory and with the use of a numerical integration and Poincaré mapping method. The results of calculation show that there exist chaotic motions in the above-mentioned system. With the help of a numerical method obtained in some parameter domains of the system were the following: bifurcation diagrams, response curves, time histories, frequency spectrum and phase diagrams, shaft centerline locus and Poincaré mapping diagram. All the above gives a visual display of the operating condition of the system in some parameter domains. Meanwhile, an analysis was conducted of the effect of the bearing geometric dimensions on the stability of the system. The results of the numerical analysis can provide a theoretical basis for the design and safe operation of this type of rotor-bearing system. **Key words**: rotor dynamics, nonlinearity, rotor-bearing system, chaotic motion, stability

重载低速动压润滑推力轴承的理论分析= **Theoretical Analysis of a Dynamic-pressure Lubricated Heavy-duty and Low-speed Thrust Bearing** [刊, 汉] / LI Jian-ping, LIU Rui (Harbin Boiler Co. Ltd., Harbin, China, Post Code: 150046) // Journal of Engineering for Thermal Energy &Power. — 2000, 15(4). —370 ~372

A theoretical analysis was conducted of a multiple-slide pad and plane thrust bearing with respect to such a variety of parameters as elastic deformation, load-bearing capacity, rigidity, oil viscosity and oil film thickness, etc. Some of the relationships governing these parameters, thus obtained, can serve as a theoretical basis for the rational design of the above-cited bearing. **Key words**: elastic deformation, dynamic pressure lubrication, oil film thickness

三压再热汽水系统 IGCC 的设计工况和变工况性能= **Design and Off-design Performance of the Integrated Gasification Gas-steam Combined Cycle (IGCC) of a Triple-pressure Reheat Steam-water System** [刊, 汉] / LU Ze-hua, ZHAO Shi-hang, SHANG Xue-wei, CAO Ren-feng (Qinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy &Power. — 2000, 15(4). —373 ~375

With the integrated gasification gas-steam combined cycle (IGCC) of a triple-pressure reheat steam-water system serving as an object of study proposed in the present paper is the design scheme of an integrated air separation IGCC system. Set up was a mathematical model involving the following units: a gasification furnace, a purification system, a gas turbine, an air separation unit, a heat recovery boiler and a steam turbine. A series of calculations were performed of both the design and off-design performance of the IGCC system. Analyzed was the effect on the system off-design performance in the case of the gas turbine adopting different control and regulation laws as well as in the case of the steam turbine assuming different operational modes. In addition, a rational operational mode has also been proposed. **Key words**: integrated gasification gas-steam combined cycle, integrated air separation unit, off-design operating conditions, regulation law and

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