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# 非对称转子—轴承系统的稳定性分析

刘占生[1], 黄森林[1], 苏杰先[1], 唐炳照[2]

(1. 哈尔滨工业大学 能源学院, 黑龙江 哈尔滨 150001; 2. 哈尔滨·第七〇三研究所, 黑龙江 哈尔滨 150036)

摘　要: 建立了非对称转子—非对称轴承系统的数学模型, 分析了外阻尼、转子刚度各向异性系数、支撑刚度各向异性系数及支撑相对柔性系数对转子系统稳定性的影响。通过分析及数值仿真发现, 转子刚度的各向异性及系统阻尼是系统失稳的主要因素。为了解决工程中的非对称转子系统的失稳问题, 提出了提高转子轴承系统支撑刚度对称性的方法, 通过实践证明是有效的。

关　键　词: 非对称转子—轴承系统; 稳定性分析; 各向异性

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## 1　前言

在工程实际中存在许多非对称转子轴承系统, 大到几百兆瓦的发电机转子, 小到内燃机中的凸轮轴, 这些转子系统的最大特点是转子轴在两个主方向上刚度不同, 同时支持轴承(几乎所有支持轴承)在两个主方向上支撑刚度一般也不同。过去人们对此类系统进行动力特性分析时, 为了减小分析的复杂性而没有将支撑刚度的非对称性和转子刚度的非对称性同时考虑进去分析, 给分析结果造成较大的误差。如文献[1]分析了转子刚度和转动惯量的各向异性对非对称转子—轴承系统稳定性的影响, 文献[2~3]用模态分析的方法, 研究了转子刚度和转动惯量的各向异性对非对称转子—轴承系统的模态特性和稳定性的影响; 文献[4]用传递矩阵的方法, 分析了轴、盘转动惯量和轴承油膜刚度的各向异性对非对称转子—轴承系统的稳定性的影响。当同时考虑转子和支撑刚度的各向异性时, 系统的运动方程是一个参数激励方程, 研究难度较大, 只能用近似的解析方法分析和必要的数值方法仿真。本文建立了非对称转子—轴承系统的数学模型, 用谐波平衡方法对数学模型进行了二阶解析分析, 并用 MATLAB 软件编程, 进行了数值仿真。分析和仿真结果表明, 可以通过改变部件的几何参数, 达到改善系统稳定性的目的。

## 2　非对称转子—轴承系统的简化模型和运动方程

设非对称转子—轴承系统是由一根各向异性的无质量弹性轴、装在轴中央的圆盘、各向异性的弹性支撑组成, 如图 1 所示。

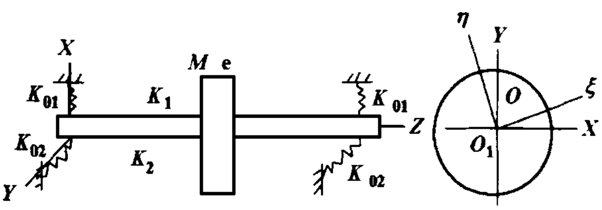


图 1　转子—轴承系统模型

设与转子等速度 $\omega$ 回转的坐标系为 $\xi o_1 \eta$。转子沿 $\xi$ 轴和 $\eta$ 轴方向的刚度系数分别为 $k_1$ 和 $k_2$, 支承沿 $X$ 轴和 $\gamma$ 轴方向的刚度系数分别为 $k_{01}$ 和 $k_{02}$, 圆盘质量为 $m$, 偏心为 $e$, 位于 o 点, 而沿 $\xi$ 轴和 $\eta$ 轴方向偏心分别为 $e_1$ 和 $e_2$。圆盘几何中心和支撑中心的坐标分别以 $\xi$、$\eta$ 和 $\xi_0$、$\eta_0$ 表示。又设外阻尼力与圆盘中心的绝对速度成正比(比例系数为 $n$), 不计支撑质量。在回转坐标系 $\xi o_1 \eta$ 下, 分别对圆盘几何中心和支撑中心进行受力分析, 得系统的运动方程(1)。

$$
\begin{aligned}
& m\ddot{\xi} = -n(\dot{\xi} - \omega\eta) - k_1(\xi - \xi_0) + 2m\omega\dot{\eta} + m\omega^2(\xi + e_1) + mg\cos\omega t \\
& m\ddot{\eta} = -n(\dot{\eta} + \omega\xi) - k_2(\eta - \eta_0) + 2m\omega\dot{\xi} + m\omega^2(\eta + e_2) + mg\sin\omega t \\
& k_{01}\xi_0\cos^2\omega t + \xi_0 k_{02}\sin^2\omega t + \eta_0\sin\omega t\cos\omega t(k_{02} - k_{01}) = k_1(\xi - \xi_0)/2 \\
& k_{01}\eta_0\sin^2\omega t + \eta_0 k_{02}\cos^2\omega t + \xi_0\sin\omega t\cos\omega t(k_{02} - k_{01}) = k_2(\eta - \eta_0)/2
\end{aligned}
\quad (1)
$$

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作者简介: 刘占生(1962—), 男, 黑龙江牡丹江人, 哈尔滨工业大学教授。

为计算方便, 对系统运动方程(1) 进行无量纲化, 令 $\omega_0=\sqrt{\frac{k_1+k_2}{2m}}$ 为刚性支撑中转子的平均临界转速; $\beta=\omega/\omega_0$ 为无量纲转速; $\delta=n/m\omega_0$ 为无量纲外阻尼系数; $u=k_1-k_2/k_1+k_2$ 为轴刚度的各向异性系数; $v=k_{01}-k_{02}/k_{01}+k_{02}$ 为支撑刚度的各向异性系数; $\alpha=k_1+k_2/k_{01}+k_{02}$ 为支撑的相对柔度系数; $\tau=\omega_0 t$, 撇号表示对 $\tau$ 求导数。无量纲化后的运动方程为式(2):

$$\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&0&0\\0&0&0&0\end{bmatrix}\begin{Bmatrix}\xi''\\\eta''\\\xi''_0\\\eta''_0\end{Bmatrix}+\begin{bmatrix}\delta&-2\beta&0&0\\2\beta&\delta&0&0\\0&0&0&0\\0&0&0&0\end{bmatrix}\begin{Bmatrix}\xi'\\\eta'\\\xi'_0\\\eta'_0\end{Bmatrix}+$$

$$\begin{bmatrix}1+u-\beta^2&-\delta\beta&-1-u&0\\\delta\beta&1-u-\beta^2&0&-1+u\\-\frac{(1+u)}{2}&0&\frac{1}{a}+\frac{v}{a}\cos 2\tau+\frac{1+u}{2}&-\frac{v}{a}\sin 2\tau\\0&-\frac{(1-u)}{2}&-\frac{v}{a}\sin 2\tau&\frac{1}{a}-\frac{v}{a}\cos 2\tau+\frac{1-u}{2}\end{bmatrix}\begin{Bmatrix}\xi\\\eta\\\xi_0\\\eta_0\end{Bmatrix}=\begin{Bmatrix}\beta^2 e_1+\frac{g}{\omega_0^2}\cos\tau\\\beta^2 e_2+\frac{g}{\omega_0^2}\sin\tau\\0\\0\end{Bmatrix}\tag{2}$$

## 3　稳定性分析

方程(2) 是一个参数激励的微分方程组, 用谐波平衡法确定系统的稳定区边界。令

$$\{x\}=\sum_{n=-\infty}^{\infty}\{\varphi_n\}e^{(\lambda+2jn)t}\tag{3}$$

其中 $\{x\}=[\xi,\eta,\xi_0,\eta_0]^T$, $\{\varphi_n\}$ 为常数。将式(3) 代入式(2), 并将与稳定性无关的参数置为 0, 其中包括两个方向的偏心距 $e_1$、$e_2$ 及重力, 得

$$\sum_{n=-\infty}^{\infty}\left(A_n\varphi_n e^{(\lambda+2jn)\tau}+B_{n+1}\varphi_n e^{(\lambda+2j(n+1))\tau}+C_{n-1}\varphi_n e^{(\lambda+2j(n-1))\tau}\right)=0\tag{4}$$

其中

$$A_n=\begin{bmatrix}(\lambda+2jn)^2+\delta(\lambda+2jn)+1+u-\beta^2&-2\beta(\lambda+2jn)-\delta\beta&-1-u&0\\2\beta(\lambda+2jn)+\delta\beta&(\lambda+2jn)^2+\delta(\lambda+2jn)+1-u-\beta^2&0&u-1\\-\frac{1+u}{2}&0&a+\frac{1+u}{2}&0\\0&\frac{-1+u}{2}&0&a+\frac{1-u}{2}\end{bmatrix}$$

$$B_{n+1}=\begin{bmatrix}0&0&0&0\\0&0&0&0\\0&0&\frac{va}{2}&-\frac{va}{2j}\\0&0&-\frac{va}{2j}&-\frac{va}{2}\end{bmatrix},$$

$$C_{n-1}=\begin{bmatrix}0&0&0&0\\0&0&0&0\\0&0&\frac{va}{2}&\frac{va}{2j}\\0&0&\frac{va}{2j}&-\frac{va}{2}\end{bmatrix}$$

从而得到类似无限希尔行列式的临界频率方程, 如下式所示:

$$\Delta(\lambda)=\begin{vmatrix}\cdots&\cdots&\cdots&&\\B_{-1}&A_{-1}&C_{-1}&&\\&B_0&A_0&C_0&\\&&B_1&A_1&C_1\\&&&B_2&A_2\end{vmatrix}=0\tag{5}$$

考虑到工程实际, 取其前两阶, 即 $n=-2,-1,0,1,2$, 得到近似特征方程。

$$\Delta'(\lambda)=\begin{vmatrix}A_{-1}&C_{-1}&\\B_0&A_0&C_0\\&B_1&A_1\end{vmatrix}=0\tag{6}$$

则稳定与不稳定区域的分界线, 对应于 $\lambda=0$(即周期为 $\pi$ 的周期解) 和 $\lambda=j$(或 $-j$)(即周期为 $2\pi$ 的周期解)。现利用这两个条件, 分析系统各参数对稳定性的影响。仿真结果如图 2 所示。

由图 2 中(a) 可知: 随着阻尼系数的增大, 不稳定区域逐渐缩小, 当 $\delta$ 大于 0.15 时, 不稳定区域消失。因此, 适当增大系统阻尼就能抑制不稳定区域的出现。

由图 2 中(b) 可知: 在低速区($\beta=0\sim0.7$), 支撑相对柔度的提高会使不稳定区域增大; 随着转速的升高, 在临界转速附近($\beta=1.0$), 支撑相对柔度的适当提高会使不稳定区域减小; 高速区的情况与低速区的情况类似。

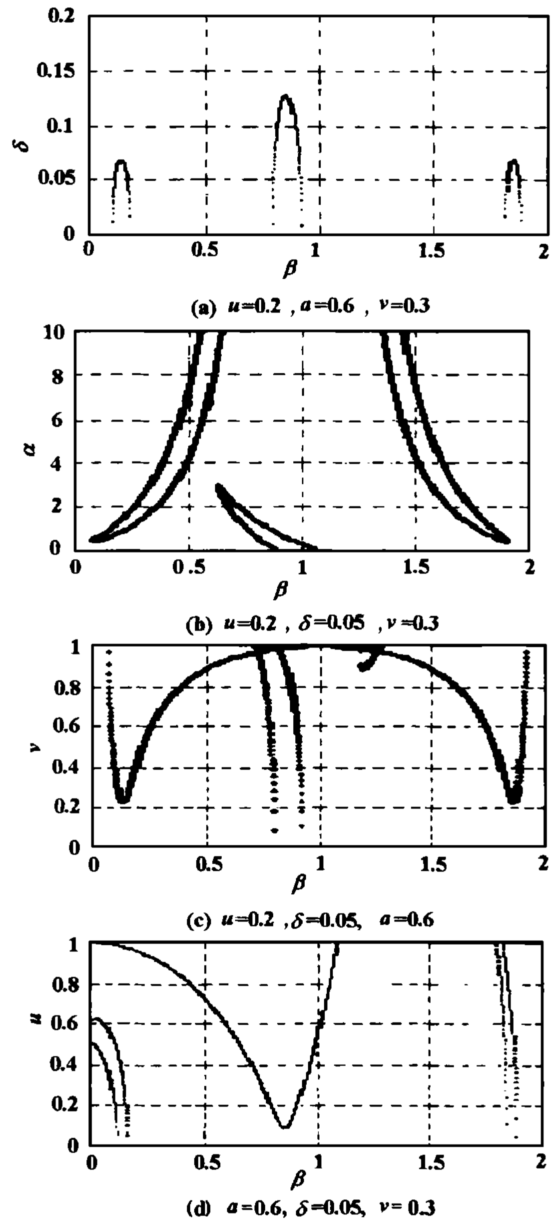


图 2　系统参数对稳定性的影响(a)、(b)、(c)、(d)

由图2中(c)可知:随着支撑刚度各向异性系数值的增大,不稳定区域逐渐增大,因此,减小支撑刚度的各向异性系数,能减小不稳定区域的大小。但在临界转速附近(β=1.0),很小的支撑刚度各向异性系数也有可能使系统失稳。

由图 2 中(d)可知:在某些转速区域,很小的转子刚度各向异性系数也有可能使系统失稳,随着转子刚度各向异性系数值的增大,不稳定区域逐渐增大,因此,减小转子刚度的各向异性系数,能减小不稳定区域的大小。

## 4　结论

根据以上的分析,可以得出以下结论:

(1)可以通过提高支撑刚度的对称性,来减小不稳定区域的大小;

(2)系统在临界转速附近非常容易失稳,可以通过提高支撑的相对柔度来消除;

(3)适当增大系统阻尼能抑制不稳定区域的出现,但从能量的观点来看,并不是一种好的方法。

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Thermal Energy &Power. —2001, 16(1). —59 ~ 62

In view of the presence of destabilizing factors in boiler steam pressure caused by the power-frequency control of current large-sized mono-block thermal power plant units the authors have performed an analysis of the digital electric-hydraulic (DEH) control modes. It is noted that there exists a substantial difference in the influence on the dynamic characteristics of a boiler object when various DEH control modes are put into use. In case the DEH control assumes the form of power-frequency one the boiler steam pressure as a controlled object can be viewed as a self balancing-absent process. When the DEH control functions as a pure speed regulation, the former represents a self-balancing process. By way of simulations the effect of fuel and load perturbations on the dynamic characteristics of a mono-block thermal power plant unit has been determined when different DEH control modes are used. At the end of the paper presented are the operating modes of the mono-block unit under unstable working conditions or in case of a high frequency of outside perturbations. In sum, the paper has provided some hints of highly practical value for ensuring the safe operation of large-sized mono-block thermal power plants. **Key words**: steam turbine unit, digital electric-hydraulic control system, dynamic characteristics of boiler as a controlled object

改进 BP 神经网络在流型判别中的应用=**The Application of an Improved BP Neural Network in the Discrimination of Various Flow Patterns** [刊, 汉] / Wang Yan-peng, Lin Zong-hu (Energy Source and Power Engineering Institute under the Xi' an Jiaotong University, Xi' an, China, Post Code: 710049) //Journal of Engineering for Thermal Energy &Power. —2001, 16(1). —63 ~ 65, 90

A new method for the discrimination of flow patterns is proposed in this paper, which is based on the use of an artificial neural network. With the help of a self-adaptive gradient reduction method and an improved simulation annealing approach, etc the convergence rate of a BP network can be accelerated. There emerged, as a result, an enhancement in the network' s ability to avoid a local minimum magnitude, which contributes to an increased capability of the network to simulate a nonlinear system. In addition, an analysis was made of the network input and output parameters, which can be used for pattern discrimination. To demonstrate the feasibility of the recommended method, the authors have employed the experimental data of scholars-forerunners to check and verify their work procedures. It has been proved that the above method can be assessed as a very effective one for the discrimination of two-phase and multi-phase flow patterns. **Key words**: neural network, two-phase flow, multi-phase flow, flow pattern discrimination

板式换热器可视化计算机辅助设计系统的研制= **The Development of a Visualized Computer-aided Design System for Plate Heat Exchangers** [刊, 汉] / Dong Chao-jun, (Wuyi University, Jiangmen, Guangdong Province, China, Post Code: 529020) //Journal of Engineering for thermal Energy &Power. —2001, 16(1). —66 ~ 69

Plate heat exchangers represent a kind of highly compact and efficient heat exchange device. As such heat exchangers feature an extremely complicated heat exchange and flow characteristics, there still lacks, to date, a unified formula for calculating their heat transfer and resistance. At present they are designed and calculated mainly by relying on manual work. However, a manual design and calculation process often suffers from both a high complexity and an extreme inaccuracy. With the comprehensive utilization of such a variety of software as Visual Basic, AutoCad and Turbo C, etc the author has on the platform of Windows 95 developed a visualized computer-aided design system. Through the use of that system a designer only needs to input some relevant parameters and the system will automatically complete the whole process starting from the design and calculation and ending with the completion of all design drawings. The system has a user-friendly interface and can be conveniently used in practical design work. **Key words**: plate heat exchanger, computer-aided design system, Visual Basic, AutoCad

非对称转子—轴承系统的稳定性分析= **An Analysis of the Stability of an Asymmetrical Rotor-bearing System** [刊, 汉] / Liu Zhang-sheng, Huang Sen-lin, Su Jie-xian, *et al* (College of Energy Source under the Harbin Institute of

Technology, Harbin, China, Post Code: 150001) //Journal of Engineering for Thermal Energy & Power. —2001, 16 (1). —70 ~ 72

A mathematical model was set up for an asymmetrical rotor-bearing system. With the help of this model the authors have analyzed the influence of a variety of factors on the stability of the asymmetrical rotor-bearing system. Among such factors one can enumerate external damping, rotor rigidity anisotropic factor, support rigidity anisotropic factor and the relative flexibility factor of the support. As a result of the analysis and numerical simulations it has been found that the rotor rigidity anisotropy and the system damping are the major factors contributing to the loss of stability of the system. To solve the issue of instability of the asymmetrical rotor-bearing system in engineering practice the authors have proposed a method aimed at enhancing the support rigidity symmetry of a rotor-bearing system, which has been proved effective in practice. **Key words**: asymmetrical rotor-bearing system, stability analysis, rigidity, anisotropy

湍流火用传递方程及其应用＝**Exergy Transfer Equation for Turbulent Flows and Its Applications** [刊, 汉] / Wang Song-ping (Qingdao University, Qingdao, China, Post Code: 266071), Chen Qing-lin, Hua Ben (South China University of Science and Technology, Guangzhou, China, Post Code: 510641) //Journal of Engineering for Thermal Energy & Power. —2001, 16(1). —73 ~ 76

The authors have derived an exergy transfer equation for turbulent flows. On this basis a study was conducted of the exergy transfer for a convection heat exchange tube with a wall surface constant heat flux. The distribution of exergy loss rate caused by viscosity dissipation, radial and axial heat conduction was calculated. The calculation results of the total exergy loss rate for a unit volume indicate that the total exergy loss per unit volume is a multi-value function of heat exchange tube geometric parameters and boundary conditions. For a given geometric parameter there exists a boundary condition, which gives a minimum value of the total exergy loss rate for a unit volume, and vice versa. The above conclusion can to a certain extent serve as a guide for the optimized design of heat exchangers and the optimal selection of heat exchangers under given boundary conditions. **Key words**: turbulent flow, exergy transfer equation, distribution of exergy loss rate

某舰用锅炉过热器胀接接头弹塑性有限元分析＝**Finite Element Analysis of the Elastic Plasticity of a Naval Boiler Superheater Expanded-joint** [刊, 汉] / Zhou Chuan-yue (Harbin Institute of Technology, Harbin, China, Post Code: 150001), Li Gui-ying, Ma Yun-xiang (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) //Journal of Engineering for Thermal Energy & Power. —2001, 16(1). —77 ~ 79

Through the use of a large-sized finite element general program ANSYS the contact analysis model of an expanded joint has been set up for the expanded joint structure of a naval boiler superheater and a finite element analysis of three-dimensional plasticity conducted. A study was performed of the effect of material properties and operating temperatures, etc on the residual contact pressure of the expanded joint. Also given in this paper are some proposals, which can serve as a guide for engineering design as well as for the prevention of failures and malfunctions. **Key words**: expanded joint, finite element method (FEM), analysis of elastic plasticity, residual stress, program ANSYS

三维紊流燃烧室流场的数值计算＝**Numerical Calculation of the Three-dimensional Turbulent Flow Field of a Gas Turbine Combustor** [刊, 汉] / Xun Bai-qiu, Qu Zhe, Zhang Yanqiu, *et al* (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) //Journal of Engineering for Thermal Energy & Power. —2001, 16(1). —80 ~ 82

By the use of a cylindrical coordinate system a numerical simulation was conducted of a single-tube return-flow combustor flow-field. A turbulent flow viscosity model was employed to evaluate the turbulent flow viscosity with the help of a $k-\varepsilon$ dual equation turbulent flow model. A combustion model was utilized to assess chemical reaction speed with the help of a EBU (eddy-break-up) vortex breakage combustion model. Thermal radiation magnitude was calculated by using a thermal radiation model with the help of a relatively simple DTR (discrete transfer radiation) model. The results of the calculation have been found to reflect quite accurately the flow condition of the combustor flow field. Moreover, these results have al-