技术交流

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不同油膜力模型下转子椭圆轴承系统的动力学分析

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摘　要: 对现有几种椭圆轴承非线性油膜力模型与直接采用有限差分数值法求解雷诺方程得出的非线性油膜力进行了分析和比较, 同时对在不同椭圆轴承非线性油膜力模型下, 实际转子－椭圆轴承系统响应的相对误差、计算速度和动力学特性进行了分析和比较。在综合考虑其计算精度、计算速度和动力学特性的情况下, 研究结果表明: 数据库方法应为优先推荐采用油膜力模型, 其次为数据库拟合表达式方法和变分法模型。研究结果为在实际旋转机械转子－椭圆轴承系统进行非线性动力学分析和设计时, 选择油膜力模型提供了依据。

关　键　词: 非线性油膜力; 椭圆轴承; 转子系统
中图分类号: O322; TH133　　文献标识码: A

1　引　言

滑动轴承的非线性油膜力模型是转子－轴承系统非线性动力学分析和研究的关键问题。滑动轴承的油膜力具有强烈的非线性特性, 研究转子－椭圆轴承系统的非线性动力学问题关键在于获得椭圆轴承的油膜力模型。其中椭圆轴承的非线性油膜力的计算精度和计算速度将直接影响到转子－轴承系统非线性动力学分析的计算精度和效率[1~2]。目前普遍采用的计算方法主要有两类, 一类是采用有限元或有限差分法直接求解雷诺方程[3~4]; 另一类是变分法、数据库方法和数据库拟合表达式法等[5~7]。

为了考察现有各种油膜力模型的计算精度和计算速度, 同时为实际转子－椭圆轴承系统进行非线性动力学分析和设计提供切实有效的非线性油膜力模型。本文对现有几种非线性油膜力模型与直接采用有限差分数值法求解雷诺方程得出的非线性油膜力进行了分析和比较; 在各种椭圆轴承的非线性油膜力模型下, 对实际转子－椭圆轴承系统动力响应的计算相对误差、计算速度和非线性动力学特性进行了分析和比较, 得出了一些有价值的结论。为旋转机械转子－椭圆轴承系统的非线性动力学分析和设计提供了必要的理论基础。

2　Jeffcott 转子－轴承系统动力学模型

如图 1 所示为 Jeffcott 刚性转子－轴承系统的动力学模型。图 2 中: O－轴瓦几何中心, O_j－轴颈中心, O_c－转子质心, 转子系统两端采用对称结构的滑动轴承支承, 转子－轴承系统动力学方程为:

$$\begin{aligned} m\ddot{x} &= -f_x + me\omega^2\sin(\omega t) \\ m\ddot{y} &= -f_y + me\omega^2\cos(\omega t) + mg \end{aligned} \tag{1}$$

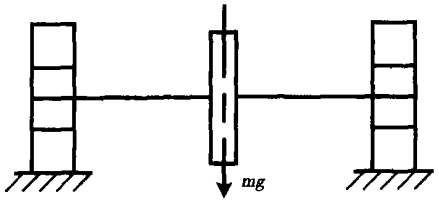

图 1　Jeffcott 刚性转子－轴承系统动力学模型

采用无量纲处理, 无量纲轴颈坐标: X, $Y=x/c$, y/c; X', $Y'=\dot{x}/(c\omega)$, $\dot{y}/(c\omega)$; X'', $Y''=\ddot{x}/(c\omega^2)$, $\ddot{y}/(c\omega^2)$; 无量纲非线性油膜力分量: $F_x=(f_x\psi)/(Lr\eta\omega)$, $F_y=(f_y\psi)/(Lr\eta\omega)$; $G=g/(c\omega^2)$, 无量纲质量 $M=(mc\omega\psi)/(\eta Lr)$, 质量偏心距 $e=$

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$\overline{O_jO_c}$, 无量纲时间 $\tau=\omega t$, ω—转子角速度, rad/s; c—轴承半径间隙, mm, 间隙比 $\psi=c/r$; m—转子质量, kg; r—轴颈半径, mm; L—轴瓦宽度, mm; η—润滑油粘度(N·s/m^2)。

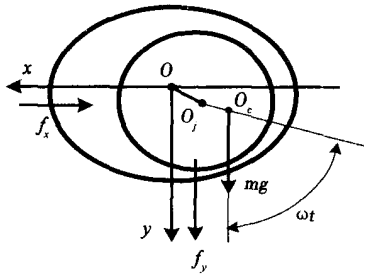

图 2　椭圆轴承受力及坐标系

设 $Z_1=X$, $Z_2=Y$, $Z_3=X'$, $Z_4=Y'$, 其中"′"表示 $d/d\tau$, 则式(2)用状态变量表示的无量纲形式为:

$$\begin{aligned} Z_1' &= Z_3 \\ Z_2' &= Z_4 \\ Z_3' &= \frac{F_x}{M}+\rho\sin\tau \\ Z_4' &= \frac{F_y}{M}+\rho\cos\tau+G \end{aligned} \tag{2}$$

3　不同椭圆轴承的非线性油膜力模型与有限差分法的分析和比较

为了验证不同椭圆轴承的非线性油膜力模型的计算精度, 下面就椭圆轴承的变分法模型、数据库方法、数据库拟合表达式模型与有限差分法进行比较。以某国产 300 MW 汽轮机组 5 号椭圆轴承为例, 其椭圆轴承参数为: 轴颈直径 $D=0.45$ m, 轴承宽度 $B=0.36$ m, 轴承宽径比 $L/D=0.8$, 间隙比 $\psi=0.003$, 瓦张角 $\alpha=150^\circ$, 椭圆度 $\sigma m=0.556$, 润滑油粘度$=0.028\ 7$ N·s/m^2。

图 3 是当偏心率 $\varepsilon=0.3$, X 和 Y 和方向速度分量为 $X'=0.5$, $Y'=0.5$ 情况下的变分法模型、数据库方法、数据库拟合表达式模型与有限差分法得到的无量纲非线性油膜力 F_x、F_y 随偏位角 θ 变化曲线的对比图。

图 4 是当偏位角 $\theta=30^\circ$, X 和 Y 和方向速度分量为 $X'=0.5$, $Y'=0.5$ 情况下的变分法模型、数据库方法、数据库拟合表达式模型与有限差分法得到的无量纲非线性油膜力 F_x、F_y 随偏心率 ε 变化曲线的对比图。

从图 3 和图 4 中看出: 变分法模型、数据库方法和数据库拟合表达式模型计算得到的 X、Y 方向非线性油膜力数值 F_x 和 F_y 与有限差分法的计算结果均吻合很好。

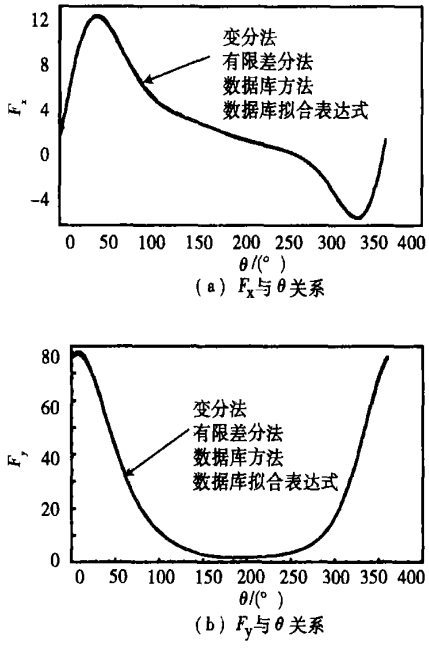

图 3　椭圆轴承几种模型的 F_x、F_y 随偏位角 θ 变化曲线对比

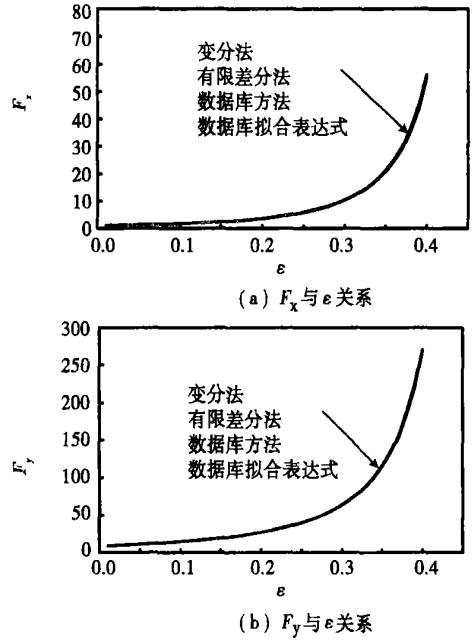

图 4　椭圆轴承几种模型的非线性油膜力 F_x、F_y 随偏位角 ε 变化曲线对比

4 刚性转子—椭圆轴承系统非线性动力学特性分析

转子系统采用一对实际椭圆滑动轴承支承，参数如下：轴颈半径 $r=180$ mm，轴承宽度 $L=288$ mm，间隙比 $\psi=0.263\%$，瓦张角 $\alpha=150^\circ$，椭圆度 $em=0.505$，轴承的静载荷 $mg=196\ 009$ N，不平衡质量偏心率 $\rho=0.2$，润滑油的粘度 $\eta=0.018\ 02\ \mathrm{N\cdot s/m^2}$。

采用数值积分法对式(2)Jeffcott 刚性转子—椭圆轴承系统进行数值积分求解。图 5～图 8 为椭圆轴承的非线性油膜力分别采用有限差分法、变分法模型、数据库方法、数据库拟合表达式法计算得到的分岔图。从图中还可以看出：各种非线性油膜力模型作用下所计算的分岔图非常接近，不同转速下转子系统的非线性动力学特性比较接近。

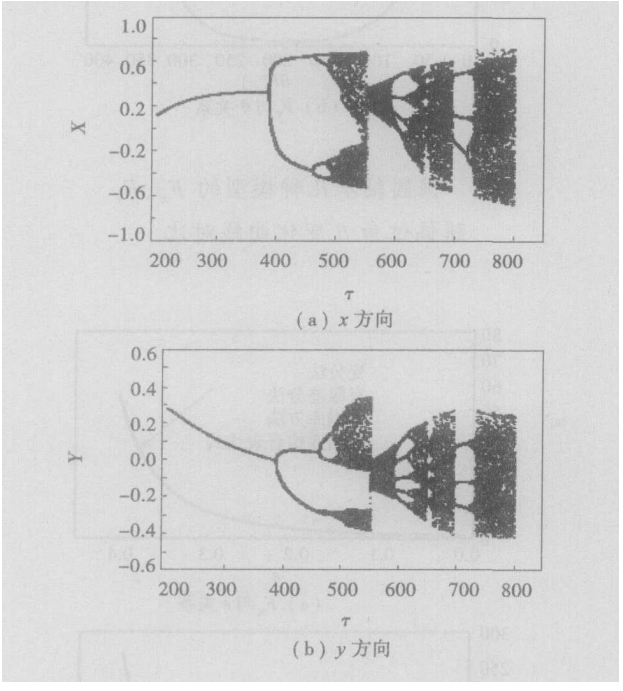

图 5 有限差分法计算的分岔图

选取初值为 $Z_1=0.505$，$Z_2=0.150$，$Z_3=0.0$，$Z_4=0.0$，计算 40π，计算步长为 π/100，轴转速为 $n=3\ 000$ r/min。图 9～图 12 是轴承的非线性油膜力分别采用有限差分法、变分法模型、数据库方法、数据库拟合表达式法求得的轴心轨迹。从图 9～图 12 中可看出：各种非线性油膜力模型作用下所计算的转子系统的轴心轨迹非常接近。

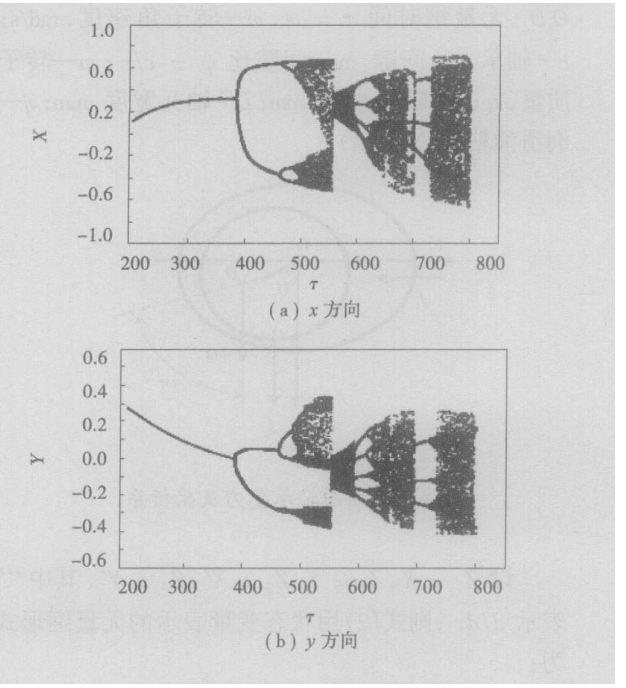

图 6 变分法计算的分岔图

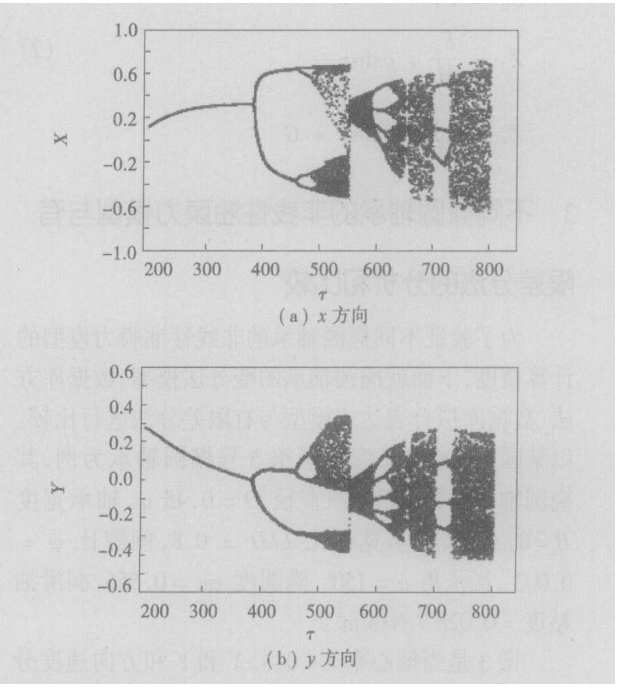

图 7 数据库方法计算的分岔图

采用上述相同的初值，通过计算各种非线性油膜力模型下，Jeffcott 刚性转子—椭圆轴承系统 Poincaré 截面上的映射点列。计算转速为 190 rad/s，计算 40π，计算步长为 π/100，共计算得出 4 000 行和 4 列 Z_1，Z_2，Z_3，Z_4 点序列。

设 $\| Z \| = \sum_{i=1}^{4} | Z_i | = | Z_1 | + | Z_2 | + | Z_3 | + | Z_4 |$ 分别计算在有限差分法、变分法模型、数据库方法、数据库拟合表达式法下, Jeffcott 刚性转子—椭圆轴承系统 Poincaré 截面的点序列值 $\| Z \|$。分别记为 $\| Z \|_1$、$\| Z \|_2$、$\| Z \|_3$、$\| Z \|_4$, 同时分别计算它们之间的相对误差:

$$R_{12} = \frac{| \| Z \|_1 - \| Z \|_2 |}{\| Z \|_1}$$

$$R_{13} = \frac{| \| Z \|_1 - \| Z \|_3 |}{\| Z \|_1} \tag{3}$$

$$R_{14} = \frac{| \| Z \|_1 - \| Z \|_4 |}{\| Z \|_1}$$

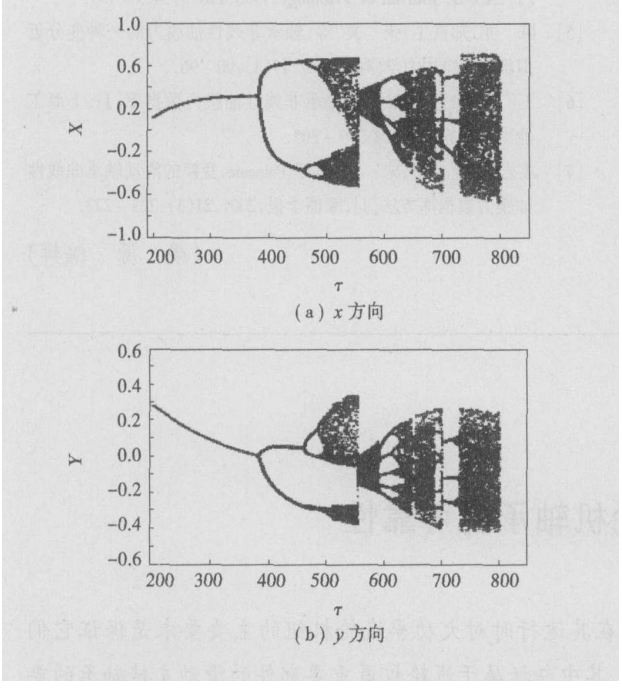

图 8　数据库拟合表达式法计算的分岔图

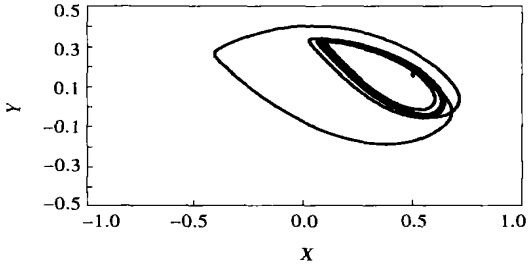

图 9　有限差分法计算的轴心轨迹

找出变分法模型、数据库方法、数据库拟合表达式法分别相对于有限差分法模型计算结果之间的最大相对误差值和最小相对误差值: max(R_{12}), min(R_{12}); max(R_{13}), min(R_{13}); max(R_{14}), min(R_{14})。表 1 为各种椭圆轴承非线性油膜力模型计算结果之间的相对误差。

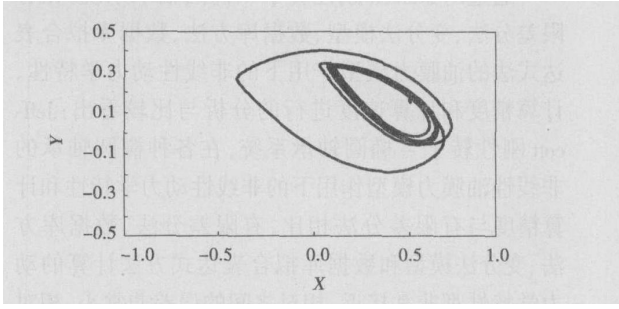

图 10　变分法计算的轴心轨迹

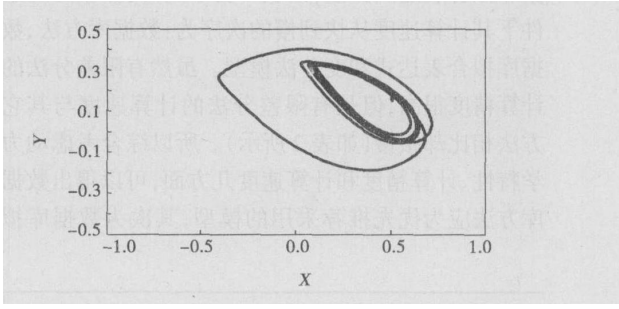

图 11　数据库方法计算的轴心轨迹

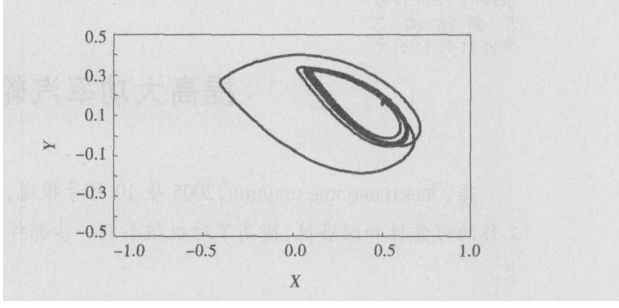

图 12　数据库拟合表达式法计算的轴心轨迹

表 1　各种椭圆轴承非线性油膜力模型之间的相对误差

误差/%	max(R_{12})	max(R_{13})	max(R_{14})
	0.638 74	1.404 0	1.582 3
误差/%	min(R_{12})	min(R_{13})	min(R_{14})
	0.000 167 5	0.000 783 7	0.000 118 2

表 2　各种椭圆轴承非线性油膜力模型的计算速度对比

	有限差分方法	变分法模型	数据库方法	数据库拟合表达式方法
计算时/s	271.328	130.178	15.610	39.859
有限差分法/各种其它方法	1.0	2.084	17.382	6.807
快慢次序	4	3	1	2

5 结 论

通过对 Jeffcott 刚性转子—椭圆轴承系统，在有限差分法、变分法模型、数据库方法、数据库拟合表达式法的油膜力模型作用下的非线性动力学特性、计算精度和计算速度进行的分析与比较看出：Jeffcott 刚性转子—椭圆轴承系统，在各种椭圆轴承的非线性油膜力模型作用下的非线性动力学特性和计算精度与有限差分法相比，有限差分法、数据库方法、变分法模型和数据库拟合表达式方法计算的动力学特性都非常接近，相对之间的误差非常小、相对误差从小到大依次为：数据库方法、变分法模型和数据库拟合表达式方法(如表 1 所示)。而在相同的条件下其计算速度从快到慢的次序为：数据库方法、数据库拟合表达式和变分法模型。虽然有限差分法的计算精度很高，但是有限差分法的计算速度与其它方法相比却很慢(如表 2 所示)。所以综合考虑动力学特性、计算精度和计算速度几方面，可以得出数据库方法应为优先推荐采用的模型，其次为数据库拟合表达式方法和变分法模型。

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(渠 源 编辑)

新 结 构

提高大功率汽轮机轴承的可靠性

据《Электрические станции》2005 年 10 月号报道，在其运行时对大功率汽轮机组的主要要求是保证它们工作的可靠性和经济性，提高了对机组个别一些部件，其中包括属于汽轮机最重要部件的滑动支持轴承的要求。

基于广泛的试验台的试验和电站试验的结果，JIM3(列宁格勒金属工厂)的专家积累了有关改进滑动轴承及其部件结构的大量的实际经验。

试验确定了一系列参数和结构要素对轴承静特性的影响，制定并实施了有关改进和提高它们工作可靠性的实际措施。

根据研究结果，研制了用于高负荷大尺寸支持轴承的改进结构。在不同的工况和工作条件下，这些结构具有高的承载能力、高的可靠性和经济性。

研制的轴承结构已在功率为 660 和 1 000 MW 的新汽轮机上应用，而它的主要部件已于热电站和核电站的功率为 200～1 000 MW 的汽轮机中在用。

(吉桂明 供稿)

and a modularized design method. The software can operate at the rear platforms of DCS work stations and prepare operational interfaces with the help of DCS configuration tools. It can make full use of powerful functions of existing DCS and its operation methods are easy for operators to get acquainted with. Unified data pretreatment mechanism and monitoring of heart-beat signals can guarantee required safety. Multiple built-in communication mechanisms make it suitable for various on-site conditions. The algorithm module structure, which can be either independent or mutually cooperative, yields a flexible configuration with a good expandability. Two kinds of improved generalized prediction control algorithm and a kind of simplified self-adaptive on-line steady-state optimization algorithm have been realized. The use of this software for implementing the advanced-control of the flue gas oxygen-content of a utility boiler has markedly improved control effectiveness. It has been found that the software under discussion involved less investment outlays and has facilitated on-site applications, achieving good results in general. **Key words**: thermal power plant, advanced-control and optimization software, DCS, oxygen-content correction

基于多层 BP 神经网络的回转窑内物料传输模型研究＝**A Study of the Transmission Model of Materials in Rotary Kilns Based on a Multi-layer BP Neural Network**[刊, 汉] /LOU Bo, LUO Yu-he, MA Xiao-qian (Electric Power College under the South China University of Science and Technology, Guangzhou, China, Post Code: 510640) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —409 ~ 413

Through experiments conducted on a rotary-kiln test rig and under the circumstances of rotary kiln speed and inclination angle changes the following law governing the variation of MRT (mean residence time) of materials for five kinds of solid waste materials with different physical-property parameters has been revealed: with an increase in rotary-kiln rotating speed and inclination angle as well as an air speed increase inside the kiln, the MRT will decrease. Among the physical-property parameters of the materials, the repose angle has a relatively great impact on the MRT. A greater repose angle will lead to a shorter MRT. The change of density, however, has a relatively minor effect. The various influencing factors mentioned above will give rise to a relatively big difference in sensitivity to the MRT. The rotary kiln speed is comparatively sensitive to the MRT, while the sensitivity of the kiln inclination angle assumes a relatively uniform character. As regards air speed in the kiln, a combination of low kiln speed and low air speed in the kiln is rather sensitive to the MRT. Taking account of the characteristics that there exist numerous influencing factors in the transmission process of materials in the rotary kiln and an intense nonlinear mechanism, a multi-layer BP neural network has been used to simulate the mapping relationship between the MRT and the various factors, establishing a nonlinear transmission model. The results predicted for 40 groups of experimental data in the model show that the values predicted by the model are in relatively good agreement with experimental results with an average relative error being assessed at 4.1%. This indicates that the model can correctly reflect the material transmission process in the rotary kiln. **Key words**: rotary kiln, BP neural network, transmission model, mean residence time (MRT), nonlinear

水平管内两相流动网丝电容层析成像＝**Wire-Mesh Capacitance Tomography of Two-Phase Flows in a Horizontal Tube**[刊, 汉] /HUANG Shan-fang, ZHANG Xiu-gang, WANG Dong, et al (State Key Laboratory on Power Engineering Multi-Phase Flows under the Xi' an Jiaotong University, Xi' an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —414 ~ 417

A wire-mesh capacitance tomography of two-phase flow distribution is presented. Thermocouple wires with an insulation film on their surface are used as capacitive transducers. The electrolyte of the capacitor is an insulation film with the two poles being respectively metal cores of thermocouple wires and electroconductive fluid film covering the surface of thermocouple wires. The capacitance is directly proportional to the length of the electroconductive fluid film and independent of the latter's distribution and shape. The wire-meshes are parallel and uniformly arranged on a pipeline section. The inner diameter of the test pipeline is 70 mm and the capacitance of each mm long mesh wire being used is 4.82 pF with the spacing of mesh wires being 4 mm. The measurement was performed by use of horizontal and vertical two-direction capacitive transducers. On the basis of knowledge about flow patterns, it is not necessary to reestablish algorithm and the phase distribution can be readily obtained. The steady-state tests show that with this method one can realize the reestablishment of flow patterns, and the section water content as calculated based on the foregoing has a maximal error of 3.9%. **Key words**: wire-mesh capacitance tomography, phase distribution, dual directional measurement, rate of water content

不同油膜力模型下转子椭圆轴承系统的动力学分析＝**A Dynamic Analysis of a Rotor-Elliptic bearing System**

Using Different Oil-film Force Models[刊, 汉] /JIAO Ying-hou, CHEN Zhao-bo, LI Ming-zhang (Electromechanical College under Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —418 ~422

The nonlinear oil-film force obtained by using several kinds of elliptic-bearing nonlinear oil-film models currently available is analyzed and compared with that derived by directly using a finite-difference numerical method for solving a Reynold equation. Meanwhile, the relative errors, calculation speed and dynamic characteristics of the response of an actual rotor-elliptic bearing system obtained under different elliptic-bearing non-linear oil-film force models have also been analyzed and compared. With the calculation accuracy, computation speed and dynamic characteristics of the above system being taken into account in a comprehensive way, research results show that a database method should be an oil-film force model to be recommended as a first priority, followed by a database fitting-expression and variation method model as a second choice. The foregoing provides a basis for the selection of oil-film force model during the nonlinear dynamic analysis and design of an actual rotating mechanical rotor-elliptic bearing system. **Key words**: non-linear oil film force, elliptic bearing, rotor system

基于D-S 证据理论的煤粉细度融合诊断= **Fusion Diagnosis of Pulverized-coal Fineness Based on a D-S Evidence Theory**[刊, 汉] /LIU Ji-zhen, CUI Ze-peng, TIAN Liang, et al (Automation Department, North China University of Electric Power, Baoding, China, Post Code: 071003) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —423 ~426

With regard to the difficult problem of performing an on-line measurement of pulverized coal fineness at power plants, a datum fusion technology is proposed to discriminate whether the pulverized coal is over-fine, normal and excessively coarse. On the basis of analyzing several operation-status parameters relating to pulverized coal fineness and according to historical operational data, typical samples of pulverized coal fineness have been identified. Thereafter, the results of various status parameters can be ascertained by use of D-S fusion rules. Concerning the problem that it is difficult to determine the basic probability assignment during the use of D-S evidence theory, a normal distribution curve was utilized to construct a similarity function followed by the acquisition of the basic probability assignment, thus reducing subjectivity. As verified by the operational data, the above method could effectively diagnose the fineness of pulverized coal and is characterized by relatively good robustness and practical value in engineering applications. **Key words**: data fusion, evidence theory, basic probability assignment, pulverized coal fineness

中压参数热电厂高压迭置的改造分析= **An Analysis of the Modification of a Thermal Power Plant of Medium-pressure Parameters by HP (High Pressure) Superimposition**=[刊, 汉] /WANG Bin, HE Wan-guo, HOU Jun-suo (Wuxi Subsidiary of Harbin No. 703 Research Institute, Wuxi, China, Post Code: 214151), YE Wen (Wuxi Huaguang Boiler Co. Ltd., Wuxi, China, Post Code: 214028) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —427 ~430

In 1980s of the 20th century, several district thermal power plants were built in southern China, which had played an extremely important role in easing the contradiction between electric power supply and demand, enhancing environment protection and energy savings as well as promoting local economic development. As the initial steam parameters of thermal machines are excessively low, their thermal efficiency is not high and coal consumption for power generation and heat supply comparatively high. Enterprises experienced difficulties in maintaining their normal operation when coal price continuously went up. In view of this, Wuxi City Thermal Power Plant has underwent a modification and expansion construction based on a HP superimposition and an energy-saving design version. The above project was put into operation in July 2005, resulting in the attainment of sizable economic benefits with the thermification power generation rate being increased by 46% and the coal consumption for heat and power supply lowered by 20%. Thereafter, the said thermal power plant has ceased to suffer operating losses and embarked on the path of sustainable development. The above-mentioned design version can serve as a guide during the modification of district thermal power plants to enhance the initial steam parameters of thermal machines. Key words: HP superimposition, energy saving, modification analysis