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劳伦斯法在热工对象动态特性辨识中的应用

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摘 要:描述了利用劳伦斯法由频域数据进行传递函数拟合的过程,并采用该法对分轴燃气轮机在三个运行工况下的传递函数进行了拟合,拟合结果与实验结果在各工况下都有较好的吻合,说明劳伦斯法是可信的;此外,又采用辨识与数字仿真相结合的方法对拟合结果进行了简化,获得了与实验结果相符的简化模型。

关 键 词:劳伦斯法;系统辨识;传递函数拟合

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1 引 言

系统辨识是建立复杂热工对象数学模型的重要途径。现已应用到热工对象动态特性辨识中的方法主要有切线法、面积积分法、数值积分法、Levy 法等[1~3]。其中前三种属于时域辨识法,多用于由实验测取的阶跃响应曲线来拟合传递函数的过程;而 Levy 法属于频域辨识法[4],是一种由频率特性拟合传递函数的方法,因其参数估计不是无偏的,且要求采样频率范围不能伸展得很宽,故在工程应用上还存在一些问题。文献[5]利用 Levy 法对分轴燃气轮机三个运行工况下的采样数据进行了传递函数的拟合,为了克服 Levy 法的缺陷,采用了高、低频分段拟合然后相乘的方法,得到了较为满意的结果。但高、低频综合考虑分段拟合不仅增加了计算量,而且对方法及应用软件的使用者提出了更高的要求。本文采用劳伦斯(Lawrence)法对该实验结果直接进行了拟合[6],得到了与实验结果吻合较好的传递函数模型,并采用辨识与数字仿真相结合的方法对拟合结果进行了简化,使高阶系统中的容量延迟转换为低阶系统中的纯延迟特性,从而获得了与实验结果相符的简化模型。

2 方法描述

设 $G(j\omega)$ 为辨识实验所测得的频率特性,$G(j\omega)$ 为待拟合的频率特性,则根据线性系统传递函数的一般形式,可将其频率特性写成如下形式:

$$G(j\omega)=\frac{b_0+b_1(j\omega)+\cdots+b_m(j\omega)^m}{1+a_1(j\omega)+\cdots+a_n(j\omega)^n}=\frac{B^TM(j\omega)}{1+A^TN(j\omega)} \tag{1}$$

其中:$A^T=[a_1,a_2,\cdots a_n]$, $B^T=[b_0,b_1,\cdots b_m]$ 为待辨识的参数向量;

$N(j\omega)=[j\omega,(j\omega)^2,\cdots(j\omega)^n]^T$;

$M(j\omega)=[1,j\omega,\cdots(j\omega)^m]^T$。

对每一个选定的频率 ω_i,定义了一个新的误差函数 e_i:

$$e_i=\frac{|G(j\omega_i)(1+A_K^TN(j\omega_i))-B_K^TM(j\omega_i)|}{|1+A_{K-1}^TN(j\omega_i)|}$$

则全部采样频率上的误差的平方和为

$$E=\sum_{i=1}^{N}e_i^2=\sum_{i=1}^{N}|G(j\omega_i)(1+A_K^TN(j\omega_i))-B_K^TM(j\omega_i)|^2/|1+A_{K-1}^TN(j\omega_i)|^2 \tag{2}$$

式中:A_K^T, B_K^T—为本次的参数估计值,A_{K-1}^T—前一次的参数估计值,$G(j\omega_i)$—测试所得 $\omega=\omega_i$ 的频率响应,N—采样数据点的总个数。

记 $u_i^T=[M^T(j\omega_i),-N^T(j\omega_i)G(j\omega_i)]$;

$\theta_K^T=[B_K^TA_K^T]$;

$d_i=1+A_{K-1}^TN(j\omega_i)$;

d_i^*, $G^*(j\omega_i)$, u_i^*—依次为 d_i, $G(j\omega_i)$, u_i 的共轭。

则使 E 为最小的向量 θ_K 值满足下式:

$$\left\{\sum_{i=1}^{N}\frac{1}{d_id_i^*}[u_iu_i^{*T}+u_i^*u_i^T]\right\}\theta_K=\left\{\sum_{i=1}^{N}\frac{1}{d_id_i^*}[u_iG^*(j\omega_i)+u_i^*G(j\omega_i)]\right\}$$

通过引入两个辅助矩阵量 P、Q 可对上式予以修正,从而得到了下面的递推形式:

$$Q_K=P_{K-1}\left[I-\frac{f_Kf_K^TP_{K-1}}{\frac{|d_K|^2}{2}+f_K^TP_{K-1}f_K}\right] \tag{3a}$$

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$$P_K = Q_K\left[I - \frac{h_K h_K^T Q_K}{\frac{|d_K|^2}{2} + h_K^T Q_{K-1} h_K} \right] \tag{3b}$$

$$\theta_K = \theta_{K-1} + \frac{2}{|d_K|^2} P_K \{ f_K ReG(j\omega_K) + h_K ImG(j\omega_K) - (f_K f_K^T + h_K h_K^T)\theta_{K-1} \} \tag{3c}$$

其中：

$$\begin{cases} d_K = 1 + A_{K-1}^T N(j\omega_K) \\ u_K^T = [M^T(j\omega_K), - N^T(j\omega_K)G(j\omega_K)] \\ f_K = Re(u_K);\ h_K = Im(u_K) \\ \theta_K^T = [B_K^T A_K^T] = [b_0, b_1, \cdots b_m, a_1, a_2, \cdots a_n] \end{cases}$$

$K = 1, 2, \cdots N$

根据辨识实验测定的频率数据序列 $G(j\omega_K)$，利用式(3a)、(3b) 和(3c) 就可以计算出式(1) 中的待定参数，从而确定对象的传递函数。由式(3a)、(3b) 和(3c) 三个递推公式可见，劳伦斯法采用逐个数据点进行拟合，同时用上一个数据点拟合得到的估值来修正权，因此该法适用于在线辨识，减小了偏向性并能提高收敛速度。

3　拟合结果

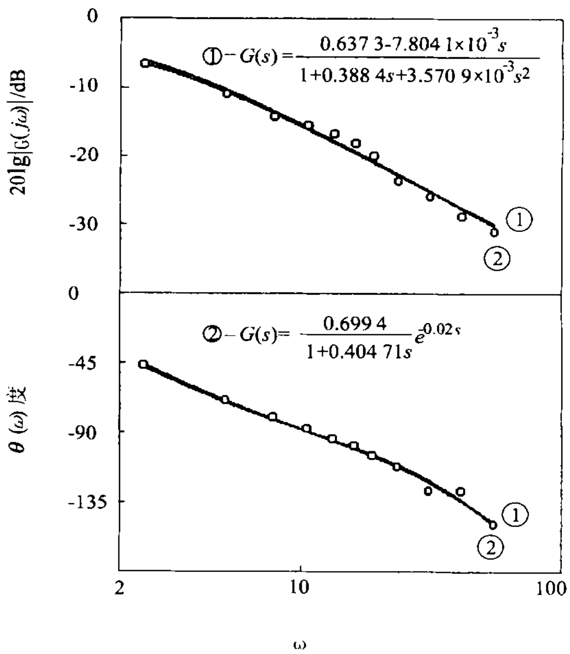
采用劳伦斯法，我们对十阶以内的系统编制了根据频域采样数据拟合传递函数的辨识软件，同时也编制了仿真程序。根据文献[5] 中对分轴燃气轮机燃油量 B 与压气机轴转速 n_1 之间的实验特性在 $\bar{n}_1 = 92\%$，$\bar{n}_1 = 83\%$，$\bar{n}_1 = 57\%$（$\bar{n}_1$ 为压气机轴相对转速）三种工况下给出的实验曲线的采样点数据，我们采用劳伦斯法直接拟合出了它们的传递函数，然后又根据拟合出的传递函数的特点，并结合我们的辨识与仿真软件，对各工况下的拟合结果进行了简化，所得结果如表 1 所示。

对上面的传递函数进行简化时，我们采用辨识软件先以较低阶次的传函形式拟合出与实验结果吻合较好的幅频特性，然后结合仿真通过串以纯延迟环节来修正相频特性，使高阶系统中的容量延迟转换为低阶系统中的纯延迟特性，从而得到了如表 2 所示的简化形式。

表 2

工况	传递函数	时间常数
$\bar{n}_1 = 92\%$	$\frac{0.6599}{1+0.4047s}e^{-0.02s}$	0.404 7
$\bar{n}_1 = 83\%$	$\frac{0.4343}{1+0.5269s}e^{-0.0215s}$	0.526 9
$\bar{n}_1 = 57\%$	$\frac{2.0263}{1+1.0121s}e^{-0.0175s}$	1.012 1

图 1 给出了三种工况下拟合结果以及简化结果的频率特性曲线，图中的符号“□”表示实验采样点数据[5]。从图中可以看出，拟合结果和实测数据有较好的吻合。



(a) $\bar{n}$=92%工况

图 1　$B \sim n_1$ 开环幅频和相频特性曲线

表 1

$\bar{n}_1$	传递函数	拟合误差	数据点数	频带宽 / Hz
92%	$\frac{0.6373 - 7.8041\times10^{-3}s}{1+0.3884s+3.5709\times10^{-3}s^2}$	1.4275×10^{-3}	11	0.390 6 ~ 8.202 6
83%	$\frac{0.4248 - 4.0705\times10^{-3}s}{1+0.5157s+6.9385\times10^{-3}s^2}$	2.5251×10^{-3}	10	0.390 6 ~ 6.640 2
57%	$\frac{2.0682+0.3249s+7.3\times10^{-3}s^2}{1+0.8564s+0.2131s^2+3.24\times10^{-3}s^3+1.136\times10^{-4}s^4}$	0.015 6	11	0.390 6 ~ 7.812

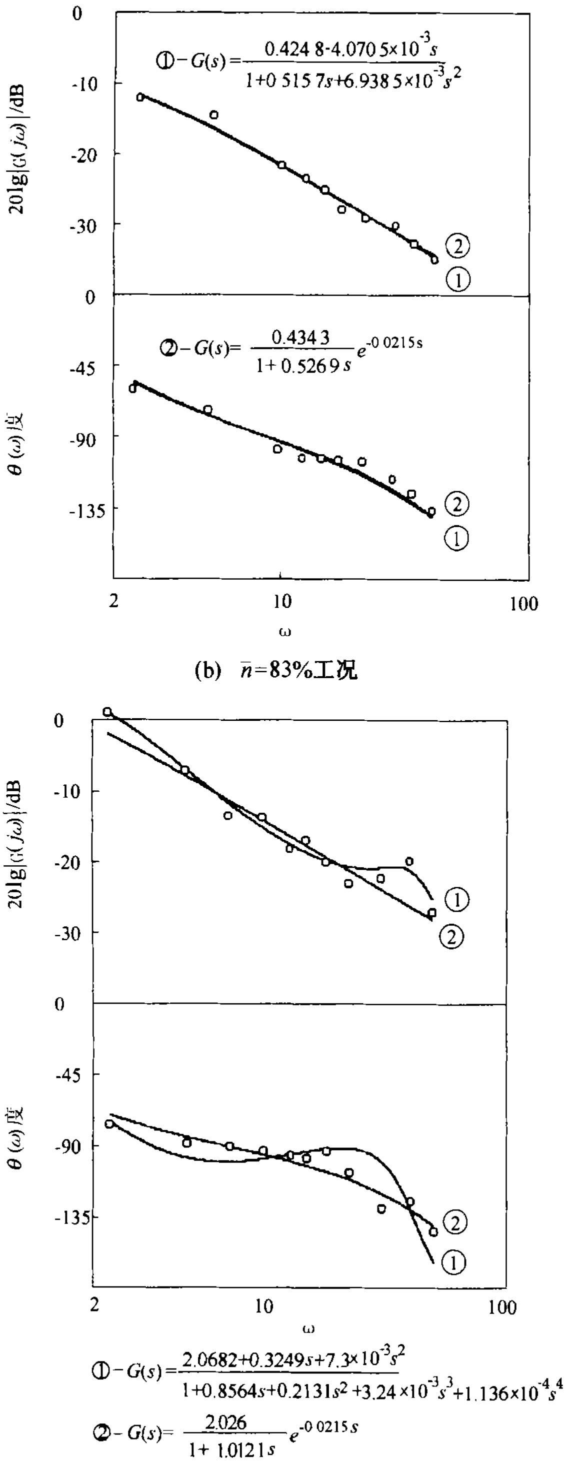


图 1　$B\sim n_1$ 开环幅频和相频特性曲线

4　结论

（1）由拟合传递函数的频率特性与实验特性采样点比较可看出，三种工况下的拟合结果与原实验数据都有较好的吻合，这说明采用劳伦斯法是可靠的，可作为热工对象动态特性辨识过程中由频域数据拟合传递函数的一种实用方法。

（2）劳伦斯法逐点拟合的递推特点使其不仅可作为一种离线辨识方法，而且也可用于热工对象动态特性的在线辨识。

（3）采用辨识与仿真相结合的技术，不仅可得到与实验结果相符的简化模型，还可以辨识出 Levy 法、劳伦斯法都无法拟合出的纯延迟特性。

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various channels as well as the structural parameters of the heat exchanger. As a result, obtained were the fluid temperature distribution of various channels and the fluid temperature difference of neighboring channels. Furthermore, analyzed was the effect of the variation of fluid parameters, flow modes and structural parameters on the fluid temperature crossover of the neighboring channels. **Key words**: multi-stream plate-fin heat exchanger, temperature crossover, fin bypass, flow mode

烟气含氧量软测量新方法研究＝**The Study of a New Method Incorporating the Soft Sensing of Oxygen-content in Flue Gases** [刊,汉] / LU Yong, XU Xiang-dong (Department of Thermal Engineering, Tsinghua University, Beijing, China, Post Code: 100084) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). —614～617

In view of the high first cost of conventional oxygen-content analyzers for industrial applications, their high maintenance expenses and low durability the authors have on the basis of comparing several commonly used methods come up with a new method for measuring oxygen content in flue gases. The proposed method involves an oxygen-content soft sensing model set up through the use of a NNPLS (neutral network partial least square) approach based on statistical analyses and neural network technology. It enjoys both the merits of PLSR (partial least square regression) and neural network technology, making it possible to identify a target model by utilizing historical process data. A simulation verification of the method has been conducted by using on-site industrial data. In addition, the simulation results are compared with traditional linear PLSR method and the direct neural network-based modeling method. The results of comparison indicate that the soft sensing model based on the NNPLS approach features a more effective generalizing ability. Furthermore, an extension of a static model to a dynamic one was also performed. **Key words**: soft sensing, partial two least squares, neural network, cross validation, generalizing ability

用预报误差校正的锅炉燃烧系统预测控制研究＝**A Study of the Predictive Control of a Boiler Combustion System through the Correction of a Forecast Error** [刊,汉] / ZHU Xue-li, QI Wei-gui, LI Li-yan (School of Electric Engineering and Automation under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). —618～621

To improve the performance of a boiler-combustion control system, a dynamic matrix control (DMC) - based algorithm with the correction of a forecast error has been put forward to fulfill relevant control functions. After a brief description of the DMC composition and an internal-model control structure a model error is predicted based on a time sequence analysis, parameter estimation and an optimum forecast theory. Furthermore, by forecasting the model error and using the model forecast error to replace the model error the rolling optimization of a predictive control can be duly corrected. Finally, through the simulation tests of the predictive control for the boiler control system it is shown that the correction of the forecast error can result in a marked improvement in such characteristics as tracking ability, anti-interference and robustness when compared with an error correction algorithm in general. **Key words**: combustion system, predictive control, time sequence, forecast error

劳伦斯法在热工对象动态特性辨识中的应用＝**The Application of Lawrence Algorithm in the Identification of Dynamic Behavior of Thermodynamic Objects** [刊,汉] / XU Hou-qian, JIANG Gui-zhen (Power Engineering College under the Nanjing University of Science & Technology, Nanjing, China, Post Code: 210094) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). —622～624

Described is the process of a transfer-function fitting performed through the use of Lawrence algorithm by way of frequency domain data. Furthermore, the above method was employed to conduct the fitting of transfer functions for a split-shaft gas turbine under three operating conditions. Under various operating conditions the results of fitting agree relatively well with those of experiments, testifying to the credibility of the Lawrence algorithm. In addition, by using a method, which com-

bines system identification with a numerical simulation, the results of fitting were simplified, thereby obtaining a simplified model, which complies with experimental results. **Key words**: Lawrence algorithm, system identification, transfer function fitting

基于OPC规范的火电厂监控信息系统研究＝**A Study of the Supervisory information System for a Thermal Power Plant Based on an OPC (Object-linking-and-embedding for Process Control) Specification** [刊, 汉] / QUAN Xin-jian, LIN Zhong-da (Power Engineering Department, Southeastern University, Nanjing, China, Post Code: 210096) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). —625～628

The study mainly focuses on a plant-level supervisory information system for a thermal power plant by adopting the design conception of a modularized program based on COM/DCOM technology. A standard OPC (object-linking-and-embedding for process control) interface (OPC client program and OPC server program) in compliance with OPC specification has been adopted to serve as the communication interface of the supervisory information system. This gives full play to the identity and opening characteristics of the OPC interface, thereby providing a new realistic approach for organizing an open and flexible plant-level supervisory information system for thermal power plants. **Key words**: thermal power plant, supervisory information system, design

饱和蒸汽减温在燃机余热锅炉的应用＝**The Application of Saturated Steam Attemperation in Gas-turbine Heat Recovery Boilers** [刊, 汉] / ZHANG Yong, YAO Dong, WEI Shao-jie (Harbin No.703 Research Institute, Harbin, China, Post Code: 150036), ZHAI Zuo-wu (Harbin No.3 Power Generation Co. Ltd., Harbin, China, Post Code: 150036) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). —629～631

Described is a method of superheated steam regulation for the heat recovery boiler of a gas-steam combined cycle power plant, the so-called boiler-drum saturated steam attemperation. The design of such a saturated-steam attemperating system is analyzed with some problems worthy of close attention in practical use being pinpointed. **Key words**: gas-steam combined cycle power plant, heat recovery boiler, saturated steam attemperation

百叶窗式水平浓淡煤粉燃烧器在燃贫煤300MW机组的应用＝**The Use of a Horizontal and Louver-type Concentrated-diluted Pulverized Coal Burner in a 300 MW Lean Coal-fired Power Plant** [刊, 汉] / WANG Ji-hong (Boiler Repair Shop at Anyang Power Plant, Anyang, Henan Province, China, Post Code: 455004) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). —632～634

The steady combustion and low NOx emission mechanism of a horizontal and Louver-type concentrated-diluted pulverized coal burner was analyzed from the perspective of its construction features. After a modification of the burners installed on boilers No.9 and 10 of Anyang Power Plant test results indicate that an optimum performance has been attained in respect of both NOx emissions and combustion stability. This has a certain reference value for similar type of boiler units. **Key words**: 300MW power plant, horizontal and Louver-type concentrated-diluted pulverized coal burner, modification, test, combustion stability

高水分燃料的沸腾层烟气热平衡方程＝**A Thermal Energy Balance Equation Obtained for the Flue Gases of a Fluidized Bed When High-moisture Fuels Were Fired** [刊, 汉] / HUANG Yi-min, YU Hong-bin (Power Engineering Department, Harbin Institute of Technology, Harbin, China, Post Code: 150001) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(6). —635～637

A thermal energy balance equation has been obtained for the flue gases of a fluidized bed operating on high-moisture fuels. With bark, lignite and bituminous coal of grade 1 serving as fuels analyzed was the effect of heat absorption during the water evaporation of unburned fuel in the fluidized bed on two factors. The latter are the quantity of heat absorbed by a submerged tube and the temperature of the fluidized bed. The results of calculation and analysis indicate that when