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一种汽轮机转子的热应力测试系统

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摘　要: 介绍一种测量汽轮机转子热应力的系统。该系统中采用了一种测差法, 该方法减小了测量中模数转换器的量化误差的影响, 提高了温升率测量的准确度和热应力计算的准确度。同时, 该系统把所测的热应力以 4～20 mA 的形式输出, 供其它系统分析, 为今后计算汽轮机组的寿命提供数据。

关　键　词: 转子热应力; 实时监测; 测差法
中图分类号: TK263.61, TK31

1　引言

转子是汽轮机的关键部件之一, 工作于高温、高压及自身也在高速旋转中, 除承受自身的重量和离心力外, 还要承受由温度变化引起的交变应力以及扭转应力等的作用, 其受力状态是复杂的。因此, 转子是机组在线监测的重点, 转子的寿命基本上反映了机组的寿命。据文献[1]给出, 转子热应力占机组寿命损耗的 70%。测量汽轮机转子的热应力的两个目的是:

①可以通过测量汽轮机转子热应力的大小, 间接计算出机组的寿命。

②通过监视转子热应力的大小, 调整起停机的速度, 既保证机组的安全, 也可节省起停机的费用。

传统的转子热应力计算方法主要有两种[1]: 一种方法是有限元数值解法, 将转子视为轴对称的二维模型, 这种计算方法可以得到精确的结果, 但这种方法计算时间长, 不适合现场实时计算热应力; 另一种方法是解析法, 将转子视为无限长的一维模型, 根据其温度分布计算出热应力。解析法计算的热应力误差较大, 但其计算速度快, 满足实时性。本装置所采用的计算方法即为解析法。

公式[1]为:

$$\sigma_\theta = \frac{\beta E}{1-\upsilon} \times \left[\frac{1-\rho_2^2}{8} + A_2 \left(\eta_1 e^{-K_1 \tau / R_0^2} + (\eta_2 - \eta_1) \times e^{-k_1 (\tau - \tau_1)/R_0^2} \right) \right] \quad (1)$$

公式(1)中影响热应力的主要变量是温升率, 其它的参数可根据机组的不同而定。对公式(1)进行修正后, 应用与本系统。本系统能够测量汽轮机的高压缸、中压缸的温度、压力、转速、应力, 同时设定各个参数的报警值。

2　测量装置

热应力测试系统的原理框图如图 1 所示。

本系统的输入为汽轮机的高压缸、中压缸的温度、压力及转速。

热应力的计算主要是通过高、中压缸温度单位时间的变化(温升率)计算得出的。本装置把热应力的计算结果经过 D/A 转换器的变换后, 以 4 ～ 20mA 输出, 留待其他系统分析。

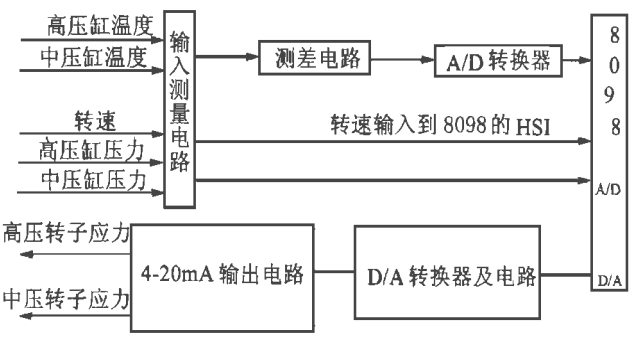

图 1　热应力测试系统原理框图

信号的获取:

3　测量系统中的关键技术

3.1　测差法测温升率

汽轮机在起机、停机过程中, 温度变化范围的特点有两点:

①温度变化范围大, 从室温到 535 ℃变化。

②单位时间内温度变化幅值小, 起停机的温升率为 0～2 ℃/min。

针对汽轮机起停机的两个温度变化特点, 如果直接采用把温度转换的电压值模数转换的方法, 由于模数转换器量化误差的影响, 测量温升率就需要高位的 A/D 转换器, 高位 A/D 转换器对其 A/D 转换的参考电压及外围电路的要求也高。因此, 在参考文献[2]中提出了一种测量温升率的方法——测差法。这种方法在应用 10 位 A/D 的情况下, 减小了量化误差的影响, 测量结果相当于 14—15 位 A/D 转换器。

测差法原理: 在一次测量时间过程中, 把测量起始的值作为测差法差数的减数, 此减数在一次测量时间过程中保持不变, 而被减数为传感器直接输入的温度值, 被减数在一次测量时间过程中是随传感器测得的温度的变化而变化的。被减数与减数相减的结果经放大后, 进行 A/D 转换。在一次测量时间过程中测量多个点, 应用数学方法计算出这些点的斜率后, 再除以放大的倍数, 即为一次测量时间过程中所测温度变化的温升率。

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3.2 热应力数值转换后输出

本测量系统把热应力计算的结果，以 4～20mA 的形式输出。

采用 4～20 mA 输出的芯片为 AD693。AD693 的典型输入范围为 0～30 mV 或 0～60 mV，当应用 0～30 mV 单极性输入、4～20 mA 输出时，其基本的连接为图 2：这种电路连接满足双电源情况，即对于单片机一套电源，外部负载一套电源。内部电源＋15V 作用于 AD693 的第 9 脚。如果只采用外部一套电源，即内部不给 AD693 供电，则 AD693 的第 8 与第 9 脚相连。

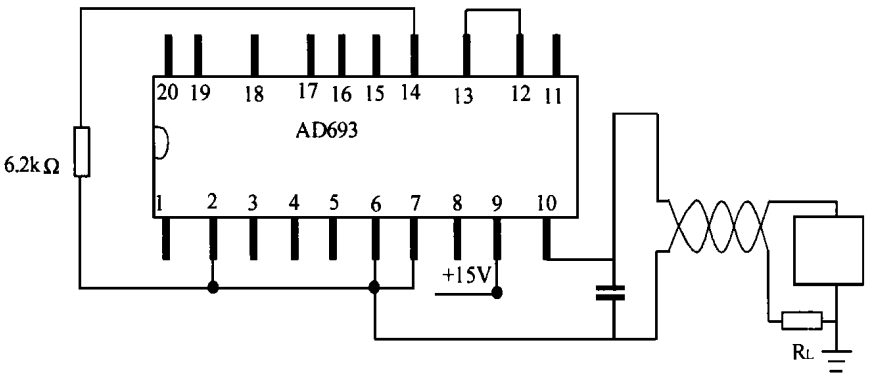

图 2 AD693 在双电源情况下的连接

电路工作过程：

单片机 8098 把热应力计算的结果转化为 8 位数字量，传输到 DAC0832，0832 把数字量转化为 AD693 要求输入的范围 0～30 mV，AD693 把 0～30 mV 转化为 4～20 mA 输出。本装置采用两套电源，单片机内部给出一套电源，外部负载给出一套电源。

4 仿真结果

有限元法计算的转子热应力准确度高，计算时间长；数值解法（简化公式）计算的热应力准确度低，但计算速度快。对装置热应力计算精度仿真采用模拟输入温度变化，装置计算的热应力与有限元法在同样温度变化计算的热应力值比较。

用人工控制电压的变化代替温度变送器的电压变化，来模拟温度值的变化。现模拟温度的变化范围为：

4.1 冷态起机温度随时间的变化为：

时间(min)	0	260	360	425
温度(℃)	120	500	535	535

冷态起机工况的热应力有限元法与简化公式计算的结果比较见图 3。

4.2 热态起机温度随时间的变化为：

时间(min)	0	20	50	110	150
温度(℃)	400	460	500	535	535

热态起机工况的热应力有限元法与简化公式计算的结果比较见图 4。

4.3 温升率分别为 0.5、1、2、3、4 ℃/min，温度范围皆为 120 ℃～500 ℃。

不同温升率工况的热应力有限元法与简化公式计算的结果比较见图 5。

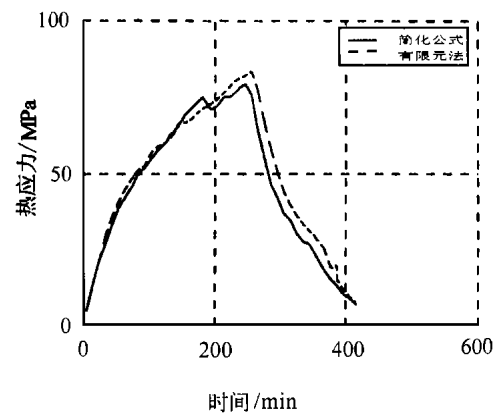

图 3 冷态起机工况的热应力

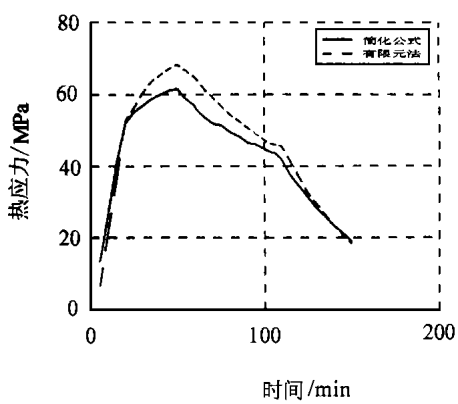

图 4 热态起机工况的热应力

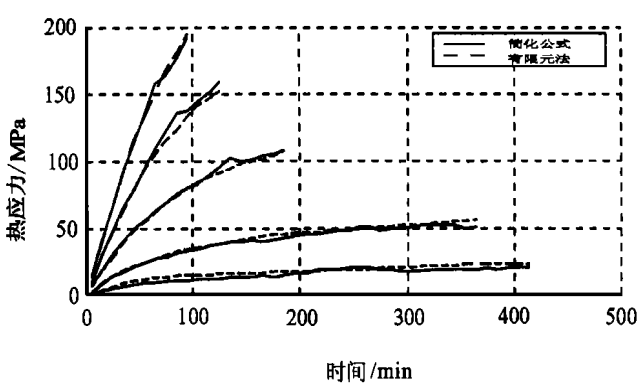

图 5 不同温升率工况的热应力

5 结论

本系统应用解析公式计算汽轮机转子热应力，虽然在精度上与有限元计算的转子热应力值有误差，但还是能满足工程上需要的。本文提出的测差法减小了热应力测量中产生的测量误差，同时，本系统把计算的热应力值以 4～20 mA 输出，为热应力的分析及寿命计算提供了条件。

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（渠 源 编辑）

Device for Pulverized Coal-fired Boilers [刊, 中] /Liu Shengyong, et al (Key Laboratory of Renewable Energy Sources under the Ministry of Agriculture) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —447~449

This paper expounds in detail the design and calculation of nozzles, injectors and burner cones of a liquefied petroleum gas-based ignition device for pulverized coal-fired boilers as well as ways and means for flame stabilization. Application results show that such ignition devices feature a high flame temperature, good adaptability in operation and ease of use, etc. They have broad prospects for use in utility boilers that consume no oil or only a limited amount of oil for ignition. **Key words**: pulverized coal-fired boiler, liquefied petroleum gas, forced premixing, ignition device

旋流浓淡煤粉燃烧器出口区域气固两相流动特性的实验研究＝**Experimental Study of Gas-Solid Dual-phase Flow Characteristics at the Outlet Zone of a Dense-dilute Pulverized Coal-fired Swirl Burner** [刊, 中] /Li Zhiqiang, Li Rongxian, et al (Qinghua University) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —450~454

With the help of a three-dimensional phase Doppler particle analyzer an experimental study was conducted of the dual-phase flow characteristics at the outlet zone of a dense-dilute swirl burner. As a result, obtained are the distribution relationship of gas-solid dual-phase flow field and concentration field of the said burner under various degrees of openness of swirl blades and at different ratios of swirl secondary air and direct-flow secondary air. In addition, an analysis is also conducted of the above distribution relationship. **Key words**: dense-dilute pulverized coal-fired swirl burner, gas-solid dual-phase flow, three-dimensional Doppler particle analyzer (PDA), swirl blade openness, air flow rate proportioning

浓淡型双调风旋流燃烧器低 NO_x 特性分析＝**An Analysis of the Low NO_x Emission Feature of a Dense-dilute Dual-channel Swirl Burner** [刊, 中] /Yu Zhanying, Jiang Hongli, Tan Houzhang, et al (Xi'an Jiaotong University) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —455~457

An experimental study is conducted of a dense-dilute dual-channel swirl burner with the help of cold-state isothermal simulation technology. On the basis of the test results the structure and features of such a burner are analyzed and a study is conducted of the characteristics of a stepped air-feed and dense-dilute combustion techniques. In addition, the major role played by a combustion stabilization ring has also been investigated. All the above has led to a better understanding of the mechanism of low NO_x emission and partial load flame-stabilization of the dual-channel swirl burner. **Key words**: dual-channel swirl burner, low NO_x emission, flame stabilization, experimental investigation

带纵肋环烟管流动与传热实验研究＝**An Experimental Study on the Flow and Heat Transfer in Annular Flue Gas Pipes with Longitudinal Ribs** [刊, 中] /Wang Huaibin, Du Jun, et al (Harbin Institute of Technology) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —458~460

A new type of flue gas pipe fitted with longitudinal internal ribs and featuring an intensified convection heat exchange is proposed by the authors for use on an oil-field heating boiler. An experimental study was performed of its flow and convection heat exchange with a criterion equation of heat exchange being given. **Key words**: longitudinal rib, annular flue gas pipe, convection heat exchange

声波吹灰器的研制＝**Development of a Sonic Soot Blower** [刊, 中] /Li Qiang, Sun Cengrun, Xuan Yimin (Nanjing University of Science & Technology) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —461~462

Based on the principle of hydrodynamics and acoustic resonance the authors have developed a sonic soot blower for use on heat exchangers. A relevant experimental test has been performed of its acoustic intensity performance. The experimental test and industrial application results show that the sonic soot blower under discussion can effectively remove soot deposits from heat exchangers. **Key words**: boiler, heat exchanger, sonic wave, sootblowing

一种汽轮机转子的热应力测试系统＝**A Test System for Measuring Thermal Stresses in Turbine Rotors** [刊, 中] /Gao Jingbo, Wu Xinhua, Xia Songbo, et al (Harbin Institute of technology) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —463~464

This paper focuses on a new system for measuring turbine rotor thermal stresses. The use of a difference measur-

ing method for the system can reduce the influence of quantization error of A/D converter, thereby increasing the measurement accuracy of the temperature-rise rate and enhancing the accuracy of thermal stress calculation. In addition, the system on the basis of a measured thermal stress gives an output in the form of 4 - 20 mA to other systems for analysis, accumulating relevant data for computing turbine service life later on. **Key words**: rotor thermal stress, real-time monitoring, difference measuring method, accuracy

稠密气固两相流的直接数值模拟＝**Direct Numerical Simulation of Dense Gas-solid Two-phase Flows** [刊, 中] /Yuan Zhulin (Thermal Energy Research Institute under the Southeastern University) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —465 ~ 466

Gas-phase field and discrete particle field are treated respectively by a Eulerian method and a Lagrangian one. During the treatment of a particle field the effect of particle diameter, specific weight, rigidity of material and friction factor, etc on particle movement has been taken into account. A direct simulation method was employed to simulate funnel flow, the particle movement in a ball mill and a stouted bed. Moreover, tests were conducted to verify the simulation results obtained on the stouted bed. **Key words**: gas-solid two-phase flow, direct numerical simulation

换热系统变工况分析＝**Off-design Performance Analysis of a Heat Exchange System** [刊, 中] /Bao Demei, Fan Deshan, Xu Zhigao (Southeastern University) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —467 ~ 470

A new method for analyzing a heat exchange system performance variation is proposed along with the establishment of a relevant linear mathematical model. The proposed method can not only analyze the performance of the heat exchange system as a whole during a change in operating conditions, but also reflect the thermal excursion and temperature changes of each heat exchanger within the system and also the efficiency of the heat exchanger itself. Finally, by taking the boiler heating surface soot-blowing as an example the results obtained from the model and those from a simulated model are compared. It is shown that the proposed method features both simplicity and real-time properties. **Key words**: heat exchange system, off-design operating conditions, thermal efficiency, heat transfer unit, soot-blowing

基于模糊神经网络的高加系统内部故障诊断方法＝**A Method for the Diagnosis of Internal Malfunctions of a High-pressure Heater System Based on a Fuzzy Neural Network** [刊, 中] /Qin Zaicong, Xu Zhigao (Southeastern University), Lu Songlin (Jiangsu Provincial Electrical Power Test Research Institute) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —471 ~ 472

The authors expound the application of a fuzzy neural network for the diagnosis of internal malfunctions in a high-pressure heater system. Practice has shown that the diagnosis model under discussion has broad prospects for engineering applications. **Key words**: failure diagnosis, fuzzy neural network, high-pressure heater system

双列调节级的变工况热力计算方法及应用＝**A Method of Thermodynamic Calculation for Off-design Conditions of a Turbine Dual-row Governing Stage and Its Application** [刊, 中] /Fu Lin, Jiang Yi (Qinghua University) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —473 ~ 476

The authors have come up with a thermodynamic calculation method for a turbine dual-row governing stage. Under this method the thermodynamic properties of the governing stage, including post-stage steam enthalpy, can be speedily identified when made known are only such parameters as the relevant geometric characteristics of the stage. The method can be employed for the simplified thermodynamic calculation of heat supply units. **Key words**: dual-row governing stage, algorithm, steam extraction unit

矩阵法和偏微分理论在机组热经济性分析中的应用＝**The Use of Matrix Method and Partial Differential Theory for the Analysis of a Reheat Unit Economic Performance** [刊, 中] /Zheng Xiuping, Zheng Luying, Cai Tianyou (Northeastern University) //Journal of Engineering for Thermal Energy & Power. —1999, 14(6). —477 ~ 480

A general analysis is performed of a power plant reheat-regeneration thermodynamic system with the use of a matrix method and partial differential theory. Given are the calculation results of thermo-economic analytical parameters H_j^o and η_j^o. The proposed method is applicable for both reheat units and non-reheat ones. **Key words**: thermal system, matrix method, partial differential theory, economic performance analysis

弹性转子磁气轴承系统的 H_∞ 控制＝**H_∞ Control of the Magnetic Bearing System of a Flexible Rotor** [刊,