三轴燃气轮机并行数字计算机实时仿真

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〔摘要〕本文介绍三轴燃气轮机的实时仿真模型以及用 MIRAGE 并行数字仿真工作站进行全数字实时仿真的技术问题。为了保证进行实时仿真,并行数字计算机的计算步长除与对象复杂程度有关外,还与所选数字计算机数目有关,选取较小步长必须使用较多计算机。

关键词　燃气轮机　实时仿真　并行数字计算机

分类号　TK47　TP391.91

1　三轴燃气轮机仿真模型

通常可用三类方程组描述燃气轮机动态性能,即惯性环节微分方程组、部件特性方程组、参数联系方程组。经过迭代和大量复杂运算求解上述三类方程组从而求得燃气轮机的动态性能。普通数字计算机根本无法达到实时性。由于存在迭代运算,就是并行数字计算机也难以承担实时仿真。根据实时仿真要求,必须建立三轴燃气轮机实时仿真模型。

对于如图1所示三轴燃气轮机,惯性环节微分方程组为:

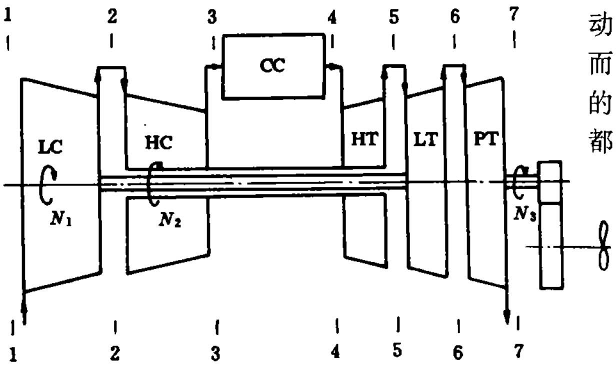

图1　三轴燃气轮机简图

$$KI_1\frac{\mathrm{d}n_1}{\mathrm{d}t}=\Delta M_1$$

$$KI_2\frac{\mathrm{d}n_2}{\mathrm{d}t}=\Delta M_2$$

$$KI_3\frac{\mathrm{d}n_3}{\mathrm{d}t}=\frac{N_e}{n_3}-M_L-M_f \qquad (1)$$

式中　I—— 转子转动惯量;n—— 转子转速;K—— 常数;ΔM_1—— 低压转子剩余力矩;ΔM_2—— 高压转子剩余力矩;N_e—— 燃气轮机有效功率;M_L—— 负荷阻力矩,M_f—— 传动系统摩擦力矩。

分析三轴燃气轮机的部件特性方程组和参数联系方程组,决定三轴燃气轮机任一非平衡状态的,除了控制量(燃油量 W_f)外,还取决于状态变量 n_1、n_2、n_3,在任何时刻,只要给定 W_f、n_1、n_2、n_3 四个量的值,就可以唯一确定发动机在该点的状态,确定所有参数的数值。因而式(1)的右函数 ΔM_1、ΔM_2、N_e 以及发动机的其它热力参数(用 E_i 表示,i = 1,2……m)都可以表达成这四个变量的函数,即

$$\begin{aligned}\Delta M_1&=f_1(W_f、n_1、n_2、n_3)\\ \Delta M_2&=f_2(W_f、n_1、n_2、n_3)\\ N_e&=f_3(W_f、n_1、n_2、n_3)\\ &\cdots\cdots\\ Z_i&=gi(W_f、n_1、n_2、n_3)\end{aligned} \qquad (2)$$

通过三轴燃气轮机的部件特性方程和参数联系方程组,可以事先求得这些函数关系,代入方程组(1),可以不需迭代完成实时仿真,如

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图(2) 所示。

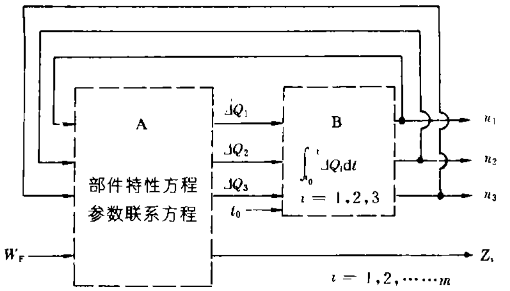

图 2　三轴系统分解图

根据对三轴燃气轮机动态过程的分析研究，由于高低压转子有着紧密的气动联系，动态过程中，高低压转子转速 n_2 和 n_1 的匹配关系与稳态时的匹配关系不会有很大偏离，可以认为在动态过程中仍有 $n_1 = n_1|_{ss} = f(n_2)$，同时动力涡轮转速 n_3 对流量特性影响较小。这样，三轴燃气轮机任一非平衡状态参数为由 W_f 和 n_2 两个参数所定义的准动态运行面所决定，该运行面如图(3) 所示。实际非平衡过程中的参数，可以以上述准动态运行面所决定的参数为基础，加上 n_1 及 n_3 对参数影响的修正，可表达为：

$$\Delta M_1 = \Delta M_1|_{sf} + \frac{\partial \Delta M_1}{\partial n_1}|_{sf}(n_1 - n_1|_{ss}) + \frac{\partial \Delta M_1}{\partial n_3}|_{sf}(n_3 - n_3|_{ss})$$

$$\Delta M_2 = \Delta M_2|_{sf} + \frac{\partial \Delta M_2}{\partial n_1}|_{sf}(n_1 - n_1|_{ss}) + \frac{\partial \Delta M_2}{\partial n_3}|_{sf}(n_3 - n_3|_{ss})$$

$$N_e = Ne|_{sf} + \frac{\partial Ne}{\partial n_1}|_{sf}(n_1 - n_1|_{ss}) + \frac{\partial Ne}{\partial n_3}|_{sf}(n_3 - n_3|_{ss}) \quad (3)$$

……

$$E_i = z_i|_{sf} + \frac{\partial z_i}{\partial n_1}|_{sf}(n_1 - n_1|_{ss}) + \frac{\partial z_i}{2n_3}|_{sf}(n_3 - n_3|_{ss})$$

式中带下标“sf”是准动态运行面上的参数或其偏导数，它们只取决于二个变量 W_f 及 n_2 而与时间无关，可以通过压气机和涡轮的部件特性方程组以及它们间的参数联系方程组求到。带下标“ss”的是稳态参数，它们是 n_2 的函数。式(3) 的右边是双变量函数与单变量函数的线性组合。只需预先设置函数断点表文件，通过断点搜索和线性插值，就能得出函数值，再经过少量计算，就能解出方程式(3)，结合方程式(1) 就可得到三轴燃气轮机的实时仿真模型。

2　三轴燃气轮机并行数字计算机实时仿真

图(4) 为由八台 TRANSPUTER 组成的 MIRAGE 并行数字计算机仿真工作站，每一台数字计算机为 25MHz 时钟及 1M 内存。

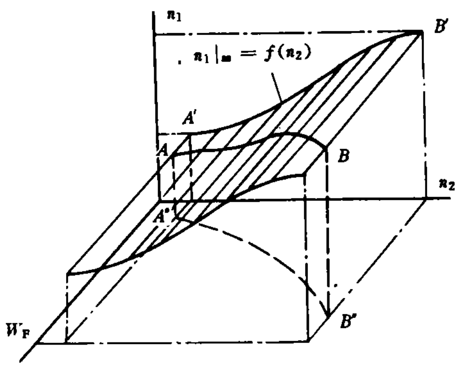

图 3　准动态运行面示意图

根据相应的拓朴结构可以在并行的八台计算机上进行实时仿真。工作站以状态方程为最小粒度进行仿真任务分配。仿真结果可由图形终端实时显示，也可通过 D/A 接口记录在绘图仪上，也可存储在 386/40 主机内存中，供事后分析及后处理用。

根据三轴燃气轮机的仿真模型，可进行并行数字计算机实时仿真。由状态方程组及代数方程组组成。状态方程组共三个，即描述系统动态过程所需的三个微分方程组：

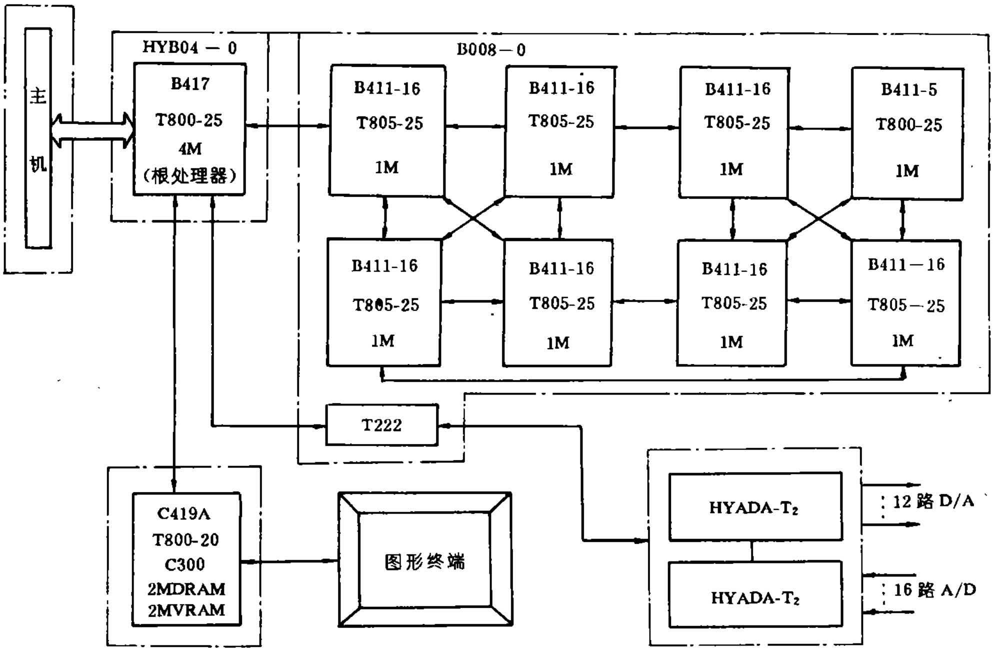

图4　MIRAGE并行计算机仿真工作站

$$\frac{dx(0)}{dt}=x_0(0)+5.1824*a(32)$$

$$\frac{dx(1)}{dt}=x_0(1)+5.3051*a(33)$$

$$\frac{dx(2)}{dt}=x_0(2)+a(40)-0.4060*(4)$$

$$-0.4060*(5)$$

式中 $x(0)$、$x(1)$、$x(2)$ 分别代表转速 n_1、n_2、n_3，$x_0(0)$、$x_0(1)$、$x_0(2)$ 分别代表低压转子、高压转子、动力涡轮转子在仿真开始时的初值，其它为代数方程的解。

代数方程共41个，它们是为了求解方程式(3)而建立的，除了四则运算外，还包括大量单变量函数取值、双变量函数取值等：

$a(0)=n_1|_{ss}=f_0(x(1))$

$a(1)=n_3|_{ss}=f_1(x(1))$

$a(2)=W_f|_{ss}=f_2(x(1))$

$a(3)=W_f=f_3(x(1))$

$a(4)=M_f=f_4(x(2))$

$a(5)=M_L=f_5(x(2))$

$a(6)=\Delta M_1|_{sf}=f_6(x(1),a(3))$

$a(7)=\frac{\partial\Delta M_1}{\partial n_1}|_{sf}=f_7(x(1),a(3))$

$a(8)=\frac{\partial\Delta M_1}{\partial n_3}|_{sf}=f_8(x(1),a(3))$

$a(9)=\Delta M_2|_{sf}=f_9(x(1),a(3))$

$a(10)=\frac{\partial\Delta M_2}{\partial n_1}|_{sf}=f_{10}(x(1),a(3))$

$a(11)=\frac{\partial\Delta M_2}{\partial n_3}|_{sf}=f_{11}(x(1),a(3))$

$a(12)=Ne|_{sf}=f_{12}(x(1),a(3))$

$a(13)=\frac{\partial Ne}{\partial n_1}|_{sf}=f_{13}(x(1),a(3))$

$a(14)=\frac{\partial Ne}{\partial n_3}|_{sf}=f_{14}(x(1),a(3))$

$a(15)=\overline{G}|_{sf}=f_{15}(x(1),a(3))$

$a(16)=\frac{\partial\overline{G}}{\partial n_1}|_{sf}=f_{16}(x(1),a(3))$

$a(17)=\frac{\partial\overline{G}}{\partial n_3}|_{sf}=f_{17}(x(1),a(3))$

$a(18)=P_2|_{sf}=f_{18}(x(1),a(3))$

$a(19)=\frac{\partial P_2}{\partial n_1}|_{sf}=f_{19}(x(1),a(3))$

$a(20)=\frac{\partial P_2}{\partial n_3}|_{sf}=f_{20}(x(1),a(3))$

$a(21)=P_3|_{sf}=f_{21}(x(1),a(3))$

$a(22)=\frac{\partial P_3}{\partial n_3}|_{sf}=f_{22}(x(1),a(3))$

$a(23)=\frac{\partial P_3}{\partial n_3}|_{sf}=f_{23}(x(1),a(3))$

$a(24)=T_2|_{sf}=f_{24}(x(1),a(3))$

$a(25)=\frac{\partial T_2}{\partial n_1}|_{sf}=f_{25}(x(1),a(3))$

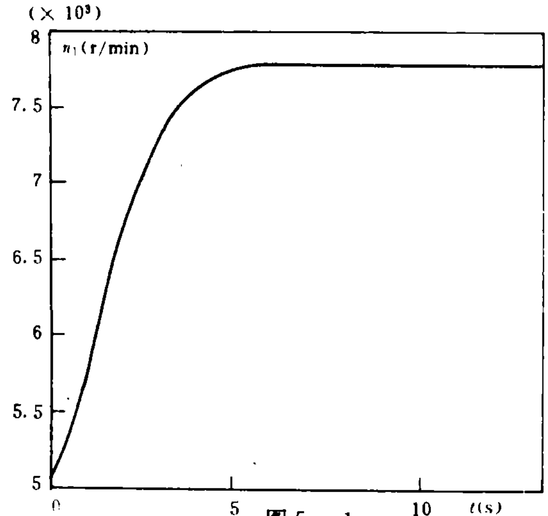

图 5 — 1

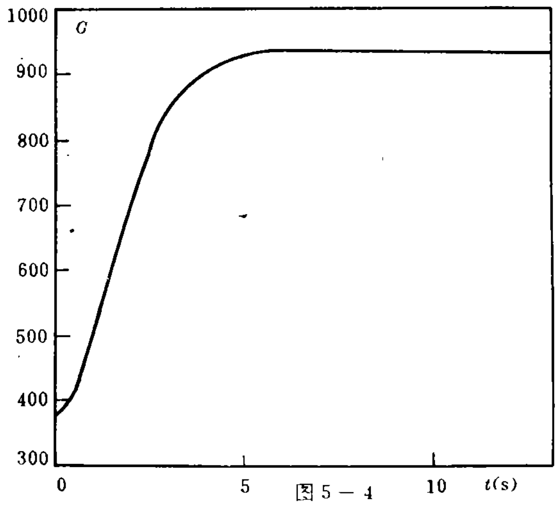

图 5 — 4

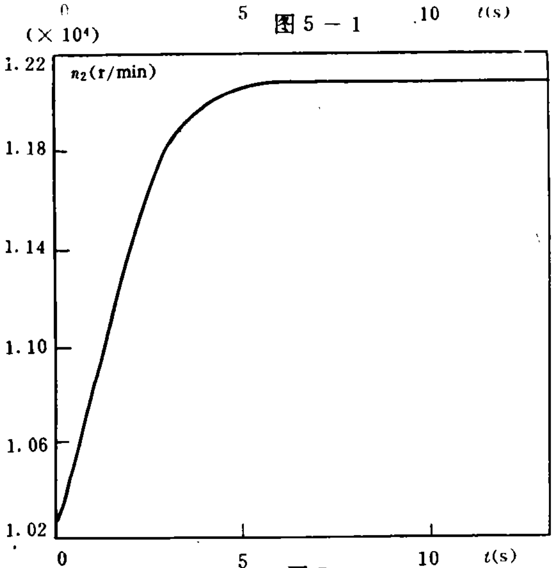

图 5 — 2

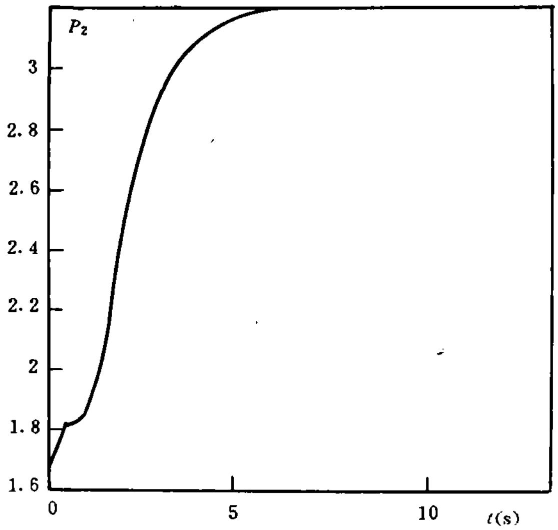

图 5 — 5

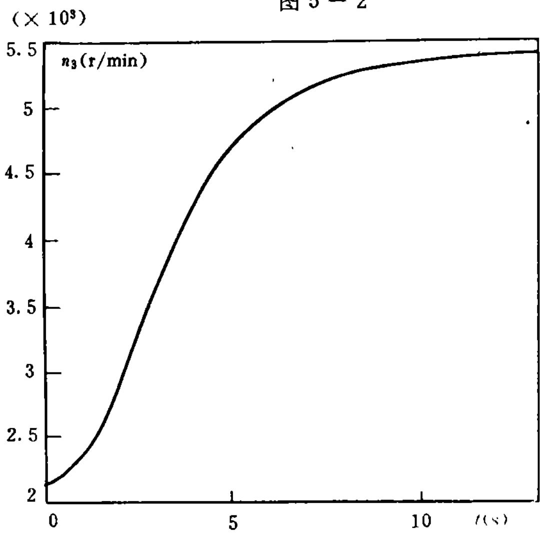

图 5 — 3

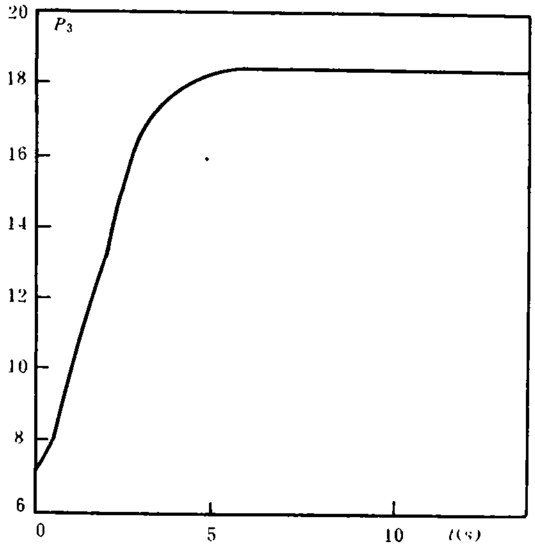

图 5 — 6

图 5　并行数字实时仿真结果记录曲线

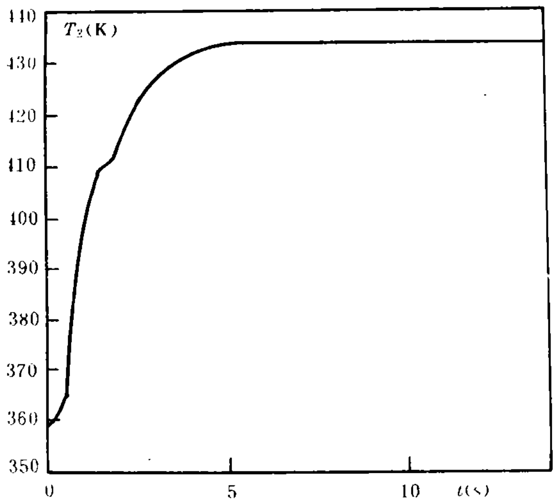

图 5－7

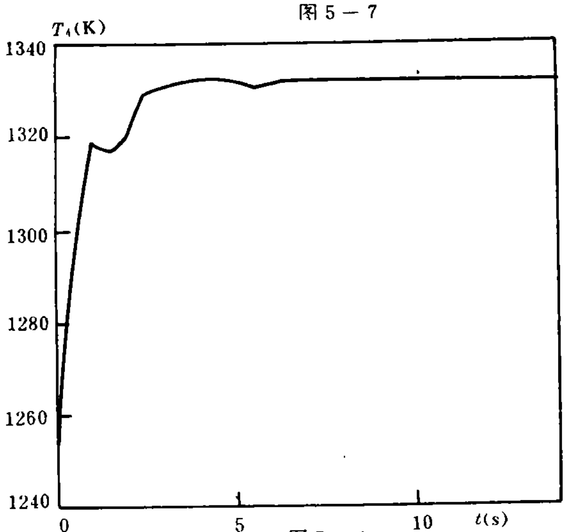

图 5－8

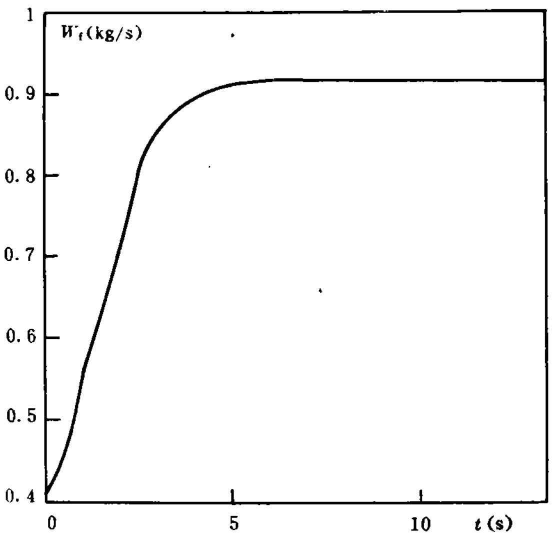

图 5－9

图 5　并行数字实时仿真结果记录曲线

$$a(26) = \frac{\partial T_2}{\partial n_3}\Big|_{sf} = f_{26}(x(1), a(3))$$

$$a(27) = T_4|_{sf} = f_{27}(x(1), a(3))$$

$$a(28) = \frac{\partial T_4}{\partial n_1}\Big|_{sf} = f_{28}(x(1), a(3))$$

$$a(29) = \frac{\partial T_4}{\partial n_3}\Big|_{sf} = f_{29}(x(1), a(3))$$

$$a(30) = x(0) - a(0)$$

$$a(31) = x(2) - a(1)$$

$$a(32) = \Delta M_1 = a(6) + a(7) * a(30) + a(8) * a(31)$$

$$a(33) = \Delta M_2 = a(9) + a(10) * a(30) + a(11) * a(31)$$

$$a(34) = Ne = a(12) + a(13) * a(30) + a(14) * a(31)$$

$$a(35) = \bar{G} = a(15) + a(16) * a(30) + a(17) * a(31)$$

$$a(36) = P_2 = a(18) + a(19) * a(30) + a(20) * a(31)$$

$$a(37) = P_3 = a(21) + a(22) * a(30) + a(23) * a(31)$$

$$a(38) = T_2 = a(24) + a(25) * a(30) + a(26) * a(31)$$

$$a(39) = T_4 = a(27) + a(28) * a(30) + a(29) * a(31)$$

$$a(40) = 0.4060 * a(34)/x(2)$$

从并行数字仿真工作站上可通过 D/A 板和图形终端将九个参数输出，即：低压转子转速 n_1、高压转子转速 n_2、动力涡轮转子转速 n_3、空气流量 $\frac{G\sqrt{T_1}}{P_2}$、低压压气机出口压力 P_2、高压压气机出口压力 P_3、低压压气机出口温度 T_2、高压涡轮进口温度 T_4、供油量 W_f 如图(5)所示。

采用并行数字仿真工作站研究动态性能时，可将一个庞大而复杂的仿真任务分成许多可并行计算的子任务，使其在一个或多个计算机上运算。任务的分配和组合的标准是方程间的相关性大小。将相关性大的几个方程分配成一个子任务，可以减少信息传递所消耗的时间。

仿真步长的取定决定了使用计算机的数目。仿真步长取得较大，则每个步长间隔中，每台计算机能有较多的时间处理更多的方程，所需的计算机数目较少。反之，仿真步长取得小，每个步长间隔中，每台计算机能处理的方程就少，因此就需要较多的计算机参与计算。工作站以状态方程为最小粒度，计算机数目最多不会超过状态方程的数目。

由于并行仿真系统中计算机数目是有限的(本仿真系统为八台)，而且计算机的数目受到状态方程数的限制，因而有一个最小仿真步长，这步长是仿真工作站进行实时仿真的极限值。三轴燃气轮机有三个状态方程，仿真任务最多只能分成三个子任务，因而最多用到三台计算机。每一台计算机进行一个步长的计算所需要的实际时间(包括计算机间信息传递时间)中的最大值就是系统的最小仿真步长，因为比这再短就不能完成一个步长的计算了。三轴燃气轮机的最小仿真步长为 0.0089 秒。当仿真步长选为 0.01 秒、0.02 秒、0.025 秒，要完成三轴燃气轮机实时仿真，分别相应需使用三台、二台和一台计算机。

根据作者对具体三轴燃气轮机对象进行仿真计算结果表明，在下面所列仿真步长范围内，不同仿真步长，对仿真结果影响不大，其动态过程比较如下：

表 1　**动态过程 n_2 值**

仿真步长	0.5 秒	2.0 秒	5.0 秒
0.01 秒	10 499	11 395	12 057
0.02 秒	10 500	11 396	12 058
0.025 秒	10 502	11 398	12 059

当三轴燃气轮机与其它对象组成复杂大系统时，应该根据其它对象的响应快慢选取适当仿真步长。

参 考 文 献

1 翁史烈. 燃气轮机性能分析. 上海交大出版社，1987

2 翁史烈，苏明，张佰年. 船用三轴燃气轮机实时仿真的动态数学模型. 上海交大学报，1988，10

3 Zhang Wenlin, Chen Delai. Implement of parallel tasks partitioning and lecating on transputer-based real-time simulation system. BICSC' 92

4 Chen Delai. Transputer-Based real-time simulation workstation for continuous system. BICSC' 92

船机应用

TriCat 高速渡轮

据 Gas Turbine World 1993 年 11－12 月号报道，怀特岛上的英国 FBM 公司得到一项 4200 万英磅的合同，为远东某主要经营者建造 5 艘"TriCat"旅客渡轮。

轻重量、铝和纤维复合材料的 TriCat 长 45m，船身最大宽度为 12m，以 47 节速度航行时能运载 332 名旅客。航程为 125 海里。

基本的双体船设计在其前端使用了独特的第三个船体，FBM 声称此第三船体将减少在颠簸海洋上航行时海浪的撞击并增加浮力。

每艘渡轮将由二台索拉公司的二轴船用金牛座，也叫 T6502M 燃机驱动。以 1 级或 2 级柴油作燃料，该发动机在 ISO 条件下的额定连续功率为 4847kW，最大额定连续功率为 5250kW。

该燃机的设计特点是二级可变速的动力涡轮，每台燃机驱动 1 个 KaMeWa 喷水推进器，通过齿轮箱把燃机名义的 12900r/min 输出轴速度减小到推进器所要求的输入速度。船用金牛座的外形尺寸为 3.8×1.8×1.8m，重量为 3t。

(学牛　供稿)

structural parameters as porosity, specific surface area, particle size, etc, which has been compared with tyat obtained on the basis lf the test results supplied by Mr. smith. **Key words:** *Pulverized coal combustion, pore strucre and variation, pore model, coal coking reactivity*

(336)**A Study on the Combustion Characteristics of Typical Chinese Anthracite Coals。。** Du Meifang (*harbin Teachers University*)

This paper presents the basic characteristics of Chinese anthracite coal and some study results concerning their ignition and burn-out conditions, Which can serve reference data and materials for relevant design and operational dipartments. **Key words:** *anthracite coal, ignition characterisics, burn-out characteristics*

(341)**An Experimental Study on a Barchan Dune Vortex Pulverized Coal Burner**……Wu Jin, Yang Shuichun, Hu Jangen (*zhejing Electrical Power Engineering Institute*)

This paper deals with the experimental study of the air flow flow field and combustion mechanism of a Barchan Dune (BD)vortex pulverized coal burner. Under the special action of the BD vortex generator there emerged at burner outlet a high-temperature nucleus and high—concentration pulverixed coal region, which promotes the ignition and combustion of the pulverized coal, resulting in a speedy ignition of the pulverized coal and significant enhancement of its combustion stability. Practical applivations have shown that the BD pulverized coal burnerw play a key role in reducing start-up oil consumption during boiler ignition and enhancing the boiler low-load combustion stability, etc. **Key words:** *Pulverized coal combustion, Barchan Dune vortex*

(345)**A Technical Analysis of Crude Oil or Residual Oil-fired Heavy-duty Gas Turbines**……Luo Siding (*Electrical Power Company of Shengli Oil Field Management Bureau*)

The author discusses and makes an analysis of the following issues: the adaptability of heavyduty gas turbines to burn such low-grade fuels as crude oil, residual oil, etc, the damage mechanism of harmful elements in low-grade fuels with respect to gas turbines operating on such fuels, and special measures to be taken for crude oil and residual oil-fired gas turbines. **Key words:** *heavy-duty gas turbine, combustion, low-grade fuel*

(351)**A New Starting Point for Heavy -duty Industrual Gas Turbibes**……Hou Yuhui, Zhou Shunjun (*Harbin Maeine Boiler &. Turbine Research Institute*)

The present paper development tendency of heavy-duty gas turbine technology with a description of the design features and performance of GT24 and GT26 gas durbines. A special mention should be made of the use of continuous cobustion system, which enables the turbines to attain the contrasictory aim of high efficiency and low emissions. High power output ,good efficiency and low emissions specific to the above-cited two types of turbines have made them to be listed among the ideal candidates destined for simple cycle and combined cycle utility gas turbines. **Key words:** *gas turbine. design, power generating set*

(356)**The Real-time simulation of a Three-shaft Gas Turbine by Using a Parallel Digital Computer**……Zhang Bainian, Weng shilie (*Shanghai Jiaotong University*)

In this paper are discussed the real-time simulation model of a three-shaft gas turbine and some technical issued of full digital real-time emulation with the help of a MIRAGE real-time simulation workstation. To ensure the real-time simulation, the step length of the parallel digital computer must be related not only to the complexity of the object but also to the number of the bigital computers selected. The selection of a relatively small step length will necessitate the employment of more computers. **Key words**: *gas turbine, real-time simulation, parallel digital computer*

(362)**STD Microcomputer Monitoring System for Use on Boilers**……Wang Jingyi ,Huang Qian, (*Harbin Marine Boiler & Turbine Research Institute*)

Described in this paper is a STD standard bus computer for industrial control(designated as STD industrial control machine for short)used for monitoring the thermotechmical parameters of a 20t/h or 35t/h power station travelling-grate boiler. the related hardware, software and control principle as well as the system functions and software development process have also been dealt with briefly. **Key words**: *STD, boiker, mictocomputer monitoring*

(366)**A Study on the Solar Energy Heat-Collection Plates Made of Black-colored Stainless Steels**……Liang Haidong, Huang Qinghai, et al (*Harbin Marine Boiler & Turbine Research Institute*)

This paper focuses on the manufacturing tichnology and properties of black-colored stainless steels as will as well as their sprcific features when used as solar energy heat-collection plates. **Key words**: *black-colored stainless steel, solar energy, heat-collection plate*

(369)**Irreversible Carnot Heat Engines in Finite-time Thermodynamics**……Yan Zijun (*Xiamen University*)

Several kinds of irreversible Carnot heat engine models are reviewed and a new irreversible Carnot heat engine model is proposed. In addition, the author emphasizes that during the study of irreversible heat engines within the framework of finite-time thermodynamics the effect of irreversibility on power output must be taken into account. **Key words**: *finite-time thermodynamics, Carnot cycle, irreversibility*

(374)**The Ecological Quality Factor for Thermodynamic Cycles**……Chen Lingen,Sun Fengrui, Chen Wenchen (*Naval Academy of Engineering*)

The putting forward of an ecological objective or target represents a sign of progress in the analysis of thermodynamic cycles. The ecological objective may be set up based on the viewpoins of energy or exergy, but the two viewpoints should not be confused in the analysis. The maximum value of the ecological objective function and its corresponding performance boundary may be taken as a defining relation for the evaluation of ecological objective function of thermodynamic cycles and their quality factor. **Key words**: *finite-time thermodynamics, quality factor, ecolgy, optimization criterion*