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分轴燃气轮机大扰动动态过程计算

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由我国自行设计和生产的燃气-蒸汽联合循环装置已经在东炼试运成功。其燃气轮机是用斯贝核心机改型的分轴燃气轮机。发电机组采用了双转速调节系统来代替功频调节系统，以消除气体燃料热值变化引起的工况变化。为确保甩负荷时大扰动动态过程计算的准确度，采用了以非稳态工况为起始点的数学模型，用变系数分段小偏差线性化的方法计算大扰动的动态过程，从而解决了非线性系统动态过程的计算问题。

一、非稳态工况数学模型

首先把大扰动的动态过程分为很多小段，再用非稳态小偏差线性化的方法，对每段进行计算。数学模型如下：

1. 燃气发生器转子

$$(2\pi\cdot J_H/60)(d\Delta n_H/dt)=\Delta M_H+M_{Ht}* \qquad (1)$$

式中　J_H、n_H、M_H分别为燃气发生器转子的转动惯量、转速和不平衡扭矩，$M_{Ht}*$为t_{io}时非平衡工况的剩余扭矩，即用t^*表示t_{io}时的值。

2. 动力涡轮和发电机转子

$$(2\pi\cdot J_L/60)(d\Delta n_L/dt)=\Delta M_L+M_{Lt^*} \qquad (2)$$

式中　J_L为动力涡轮和发电机转子转动惯量；n_L和M_L为动力涡轮转速和不平衡扭矩，$M_{Lt}*$为t_{io}时非平衡工况剩余扭矩。

3. 燃烧室至高压涡轮间壁面热交换

$$\tau_w d\Delta T_p/dt=(\Delta T_B^*+\Delta T_3^*)/2-\Delta T_p+[(T^*_{Bt^*}+T^*_{3t^*})/2-T_{pt^*}] \qquad (3)$$

式中　τ_w为时间常数；T_B^*为燃烧室出口温度；T_3^*为高压涡轮进口温度；T_p为壁面平均温度。

在方程(1)～(3)中，T_3^*和M_L两项由非平衡工况的变工况计算，其增量方程为：

$$\Delta T_3^*=(\partial T_3^*/\partial n_H)\Delta n_H+(\partial T_3^*/\partial n_L)\Delta n_L+(\partial T_3^*/\partial M_H)\Delta M_H \qquad (4)$$

$$\Delta M_L=(\partial M_L/\partial n_H)\Delta n_H+(\partial M_L/\partial n_L)\Delta n_L+(\partial M_L/\partial M_H)\Delta M_H \qquad (5)$$

由壁面换热的稳态传热方程可得到其增量方程为：

$$\left(\frac{G_g\cdot C_{pg}}{\alpha\cdot A\cdot l}+\frac{1}{2}\right)\Delta T_3^*=\left(\frac{G_g\cdot C_{pg}}{\alpha\cdot A\cdot l}-\frac{1}{2}\right)\Delta T_B^*+\Delta T_p \qquad (6)$$

式中　G_g为燃气流量；C_{pg}为燃气定压比热；α为传热系数；l为管道长度；A为管道圆周长。而T_B^*可用燃烧室热平衡方程计算：

$$T_B^*=(G_f\cdot Q\cdot\eta_B+G_B\cdot I_2^*)/G_g\cdot C_{pg} \qquad (7)$$

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式中 η_B为燃烧室效率；G_f为燃料量；G_B为空气流量；Q为发热量；I_2^*为燃烧室进口空气焓值，而I_2^*，$G_g\cdot C_{pg}$，T_B^*可分别表为：$I_2^*(n_H, n_L, M_H)$，$G_g\cdot C_{pg}(n_H, n_L, M_H)$，$T_B^*(n_H, n_L, M_H, G_f\cdot Q)$。在小偏差范围内，增量方程为：

$$\Delta T_B^* = \frac{\partial T_B^*}{\partial n_H}\cdot\Delta n_H + \frac{\partial T_B^*}{\partial n_L}\cdot\Delta n_L + \frac{\partial T_B^*}{\partial M_H}\cdot\Delta M_H + \frac{\partial T_B^*}{\partial G_f\cdot Q}\cdot\Delta G_f\cdot Q \qquad (8)$$

$$\frac{\partial T_B^*}{\partial n_H} = \frac{\partial I_2^*/\partial n_H}{G_g\cdot C_{pg}} - \frac{(G_f\cdot Q\cdot\eta_B + I_2^*)}{(G_g\cdot C_{pg})^2}\,\frac{\partial(G_g\cdot C_{pg})}{\partial n_H};$$

$$\frac{\partial T_B^*}{\partial n_L} = \frac{1}{G_g\cdot C_{pg}}\,\frac{\partial I_2^*}{\partial n_L} - \frac{(G_f\cdot Q\cdot\eta_B + I_2^*)}{(G_g\cdot C_{pg})^2}\,\frac{\partial(G_g\cdot C_{pg})}{\partial n_L};$$

$$\frac{\partial T_B^*}{\partial M_H} = \frac{1}{G_g\cdot C_{pg}}\,\frac{\partial I_2^*}{\partial M_H} - \frac{(G_f\cdot Q\cdot\eta_B + I_2^*)}{(G_g\cdot C_{pg})^2}\,\frac{\partial(G_g\cdot C_{pg})}{\partial M_H};$$

$$\frac{\partial T_B^*}{\partial G_f\cdot Q} = \frac{1}{G_g\cdot C_{pg}}\cdot\eta_B$$

将(4)，(5)，(6)和(8)式写成矩阵形式：

$$\begin{bmatrix} 1 & -\frac{\partial T_3^*}{\partial M_H} & 0 & 0 \\ K_1 & 0 & 0 & -K_2 \\ 0 & -\frac{\partial M_L}{\partial M_H} & 1 & 0 \\ 0 & -\frac{\partial T_B^*}{\partial M_H} & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta T_3^* \\ \Delta M_H \\ \Delta M_L \\ \Delta T_B^* \end{bmatrix} = \begin{bmatrix} \frac{\partial T_3^*}{\partial n_H} & \frac{\partial T_3^*}{\partial n_L} & 0 \\ 0 & 0 & 1 \\ \frac{\partial M_L}{\partial n_H} & \frac{\partial M_L}{\partial n_L} & 0 \\ \frac{\partial T_B^*}{\partial n_H} & \frac{\partial T_B^*}{\partial n_L} & 0 \end{bmatrix} \begin{bmatrix} \Delta n_H \\ \Delta n_L \\ \Delta T_P \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{\partial T_B^*}{\partial G_f\cdot Q} \end{bmatrix} [\Delta G_f\cdot Q] \qquad (9)$$

式中：$k_1 = (G_g\cdot C_{pg}/\alpha\cdot A\cdot l + 1/2)$；$k_2 = (G_g\cdot C_{pg}/\alpha\cdot A\cdot l - 1/2)$

由(9)式可求出方程(1)～(3)中的4个中间变量ΔT_3^*，ΔM_H，ΔM_L和ΔT_B^*。方程(1)～(3)用状态空间法可写为以相对增量形式表达的标准形式：

$$X_{nH} = -(X_{nH} + K_{nH\cdot nL}\cdot X_{nL} + K_{nH\cdot TP}\cdot X_{TP} + K_{nH\cdot Gf}\cdot X_{Gf\cdot Q} + Y_{nH})/\tau_{nH} \qquad (10)$$

$$X_{nL} = (K_{nL\cdot nH}\cdot X_{nH} - \beta_{nL}\cdot X_{nL} + K_{nL\cdot TP}\cdot X_{TP} + K_{nL\cdot Gf}\cdot X_{Gf\cdot Q} + Y_{nL})/\tau_{nL} \qquad (11)$$

$$X_{np} = (K_{nTP\cdot H}\cdot X_{nH} + K_{TP\cdot nL}\cdot X_{nL} - \alpha_{TP}\cdot X_{TP} + K_{TPGf}\cdot X_{Gf\cdot Q} + Y_{TP})/\tau_w \qquad (12)$$

二、双转速控制系统的数学模型

双转速控制系统示于图1。

图中u^*_m为转速给定值；δ为不等率；τ_s为油动机时间常数；τ为无差弹性反馈时间常数；Xz为油动机的相对位移；Xz_1为无差弹性反馈的相对位移；X_{yt}.为非零起始值；X_{zt}.为X_z的非零起始值。

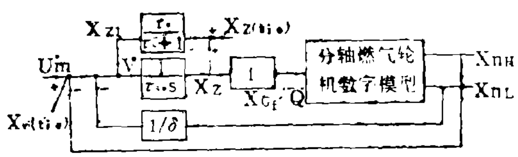

图1 分轴燃气轮机发电机组的双转速调节系统

以双转速调节系统来消除热质变化所引起的功率波动，没有功频调节系统反调的弊

病。对分轴燃气轮机而言，当大气温度Ta和大气压力Pa以及动力透平转速n_L不变时，输出功率和燃气发生器转速n_H之间有一一对应的关系。因此，当分轴燃气轮机发电机组并网运行时，动力涡轮转速n_L不变，则可以用n_H信号取代功率信号，组成 n_H-n_L双转速调节系统。它实质上是一种状态反馈调节系统。

由图 1 不难列出双转速调节系统的状态方程：

$$\dot{X}z = -X_{nH}/\tau_s - X_{nL}/\tau_s\delta - X_{z1}/\tau_s + u_m^*/\tau_s + Xy_{t}\cdot/\tau_s \quad (13)$$

$$\dot{X}z_1 = X_{nH}/\tau_s - X_{nL}/\tau_s\delta - (1/\tau_s + 1/T)X_{z1} + u_m^*/\tau_s + Xy_{t}\cdot/\tau_s - X_{z}/\tau_s \quad (14)$$

三、状态空间数学模型

由方程(10)～(14)可列出带双转速调节系统的分轴燃气轮机的状态空间数学模型。

设：

$$X = \mathbf{A}\cdot\mathbf{X} + \mathbf{B}\cdot\mathbf{u} \quad (15)$$

$$Y = \mathbf{C}\cdot\mathbf{X} \quad (16)$$

四、非平衡工况变工况和大扰动动态过程的计算

为求取(15)和(16)式中系数阵A，B，u中的各项系数值，需对分轴燃气轮机进行非平衡工况的变工况计算，并将计算结果以所需数组的形式建立数据文件包，以备大扰动动态计算时使用。图 2 给出了当动力涡轮转速n_L在额定转速8000rpm时的一组计算结果。

变系数法分段线性化是将大拢动的动态过程分为i段考虑，而每小段即处小偏差范围，以便沿用常系数法计算。甩满负荷时的一组计算结果示于图 3 。

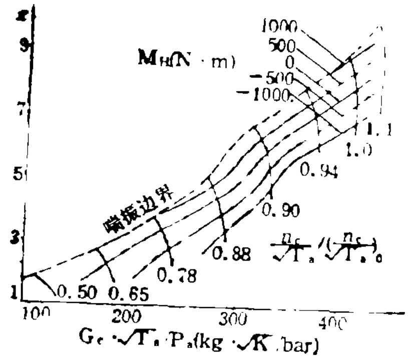

图2　当n_L = 8000rpm时的一组变工况计算结果

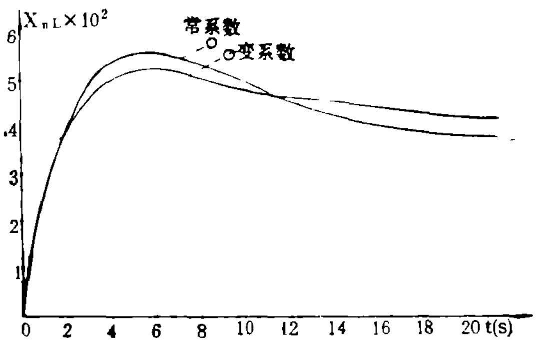

图3　甩满负荷时的动态过程曲线

(n_{Lo} = 8000rpm，τ = 5s，τs = 0.1s，δ = 0.04)

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COMPUTATION OF DYNAMIC PROCESS WITH LARGE DISTURBANCE FOR SPLIT-SHAFT GAS TURBINE

Lu Zehua and Ye Bosheng (*Tsinghua University*)

Taking Spey core engine used in a gas-stream combined cycle as an example, this paper deals with computation of dynamic process with large disturbance for split-shaft gas turbine with a variable-coefficient divisional small-disturbance for linearization method.

OPTIMIZING DESIGN FOR TURBOENGINE DIGITAL SPEED CONTROLLER

Yang Shengfa (*Northwestern Polytechnical University*)

A method for optimizing characteristics of digital speed controller of a turbo-engine is presented. A dynamic model of this system has been developed. According the chosen quadratic property criterion, six characteristic quantities of the digital controller are optimized by system simulation in a digital computer. As JT15D-4 turbofan is taken for example, its digital speed controller system optimized by the present method is obviously better than the original hydromechanical system.

STUDY ON EXCHANGE OPERATION BETWEEN TWO MICROCOMPUTERS IN AEROENGINE DIGITAL CONTROL

Xu Qihua and Wu Qihua (*Northwestern Polytechnical University*)

Communication and trouble-selfdetection of microcomputers in dual-computer system of aeroengine digital control are considered, and exchange operation between two microcomputers is discussed emphatically. The simulation tests of the exchange operation in dual-computer engine speed control system have been performed. The results of the tests are satisfactory.