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WZ5G发动机驱动的增压站的数学模型和动态分析

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拟议在中原油田300多公里的长距离输气管线只建一个燃气轮机压缩机增压站。如图1所示，增压站由两台航机陆用型机组WZ5G，分别带动串联的两台低、高压离心式压缩机。选用输气管线的首端压力Pg_2作为被控参数。要控制Pg_2，首先要确定在同样首端压力下，两台燃气轮机的负荷如何分配才能使总的燃料消耗量为最小，这是一个静状最优化的问题。对于分轮燃气轮机而言，负荷大小取决于燃气发生器转速n_{11}和n_{21}的高低，为此在两台机组的燃气发生器转速给定信号x^*_{n11}和x^*_{n21}前加了函数发生器。静态优化计算是以在输送同样体积的天然气时，两台机组的总燃料消耗量ΣG_f最小为优化指标的。计算表明两台燃气发生器转速相同和不同对总的燃料消耗量的影响甚微。控制系统数学模型可简化为图2的形式。

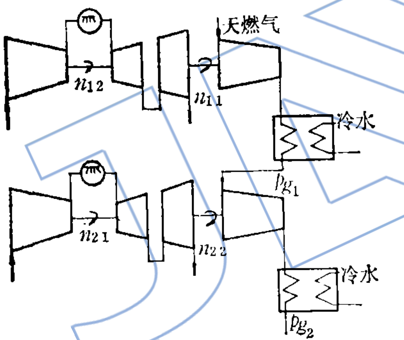

图1 燃气轮机——离心压缩机增压站

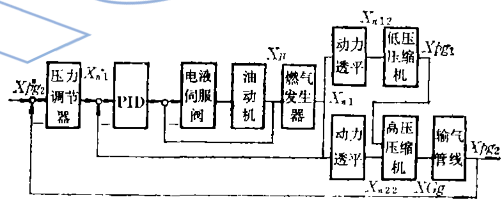

图2 简化的主控系统图

一、数学模型

1. 转速调节系统数学模型

转速变换器：$K_0/(T_0 \cdot S+1)$　(1)　$K_0=1$　$T_0=0.1s$

电液伺服阀：$K_2/(T_2 \cdot S+1)$　(2)　$K_2=1$　$T_2=0.08s$

油动机：$K_3/(T_3 \cdot S+1)$　(3)　$K_3=1$　$T_3=0.21s$

PID 调节器：$0.45(S+1)/S$　(4)

2. 燃气发生器数学模型：令Xn_1为相对转速，X_B为相对燃料量。

$$(Tn_L \cdot S+1)Xn_L = K_B \cdot X_B \quad (5)$$

3. 动力透平数学模型：令Xn_L为相对转速．X_L为相对负荷，

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$$(Tn_2 \cdot S + \rho'n_2)Xn_2 = Kn_2 \cdot n_1 \cdot Xn_1 + Kn_2 \cdot {}_B X_B - X_L \qquad (6)$$

4. 压缩机数学模型

（1）低压压缩机：令Xpg_1为出口相对压力，X_{NL_1}为相对功率，

$$X_{Pg1} = K_{Pg1} \cdot n_{12} \cdot Xn_{12} - K_{Pg1} \cdot G_{g1} X_{Gg1} \qquad (7)$$

$$X_{NL1} = K_{NL1} \cdot n_{12} \cdot Xn_{L2} - K_{NL1} \cdot G_{g1} X_{Gg1} \qquad (8)$$

（2）高压压缩机：令X_{Gg2}为相对流量，$X_{P'g1}$为进口相对压力，X_{Pg2}为出口相对压力，

$$X_{Gg2} = K_{Gg2} \cdot n_{22} Xn_{22} + K_{Gg2} \cdot P'_{g1} X_{P'g1} - K_{Gg2} \cdot P_{g2} X_{Pg2} \qquad (9)$$

$$X_{NL2} = K_{NL2} \cdot n_{22} Xn_{22} + K_{NL2} \cdot P'_{g1} X_{P'g1} + K_{NL2} \cdot G_{g2} X_{Gg2} \qquad (10)$$

5. 动力透平带动低压压缩机的数学模型：由公式（6），（7）和（9）可得下式：

$$(Tn_2 \cdot S + \rho'_{n2})Xn_{12} = Kn_{12} \cdot n_1 Xn_1 + Kn_{12} \cdot {}_B X_B + Kn_{12} \cdot n_{12} Xn_{12} + Kn_{12} \cdot n_{22} Xn_{22} + Kn_{12} \cdot P_{g2} X_{Pg2} \qquad (11)$$

6. 动力透平带动高压压缩机数学模型：由公式（6）、（7）、（8）、（9）、（10）可得下式：

$$(Tn_2 S + \rho'_{n2})Xn_{22} = Kn_{22} \cdot n_1 Xn_1 + Kn_{22} \cdot {}_B X_B + Kn_{22} \cdot n_{12} \cdot Xn_{12} + Kn_{22} \cdot n_{22} Xn_{22} + Kn_{22} \cdot P_{g2} \cdot X_{Pg2} \qquad (12)$$

7. 输气管线数学模型：令V_0为管道容积，E_1为首尾压比，其传递函数表示为下式[1]：

$$\frac{X_{Pg2}}{X_{Gg2}} = \frac{K \cdot G_{g0}}{V_0 \cdot \rho_s} \cdot \frac{1}{S} \frac{3KG_{g0}}{V_0 \cdot \rho_s} \cdot E_1 \cdot \left(\frac{1.36 T_1}{\frac{T_1}{2} S + 1} + \frac{0.13 T_1}{\frac{T_1}{22} S + 1} + \frac{0.1535 T_1}{\frac{T_1}{160} S + 1} \right) \qquad (13)$$

二、系统开环传递函数$W_{k(s)}$的计算

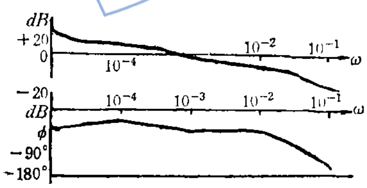

图 3　系统开环频率特性$W_{k(j\omega)}$图

在上述诸式中，把燃气发生器转速给定信号X^*_{n1}看作输入信号u，把输气管线首端压力X_{Pg2}看作输出信号y，可写成状态空间表达式的形式。

$$\begin{cases} \dot{X} = Ax + Bu \\ y = C \cdot x \end{cases} \qquad (14)$$

经非奇异变换可以得到传递函数为：

$$\frac{Y_{(s)}}{U_{(s)}} = W_{k(s)} = \frac{(\beta_{n-1} S^{n-1} + \cdots\cdots \beta_1 S + \beta_0)}{(S^n + \alpha_{n-1} S^{n-1} + \cdots\cdots + \alpha_1 S + \alpha_0)}$$

$$W_{k(s)} = \frac{0.85 \times 10^{-7} S^8 + 0.56 \times 10^{-2} S^7 + 0.08 S^6 + 0.293 S^5 + 0.244 S^4 + 0.028 S^3 + 0.17 \times 10^{-3} S^2 + 0.17 \times 10^{-6} S + 0.46 \times 10^{-11}}{S^{11} + 24.6 S^{10} + 233 S^9 + 1009 S^8 + 1524 S^7 + 690 S^6 + 109 S^5 + 6.26 S^4 + 0.099 S^3 + 0.272 \times 10^{-3} S^2 + 0.61 \times 10^{-7} S + 0.272 \times 10^{-12}}$$

$W_{k(s)}$的频率特性计算结果示于图 3。

三、系统的稳定性分析和动态校正

1. 稳定性分析和动态校正　为使燃气发生器工况稳定及系统能在大范围内稳定工作，压力调节器只采用比例调节。当比例调节放大倍数K选不同值时，结合图 3 讨论如下：

$K=1$，0 db时，相角裕量φ为130°，特征频率ω为3.5×10^{-4}。φ过大，动态过程将会十分缓慢。

$K=10$，φ为70°，ω为0.03。当输入单位阶跃信号时，稳态余差e_{ss}可由终值定理计算：

$$e_{ss}=\lim_{s\to0}\frac{S\cdot R_{(s)}}{1+W_{K(s)}}=\left(1+\frac{0.46\times10^{-10}}{0.272\times10^{-12}}\right)-1=0.0059$$

误差约0.6%。动态过程自然振动频率近似为5.3×10^{-2}。与$K=1$相比，速度快了近百倍。

$K=20$，φ为45°，ω为0.09。单位阶跃输入时的稳态余差e_{ss}为：

$$e_{ss}=\left(1+\frac{0.46\times10^{-10}\times2}{0.272\times10^{-12}}\right)-1=0.00295$$

φ适中，稳定余差千分之三，动态过程与$K=10$情况相比，加快不明显。

上述分析可知。不同K值对整个调节系统的灵敏度以及动态过程快慢的影响甚剧。本系统当$K=10$至$K=20$之间时，系统的动态和静态指标皆优，得到了和谐的统一。

2. 系统仿眞计算和动态过程分析　仿真计算参阅文献〔2〕。$K=10$和$K=20$时仿真计算结果示于图 4 。当$K=10$时，无超调，100秒时的输出值达输入值的82%。$K=20$时，超调量为 16%，100 秒时输出值为输入值的93%，100秒以后动态过程近似为时间常数很大的惯性环节。当放大倍数K选择合适值如$K=20$时，在100秒时间内，动态过程的输出值已达输入值的90%以上，对长距离输气管线管首压力如此快速调节是十分令人满意的。

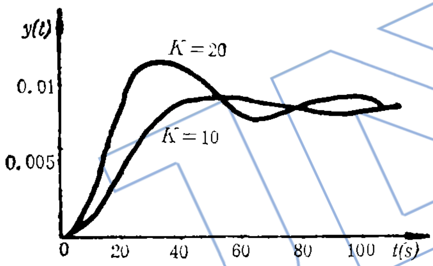

图 4　管首压力的动态过程曲线

长距离输气管线数学模型(13)式，可看作一个积分环节和三个惯性环节并联，可看出：

时间常数小的惯性环节：$(0.1535T_1)/[(T_1/160)S+1]$决定动态过程的起始阶段。

时间常数较大的惯性环节：$1.3611T_1/[(T_1/2)S+1]$和$0.1303T_1/[(T_1/22)S+1]$决定动态过程中间阶段。

系数非常小的积分环节：$KGg_0/V_0\cdot\rho_sS$ 式中因V_0一项很大使积分环节系数非常小，此项决定了动态过程的结尾阶段。

长距离输气管线以管首压力为被控参数时，动态过程的稳定性和超调大小起主导作用的是时间常数最小的环节。当选择合适的压力调节器放大倍数时，长距离输气管线这种近似于无穷大容积的系统的管首压力的动态过程是非常快的；但放大倍数K的可选择范围十分窄。

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〔2〕 熊光楞，“控制系统数字仿真”，清华大学出版社，北京，1982。

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values as input data for the Jacocks' method. The comparison of the distortion prediction results with the experimental data demonstrates better agreement.

APPLIED PROGRAM OF IDENTIFYING TRANSFER FUNCTION

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Abstract

The algorithm and the computer program TFIP used to identify the transfer function models from experimental freguency response data are presented. It is also considered how the selection of the model orders, the selections of the equation error and real error tolerance, and the modes for updating weight coefficients affect the convergent speed and identification results. The new term rejection criterion and the method for updating weight coefficients by variable mode are proposed, the former can simplify the program, and the latter may greatly accelerate the convergence of the weight coefficients.

A SCHEME OF CONDITION MONITORING AND MAIN FAULTS DIAGNOSING SYSTEM FOR A TURBOJET ENGINE

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Abstract

In order to enhance the ability of diagnosing faults and improve maintenance,we develop a condition monitoring and main faults diagnosing system for a turbojet engine. The whole system is divided into two sub-systems: the engine operation monitoring and the ground computer data processing. The former is used for analysing engine performance tendency and diagnosing some main faults in the engine, i.e., engine-surge, exceeding drop rpm, auto-flameout and so on. Inaddition, it can record the parameters at take-off or before and after fault occurs. When faults take place in the engine, it can also give pilots warning. The latter is used for analysing reasons of faults and estimating engine performance tendency.

MATHEMATICAL MODELLING AND DYNAMIC ANALYSIS OF A BOOSTER STATION DRIVEN BY WZ5G AEROENGINES

Lu Zehua, Ye Bosheng, Yang Yiming *(Tsinghua University)*

Xu Chaoqun *(Wuxi Aeroengine Research Institute)*

Abstract

A split-shaft gas turbine adapted from WZ5G aeroengine is quite suitable for driving a booster compressor station in a long gas pipeline. A mathematical model is established for a booster station with two series centrifugal compressors driven separately by the split-shaft gas tnrbine of WZ5G aeroegine. The model is simplified by a static state optimization. Its transfer functions are obtained through a nonsingular transformation. The model is applied to analysing the stability and dynamic responses of the system. Some conclusions are drawn which are helpful to controlling of the long gas pipeline.

A DIGITAL ELECTRONIC CONTROL SYSTEM RST-6 FOR WZ6G ENGINE

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Abstract

A digital electronic control system RST-6 for WZ6G engine, in which a CMC-80 microcomputer and a step-motor driven by a needle metering valve are used. In order to enhance the accuracy of control and the speed of system response, variable coefficient dual-speed control with PID feedback is adopted. A large number of integrated elements and anti-interference measures are employed to increase the reliability of the system.

The present system has run on trial 4200 hours in the Zhongyuan oil field.

A FULL-AUTHORITY DIGITAL ELECTRONIC CONTROL UNIT QSK-06 FOR AEROENGINE WJ6G2B

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Abstract

A full-authority digital electronic control unit QSK-06 has bees designed for industrial application of turboshaft aeroengine WJ6G2B. By adopting the dual channel structure and some effective measures in both hardware and software, high reliability is achieved. A gain-variable PI control is considered to offset the influence of system performance caused by engine conditions. The design ensures meeting the special requirements for long-time operation of industrial gas turbine. The QSK-06 has undergone a verification test on the WJ6G2B rig with a compressor as a load. This paper covers the design of QSK-06, the approaches to enhance the operating reliability and the engine test results.