

多约束自适应控制在 在航空发动机自动试车中的应用

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【摘要】 对采用模型参考自适应控制方法设计带有多项约束条件的航空发动机试车自动试车控制系统进行了研究。仿真结果表明: 这种控制方法不仅对被控对象含有的非线性环节, 以及被控对象参数在较大范围内的变化具有较好的适应能力。而且当约束条件超限时, 通过对控制器参数的调整, 可使主控参数和约束条件参数均满足相应的控制指标。

主题词: 自适应控制 约束条件 航空发动机 试车台

分类号: TP273.2

1 自动试车控制系统设计

1.1 控制对象模型

试车控制器是以波波夫超稳定性理论为基础设计的模型参考自适应控制器。控制对象由试车台油门操纵装置加上航空发机构成。主控参数为推力, 其基本模型(归一化模型)如图 1 所示。此模型中的限幅及滞环非线性是由于试车台油门操纵装置的实际油门转角最大最小允许值及装置与发动机油门手柄连接机构而造成的。其线性部分的参数变化范围为: $0.5\xi_0 < \xi < 1.3\xi_0$; $0.7\omega_0 < \omega < \omega_0$ 。

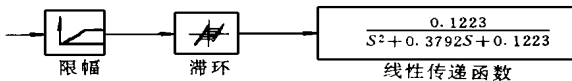


图 1 被控对象(上限= 1, 下限= 0, 宽度= 0.1%)

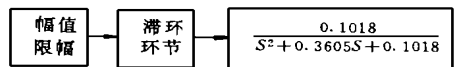


图 2 高压压气机转速约束参数模型

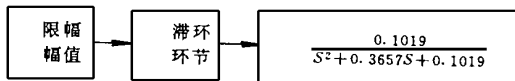


图 3 低压压气机转速约束参数模型

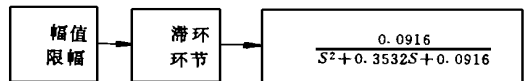


图 4 涡轮后温度约束参数模型

高、低压压气机转速约束参数模型分别为图 2 和 3 所示, 涡轮后温度约束参数模型如图 4 所示。主控参数的控制指标是: 阶跃响应调节时间 ≤ 20 秒, 超调量 $\leq 5\%$ 。系统的稳态误差 $\leq 2\%$ 。主控参数的参考模型数学表达式确定为:

$$G_m(S) = \omega_h^2 / (S^2 + 2\xi\omega_h S + \omega_h^2) = 2.371369 / (S^2 + 2.649164S + 2.371369)$$

此模型所具有的时域动态指标为: 阶跃响应的超调量 $\sigma = 5\%$; 峰值时间 $t_p = 4$ 秒。

1.2 自适应模型跟随控制算法推导和参数数值确定

设航空发动机推力的传递函数线性部分为:

$$Y_p = b_0 \mu / (S^2 + a_1 S + a_0) = \hat{M}(S) / \hat{N}(S) \quad (1)$$

$$\text{参考模型的传递函数为: } Y_m = b_0 p / (S^2 + a_1 S + a_0) = M(S) / N(S) \quad (2)$$

广义输出误差: $\epsilon = Y_m - Y_p$

设计的目标是: 确定对象的控制输入 μ , 使得对于任何的输入 p 以及在 $\epsilon(0) = 0$ 的条件下, 都有 $\epsilon(t)$ 趋于零。设计方案中的限制是: 不能使用 Y_p 和 p 的导数。但能够使用由状态变量过滤器得到的 Y_{pf} 和 p 的过滤导数 Y_{pf} 与 p_f 。于是, 系统的等价结构如图 5 所示。图中: $B(S)$ 、 $\hat{B}(S)$ 、 $C(S)$ 、 $D^+(S)$

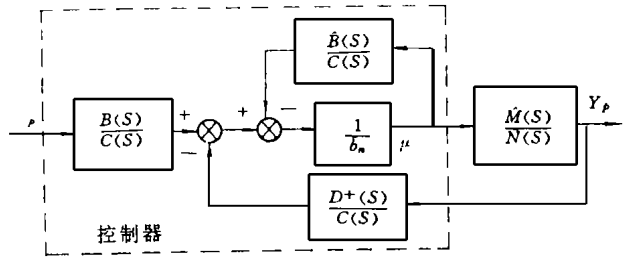


图 5 系统的等价结构

(S) 均为 S 的多项式。要使系统能达到模型跟随的目的, 必须有:

$$Y_p(S) / p(S) = B(S)M(S) / [C^*(S)N(S) + D^+(S)M(S)] = M(S) / N(S)$$

求解上式可得:

$$\mu = [-\hat{B}(S)\mu_f + B(S)p_f - D^+(S)Y_{pf}] / \hat{b}_m = K_1 S \mu_f + K_2 p_f + (K_3 S + K_4) Y_{pf}$$

其中: $K_1 = \hat{b}_0 / C_0 \hat{b}_m$, $K_2 = \hat{b}_0 / \hat{b}_m$, $K_3 = -\hat{d}_1^* / \hat{b}_m$, $K_4 = -\hat{d}_0^* / \hat{b}_m$

$$C_0 = 20, \quad \hat{b}_m = \hat{b}_0 / C_0, \quad \hat{d}_1^* = \Delta a_1 = a_1 - \hat{a}_1, \quad \hat{d}_0^* = \Delta a_0 = a_0 - \hat{a}_0$$

$$\mu_f = \mu / (S + C_0), \quad Y_f = Y_{pf} / (S + C_0), \quad p_f = p / (S + C_0)$$

由上式即确定了自适应控制器的结构。由于被控对象模型参数的不确定性, 可知 $K_1 \sim K_4$ 是可调变量(自适应变量), 则由被控对象基本模型参数算出的 $K_1 \sim K_4$ 的数值即是各可调变量的初值(令其分别为 K_{10} 、 K_{20} 、 K_{30} 和 K_{40})。

利用波波夫超稳定性理论, 当可调参数 $K_1 \sim K_4$ 的自适应调节规律为:

$$\begin{cases} \dot{K}_1 = \alpha_1 V \mu_f \hat{b}_m p & (\alpha_1 > 0), & \dot{K}_2 = \alpha_2 V p_f & (\alpha_2 > 0) \\ \dot{K}_3 = \alpha_3 V Y_{pf} p & (\alpha_3 > 0), & \dot{K}_4 = \alpha_4 V Y_{pf} & (\alpha_4 > 0) \end{cases} \quad (3)$$

可使上述控制系统满足超稳定要求。

根据前述推导可算出控制器参数数值如下: $\alpha_1 = 0.98$, $\alpha_2 = 0.69$, $\alpha_3 = 96$, $\alpha_4 = 2.68$

$$K_{10} = 1, \quad K_{20} = 387.7954, \quad K_{30} = -371.2124, \quad K_{40} = -367.7954$$

2 数字仿真和结果分析

2.1 带有非线性环节的自动试车模型参考自适应控制系统的数字仿真和结果分析

仿真结构示意图如图 6 所示(不含虚线框部分)。表 1 为慢车至各种不同状态的阶跃响应结果。可以看出: 控制系统能够满足设计要求。

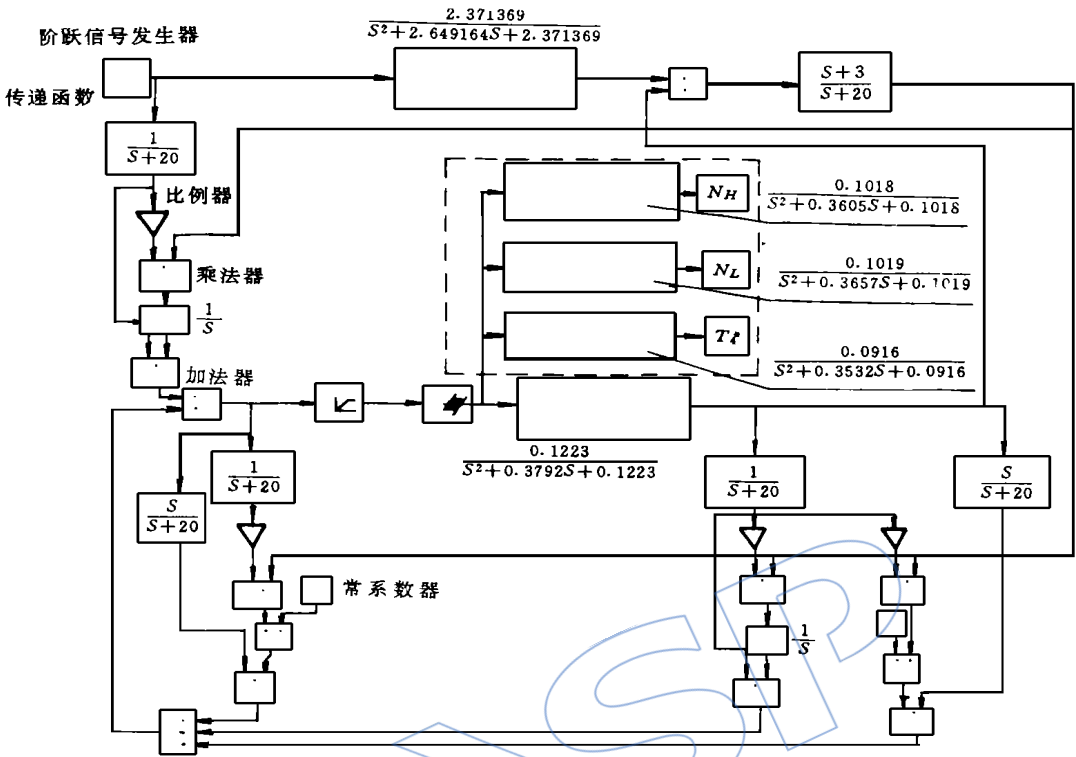


图 6 仿真结构示意图

表 1 阶跃响应结果

	最大连续状态	0.85 最大连续	0.6 最大连续	0.4 最大连续
调节时间(秒)	7.3	6.2	4.9	4.9
超调量(%)	0.27	0.33	0.46	3.04
稳态误差($\times e^{-4}$)	7.43	15	- 9.11	- 5.86

当主控参数推力线性部分模型参数在 $0.4\xi_n \leq \xi \leq 2\xi_n$, $0.5\omega \leq \omega \leq 8\omega$ 范围内变化时控制系统的输出响应仍可满足系统的控制指标。这表明控制器的适应性较好。

2.2 自适应控制器参数对约束条件的影响

约束参数的超限原因一般有: (1) 环境条件变化; (2) 试车控制器参数不匹配; (3) 发动机性能不满足设计指标。本文的研究适用于解决前两项超限原因。

含有约束条件的系统仿真结构如图 6 所示(包括虚线框部分)。当系统出现异常情况而超温或超转时, 也就是约束条件超限时, 可将其分为: (1) 约束条件参数在过渡过程中的“超调”型超限情况; (2) 约束条件参数的稳态值超过门限值的情况。

设高压压气机转速约束条件的门限值为 1.08(百分比转速, 下同), 为模拟高压压气机转速的“超调”型超限, 将其基本模型的线性部分参数改为: $G(s) = 0.1018/(s^2 + 0.25s + 0.1018)$ 。对控制律及控制器参数整定的研究表明, 可以通过调整 K_{30} 来改变系统主控参数及

约束条件参数的超调量。控制器其余各参数数值保持为原设计值仅改变 K_{30} 的仿真结果示于表 2 的左半部分。可以看出, 随着 K_{30} 的减小, 主控参数的超调量和高压压气机转速的最大值也随之减小。当 K_{30} 由 - 371.2 变至 - 1071 时, 高压压气机转速的最大值降至 1.0696, 小于约束门限值 1.08, 而此时, 主控参数的调节时间和稳态误差仍可满足系统的控制指标要求。

表 2 仿真结果

K_{30} 和 K_{40}	- 371.2	- 471.2	- 671.2	- 1071	- 367.8	- 377.8	- 387.8	- 400.8
推力调节时间(秒)	7.3	7.7	9.5	11.7	7.3	7.8	7.8	7.8
推力超调量(%)	0.11	0.05	0.0	0.0	0.11	0.0	0.0	0.0
稳态误差($\times e^{-4}$)	- 2.115	- 2.632	- 2.677	- 1.096	- 2.115	- 180	- 489	- 783
N_H 最大值(%)	1.1286	1.1238	1.1005	1.0696	1.0984	1.0719	1.0459	1.0138
N_H 稳态误差($\times e^{-4}$)	73	69	57	45	817	519	262	- 55

同样设高压压气机转速约束条件的门限值为 1.08, 再将高压压气机转速约束条件参数改为: $G(s) = 0.11/(s^2 + 0.3605s + 0.1018)$ 。除 K_{40} 以外对其余控制器参数保持不变的仿真结果如表 2 右半部分所示。可以看出, 随着 K_{40} 的减小, 系统主控参数的稳态误差向负误差方向增大, 高压压气机转速的稳态误差则逐渐减小。当 $K_{40} = - 377.8$ 时, 高压压气机转速的稳态值等于 1.0719。小于门限值 1.08, 而此时系统主控参数仍可满足控制指标的要求。

因此, 通过以上分析可以得出以下结论: 当系统约束条件参数出现超限情况时, 如没有稳态误差, 则减小 K_{30} 的数值。可使系统在主控参数满足控制指标的情况下, 使约束条件得到满足。当出现稳态误差时, 应首先减小 K_{40} 数值, 此时系统主控参数的稳态误差随之增大, 而约束条件参数的稳态误差会减小。此时, 检查约束条件参数是否满足门限要求。如满足门限要求, 则检查系统主控参数是否满足控制指标。否则继续减小 K_{40} 数值, 当系统主控参数的稳态误差接近于 - 2% 时(系统推力参数的允差下限), 若系统约束条件仍未满足要求, 此时, 可改为减小 K_{30} 的数值。如仍达不到控制指标, 则发动机只有停车, 分解检查。

仿真结果表明约束条件低压压气机转速、涡轮后温度的超限情况也有同样结论, 且发动机同时出现超温与超转时, 其分析情况也与高压压气机转速超转情况相同。只是在考虑两个以上约束条件均出现超限情况时, 以其中超限严重的作为系统参数调整的依据即可。

结论 利用模型参考自适应控制方法设计的航空发动机试车台推力控制系统具有良好的跟踪能力, 其结构简单且容易实现, 仿真结果证明: 该控制系统对非线性被控对象以及被控对象模型参数的较大范围的变化都具有较好的适应能力。当系统出现超转、超温等异常情况, 即约束条件参数在一定范围内超限时, 可通过修改控制器参数加以调整。

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A TWO- PHASE AFTERBURNER COMBUSTION MODEL

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ABSTRACT According to the fundamental concept of two- fluids, the governing equations for description of gas- droplets turbulent combustion in an afterburner of jet engine have been formulated, in which the important injection effect of the droplets in afterburner has been taken into detailed consideration. The Favre average method has been employed to represent the effects of turbulent combustion in the afterburner. The multiple time scale turbulent k - ϵ model proposed by Kim is applied to calculating the eddy viscosity of the turbulent field. The heat flux radiation model has been taken to consider the effect of radiation at high temperature, the simple one step chemical reaction model is used to approximate the combustion of kerosene. The chemical reaction rate is assumed to be controlled by eddy break up process, and the reaction rate is modified by premixed reaction model in Arrhenius form. The application of SIMPLE algorithm indicates that the present two fluid model can calculate the two- phase turbulent combustion in the jet engine afterburner and obtain reasonable results.

Key Words Aircraft engines Gas- liquid flow Afterburners Combustion

NUMERICAL SIMULATION OF COMBUSTOR FLOWS

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ABSTRACT A method has been developed for calculation of three- dimensional flows in aeroengine combustor including diffuser and flame tube, inner and outer annuli. The 3D body- fitting grid has been generated to deal with the complex geometry of the combustor. The non- staged grid scheme and k - ϵ turbulence model has been adopted. The mass flowing through primary holes, dilution holes and film cooling holes has been calculated. The calculated results are consistent reasonably with the experimental measurements.

Key Words Numerical simulation Combustion chambers Turbulence

AEROENGINE TEST AUTOMATION OF ADAPTIVE CONTROL WITH RESTRAINTS

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ABSTRACT An automatic control system of aeroengine test has been designed, based on the method of model reference adaptive control with restraints. According to its simulation results, this method has good adaptability when the controlled member contains non- linear elements or the controller member varies in a large range. The simulation results also show that, the controlled system still has satisfactory performance index by regulating

the controller's parameters, even if the restraints are out of limits

Key Words Adaptive control Constraint conditions Aircraft engines Test rig

ADAPTIVE PREDICTIVE PI CONTROL BASED ON NEURAL NETWORKS FOR ELECTROHYDRAULIC FORCE SERVO SYSTEM

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ABSTRACT An adaptive predictive PI controller based on neural networks for electrohydraulic servo system is presented with respect to its complex nonlinearities and uncertainties. The method can be realized by a parallel structure which is composed of a real-time controller for real-time control operation, a predictive controller for regulation of control parameters and a supervising mechanism to determine whether or not the real-time controller is replaced by the predictive controller according to the variations of control performance. Thus, the real-time controller can be adjusted independently of the real operation of the controlled system by introducing neural networks as predictive model and predictive controller. It avoids the difficulty of the real-time control in control methods based on neural networks, thus makes the on-line learning control of complex systems possible. The learning ability of neural networks enables the predictive model to be modified on-line to simulate the behavior of the controlled system, and makes the predictive controller adjustable adaptively to variation of the system dynamical properties. Simulation results demonstrate its satisfactory control performance and it has been applied to a electrohydraulic servo structural testing system with success.

Key Words Electrohydraulic Servo systems Neural networks Adaptive control

BIAS ESTIMATION RESEARCH OF FAULT DETECTION IN LIQUID ROCKET ENGINE

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ABSTRACT Two accumulative error indices are defined as the discernment signals of the fault detection in a liquid propellant rocket engine. The biases of the fault detection are selected by way of the interval estimations of the discernment signals, and the operation conditions of the rocket engine are monitored on the basis of the biases derived from the interval estimations. Moreover, the maximum optimal questions of the fault isolation thresholds are considered with the aid of the probability density function for the discernment signals of the fault isolation. The data analysis of the test firings in a large turbo-pump fed liquid rocket engine demonstrates that the estimation techniques of confidence interval can improve fault detection time compared to the current engine redline monitoring system. In the detection of anomalous test firings, both of the accumulative error indices correctly detected all faults. In the detection of normal ones, no false alarms were indicated by the first accumulative error index, while only one false alarm was indicated by the second accumulative error