

一种新的变结构自适应控制方法 及其应用研究

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【摘要】 本文提出一种新的变结构自适应控制方法,并将其应用于航空发动机控制。这种方法只利用系统输入输出信号,与传统的自适应控制方法相比,具有收敛特性好,对对象的参数变化及未建模动态有很好的鲁棒性,同时其算法简单,易于实现。仿真表明该方法适用于航空发动机控制。

主题词: 航空发动机 自适应控制 鲁棒性

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1 前言

自适应控制 (Adaptive Control) 开始研究于五十年代,经过近四十年的研究,已具备完整的理论体系和方法。其中的模型参考自适应控制 (Model Reference Adaptive Control-MRAC) 应用最广。六十年代前后,美国曾将其用于飞机和发动机的控制系统设计,表明自适应控制的应用对提高飞机及发动机性能有很大作用。以后国内外大量学者进行自适应控制理论及应用研究,取得了许多理论研究成果及成功的实际应用。

变结构控制 (Variable Structure Control-VSC) 是近年来研究较多的一种非线性综合方法,它的突出特点是鲁棒性极强。随着计算机及快速切换元件的发展,变结构控制理论及应用研究已成为非线性控制理论的研究热点。

传统自适应控制对干扰及未建模动态 (Unmodeled Dynamics) 鲁棒性差的问题一直未能很好解决,严重妨碍了其理论的进一步发展及大量的实际应用,因此提高自适应控制的鲁棒性是近年来控制理论研究的难点问题之一。其中将变结构控制方法与自适应控制相结合形成的变结构自适应控制 (VSC-MRAC) 是一种有效途径,基于输入输出测量的变结构模型参考自适应控制 (MRAC Based on I/O) 方法不需全状态测量,不需对测量信号微分,算法简单,可以有效地改善系统鲁棒性,且保证全局收敛性能好。本文针对航空发动机的具体情况,在综合文献 [1-3] 方法的基础上,提出一种新的 VSC-MRAC 方法,并进行了仿真研究,结果表明该方法比传统的自适应控制有明显的优越性且适合于航空发动机控制。

2 变结构自适应控制原理

以二阶系统为例,被控对象传递函数为:

$$y(s)/u(s) = k_p(s + b_p)/(s^2 + a_{p1}s + a_{p2}) \quad (1)$$

其中: y 和 u 分别为输入输出。

取参考模型为: $y_m(s)/r(s) = k_m(s + b_m)/(s^2 + a_{m1}s + a_{m2})$ (2)

其中 y_m 和 r 分别为理想输出及参考输入信号。控制器设计的目的是寻找控制 u 使误差:

$$e = y - y_m \quad (3)$$

趋近于零对任意初始条件及任意连续有界参考信号 $r(t)$ 。

设输入和输出滤波器为: $\dot{v}_1 = \Lambda v_1 + gu$, $\dot{v}_2 = \Lambda v_2 + gy$ (4)

Λ 的选择应使其极点与多项式的根相同, 即: $\det[sI - \Lambda] = Z_m(s)$

控制规律为: $u = \theta^{*T} \omega + \Psi^T \omega$ (5)

这里: $\Psi^T = [\Psi_1, \Psi_2, \Psi_3, \Psi_4]$, $\omega^T = [v_1^T, y, \Psi_3, v_2^T, r]$ 和 $\theta^{*T} = (\theta^*, \theta^*, \theta^*, \theta^*)$, θ^* 为根据对象标称模型使得系统达到完全跟踪而得到的参数向量值。

自适应律为: $\Psi_i = -\rho_i \text{sign}(\omega e)$ (6)

其中 $\rho_i > |\theta^*|$, θ^* 是已知的参数变化上界, 符号函数定义为:

$$\text{sign}(x) = 1 \quad \text{如果 } x > 0, \text{ 而 } -1 \quad \text{如果 } x < 0 \quad (7)$$

自适应律 (6) 完全改变了传统的积分规律, 这是提高系统鲁棒性的关键。

为了消除由于符号函数可能带来的抖颤现象, 实践中引入软化的符号函数:

$$\text{sign}(x) = \text{sign}(x) \quad \text{当 } |x| > \delta, \quad \text{sign}(x) = \delta^{-1}x \quad \text{当 } |x| < \delta \quad (8)$$

这里 δ 是 $x = 0$ 两边线性区 (边界层) 的宽度。

结合文献 [1, 3] 可以证明, 该控制算法对参数变化及未建模动态有很强的鲁棒性, 且可以保证收敛过程性能优良。

以上控制方法适合于对象阶数, 阶差已知, 已知其标称数学模型参数, 且参数的变化界限已知的任意控制对象。

3 VSC-MRAC 用于发动机控制

某型发动机某状态的传递函数如 (1), 输入量为供油量, 输出量为低压转子转速。其中设计点的参数为: $k_p = 0.36$, $b_p = 2.78$, $a_{p1} = 11.05$, $a_{p2} = 7.15$ 。取参考模型为:

$$y_m/r = 4(s + 2.5)/(s^2 + 7.0s + 10.0) \quad (9)$$

下面就本文所提出的控制方法与传统自适应控制方法进行仿真研究。其中考虑可能的两种未建模动态, 一阶形式 $15/(s + 15)$ (简称A型), 二阶形式 $229/(s^2 + 30s + 229)$ (简称B型)。

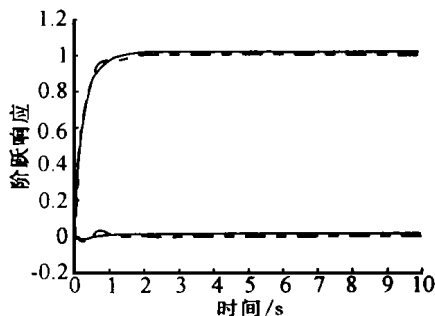


图1 参数变化时系统阶跃响应及误差曲线

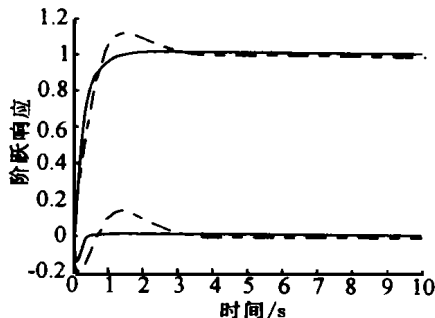


图2 具有未建模动态A时系统响应及误差曲线

图 1 为当对象参数变化时对象输出及误差的阶跃响应曲线。(图中实线, 虚线分别代表 VSC-MRAC 及 MRAC 方法, 上边曲线代表输出, 下边曲线代表误差。其它图相同)。这里参数 b_p 和 a_{p1} 增大 10%, 而 a_{p2} 减小 10%。可以看出两种方法对对象参数变化都有很好的适应性; 图 2 和图 3 是在上面参数变化的基础上分别考虑具有 A 和 B 型的未建模动态。这时 MR

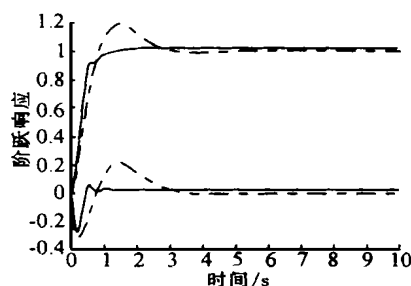


图 3 具有未建模动态 B 时系统阶跃响应及误差曲线

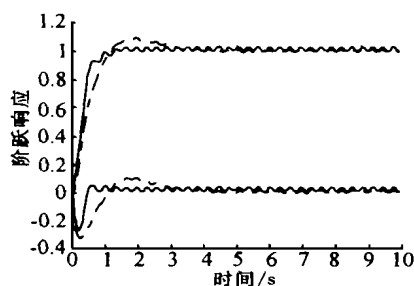


图 4 考虑测量噪声时系统阶跃响应及误差曲线

AC 方法性能明显变差, 验证了其积分自适应律对对象未建模动态鲁棒性差的缺陷, 同时看出 VSC-MRAC 方法对对象未建模动态鲁棒性强且收敛过程性能优的特点; 图 4 考虑了对象参数变化, B 型未建模动态且输出端有测量噪声 $0.1\sin 20t$ 的情况。文献 [2] 中提到此情形 MRAC 方法很可能出现系统发散, 尽管仿真中未出现此现象, 但动态性能不好, 而 VSC-MRAC 方法同样具有优良性能。

4 结 论

本文在综合了文献 [1- 3] 研究的基础上, 提出了一种新的鲁棒自适应控制方法, 即基于输入输出的变结构模型参考自适应控制方法。它适合于对象阶数, 阶差已知, 已知其标称数学模型参数, 且参数的变化界限已知的任意控制对象。通过将该控制方法用于航空发动机控制的仿真研究表明, 该控制算法对对象参数变化及未建模动态有很强的鲁棒性, 可以保证收敛过程性能优良, 具有较好的抗干扰的性能, 且其算法简单, 易于实现, 优于传统的模型参考自适应控制方法。

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has excellent static and dynamic performance. It is insensitive to environmental conditions.

Key Words Gas lubricated bearing Journal Performance compliant
Multileaf experiments

MULTIVARIABLE CONTROL FOR AEROENGINE WITH 3- LAYER NEURAL NETWORKS

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ABSTRACT A multivariable neural network adaptive control is provided for a turbofan engine. The nonlinear system is compensated dynamically by a 3- layer neural network. An on- line weight- tuning algorithm with simplified Hebbian rule and e- modification is worked out to guarantee tracking performance as well as bounded weights without off- line training. The precise model of the engine is not necessary for design of control system. The multivariable control system has satisfactory performance for the full flight envelope with good adaptation and robustness. Simulation results show satisfactory dynamic and static performance within the whole flight envelope and good effectiveness of reducing interaction in the multivariable system with significant coupling.

Key Words Aeroengine Neural networks Multivariable control

DESIGN OF AEROENGINE LQG/LTR CONTROLLER ACCORDING TO PERFORMANCE TARGET

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ABSTRACT When LQG/LTR methodology is applied to control system design, it is not easy to choose proper covariance matrices for Kalman filter design for good dynamic performance and robustness of the control system. The methodology is based on the idea that if the control system is decoupled, the target close loop transfer functions of each channel can be presented according to the demands of dynamic performance. After the recovery procedure is finished, the system performance must approximate the target. With the methodology provided for designing the Kalman filter, the Kalman filter gain matrix can be calculated directly in accordance with the performance targets and state space matrices of the plant so that it is unnecessary to solve the Riccati equation. The simulations show that dynamic performance of the control system designed by using this methodology meets the design target, and its robustness is good.

Key Words Aeroengine Performance Kalman filter Robustness

A NEW VARIABLE STRUCTURE ADAPTIVE CONTROL SCHEME AND ITS APPLICATIONS

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ABSTRACT A new variable structure adaptive control scheme is proposed. The

scheme consists of conventional model reference adaptive control and sliding mode control. The adaptive control based on plant's normalized model can match reference model exactly at the design point. The sliding mode control copes with bounded parameter variations and unmodeled dynamics. Signal synthesis is used as adaptive law instead of the conventional integral law. Through introducing linear zone to sliding mode, the chattering phenomenon is eliminated to a great extent. In comparison with conventional adaptive control, the scheme needs only the plant's input-output measurements, and has superiority in fine convergence, strong robustness to parameter variation and unmodeled dynamics. The simulation results indicate that this scheme is applicable to aero-engine control.

Key Words Aeroengine Adaptive control Robustness

TECHNICAL NOTES

DESIGN OF AERO-ENGINE CONTROLLER WITH QUADRATIC STABILITY AND DISTURBANCE-RESTRAINING PERFORMANCE

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ABSTRACT A methodology is presented to design aeroengine output dynamic feedback controller. When the state and output matrices of a control system are perturbed, the controller designed in this way can lead the system to be quadratic stable. When disturbances are equal to zero, the system will be of quadratic disturbance-restraining performance when the perturbation of the matrices does not exist. The problem is simplified into a standard output dynamic feedback control problem on the basis of two theorems about quadratic stability and disturbance-restraining performance. From the two theorems, an augmented plant is derived. With the augmented plant, the controller is designed by using control theory. For an example, the flight envelope of the engine is divided into 12 subregions, and in each subregion the simulation under different flying conditions is given. It is shown that the dynamic performance of the control system meets the design target and the robustness of stability is good.

Key Words Aeroengine Controller Robustness

AN EXPERIMENTAL INVESTIGATION OF FILM COOLING EFFECTIVENESS ON LEADING EDGE OF TURBINE BLADE

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ABSTRACT Film cooling effectiveness of hole-rows on leading edge of turbine blade has been studied experimentally. The model is a blunt body with a half-cylinder leading edge and two flat side-walls. Six rows of round holes were ungradationally located at