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ScienceDirect
Journal of the Franklin Institute 345 (2008) 851–876
Journal of The Franklin Institute
www.elsevier.com/locate/jfranklin

Nonlinear H_∞ robust control applied to F-16 aircraft with mass uncertainty using control surface inverse algorithm

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Received 29 August 2005; received in revised form 6 April 2008; accepted 5 May 2008

Abstract

In this paper, an analytic solution of nonlinear H_∞ robust controller is first proposed and used in a complete six degree-of-freedom nonlinear equations of motion of flight vehicle system with mass and moment inertia uncertainties. A special Lyapunov function with mass and moment inertia uncertainties is considered to solve the associated Hamilton–Jacobi partial differential inequality (HJPDI). The HJPDI is solved analytically, resulting in a nonlinear H_∞ robust controller with simple proportional feedback structure. Next, the control surface inverse algorithm (CSIA) is introduced to determine the angles of control surface deflection from the nonlinear H_∞ control command. The ranges of prefilter and loss ratio that guarantee stability and robustness of nonlinear H_∞ flight control system implemented by CSIA are derived. Real aerodynamic data, engine data and actuator system of F-16 aircraft are carried out in numerical simulations to verify the proposed scheme. The results show that the responses still keep good convergence for large initial perturbation and the robust stability with mass and moment inertia uncertainties in the permissible ranges of the prefilter and loss ratio for which this design guarantees stability give same conclusion.

Keywords: Nonlinear H_∞ control; Control surface inverse algorithm; Robust; Prefilter

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doi:10.1016/j.jfranklin.2008.05.002

Nomenclature

b	wing span
$\bar{c}$	mean aerodynamic chord of wing
d	exogenous disturbance
$E(x)$	positive function satisfying the HJPDI
F_x, F_y, F_z	applied forces with respect to x-, y-, z-axes, respectively
g	acceleration due to gravity
I_{xx}, I_{yy}, …	moments of inertia of the flight vehicle
I_M	matrix formed by moments of inertia
C_σ, C_ω	controller gain
L, M, N	roll, pitch and yaw moments
m_s	vehicle's mass
$\Omega = [P \quad Q \quad R]^{\mathrm{T}}$	roll, pitch and yaw rates about body axis
$\omega = [p \quad q \quad r]^{\mathrm{T}}$	deviations of roll, pitch and yaw rates from the trim condition
P_{s}	static pressure
$\bar{q}$	free-stream dynamic pressure
ρ_u	control loss ratio by actuator
$K_{\mathrm{s}} = k_{\mathrm{a}} W_{\mathrm{s}}$	prefilter to avoid actuator saturation
S	cross-product matrix
s	Laplace variable, $1/s$
S_{w}	reference wing area
$\Sigma = [U \quad V \quad W]^{\mathrm{T}}$	components of airplane velocity along x, y, z
$\sigma = [u \quad v \quad w]^{\mathrm{T}}$	deviations of x-, y-, z-axes velocity from the trim condition
u^{c}	nonlinear H_∞ control command
u^{i}	force and moment generated by control surface with ideal actuator
u^{a}	same as u^{i} but with actuator constraints
x_{cg}	center-of-gravity location, fraction of $\bar{c}$
γ_1, γ	L_2 gains
δ_i	ith control surface deflection
δ_i^*	*th tabular value of ith control surface deflection in look-up table
δ_{lef}	leading-edge flap deflection
δ_{h}, δ_{sb}, δ_{a}, δ_{r}	elevator, speed-brake, aileron and rudder deflections (°)
δ_{T}	engine power, percentage of maximum power
α, β	angles of attack and sideslip
θ, φ, ψ	Euler angles
σ_{w}, L_{w}	intensity and turbulence scale length of the wind gust
$\Delta\sigma_{\mathrm{g}}$	gust velocity vector
$\Delta\sigma_\omega$	gust angular velocity vector

1. Introduction

Control system design for nonlinear plant, especially for high-performance aircraft operating in high angle of attack and large angular rate ranges, is always a challenging work. In these operating regions, nonlinearities become a dominant feature of the aircraft