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Acceleration autopilot design for gliding guided projectiles with less measurement information

Qiuping Xu, Sijiang Chang *, Zhongyuan Wang

School of Energy and Power Engineering, Nanjing University of Science and Technology, Nanjing, 210094, China

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ABSTRACT

In this paper, a novel acceleration autopilot is proposed to solve the problem of the design of the flight control system of gliding guided projectiles under the factors such as cross-coupling dynamics, uncertainties, and constraints of the sensors, actuators, and system complexity. Unlike the traditional two/three-loop autopilot, only the measured accelerations are directly adopted as feedback in the proposed autopilot to reduce the cost and the system complexity, and to improve the reliability. The feasible and effective of the proposed autopilot is verified through several case studies. Results indicate that the designed autopilot can achieve quick, accurate, and no-overshoot tracking of the given signals, with good active-disturbance-rejection and decoupling performance and strong robustness and adaptability. The control parameters are easy and systematic to tune, and not sensitive to the perturbations of aerodynamic parameters within a wide range. In addition, the canard deflection commands change slowly from zero at the initial stage, and also yield a smooth and gentle rather than sharp change after each switching of acceleration signals, which can effectively avoid the control saturation and oscillation and enhance the flight stability.

1. Introduction

The Gun-launched gliding guided projectiles (GGP) [1,2] emerged since the attractive mission demands in range extension and high impact accuracy with low collateral damage. In some previous literatures, the problems such as the aerodynamic configuration and ballistic characteristic analysis [3–7], the trajectory optimization [8,9], and the guidance law and simple control algorithm [10–13] for GGP have been studied. The focus of this paper is on the design of its flight control system considering the following several factors.

Firstly, the cross-coupling flight dynamics between pitch and yaw channels are induced by the spinning characteristic of the projectile and the lags from control commands transmission and actuators response. With this in mind, a two-loop lateral acceleration autopilot with a rate loop and PI regulator [14] and a three-loop structure autopilot [15] were respectively designed. However, in these literatures, the uncertainties caused by the simplification of the motion model are not considered, and there are overshoot and oscillation in the tracking results.

Secondly, the existence of uncertainties and the perturbation of aerodynamic parameters increase the design difficulty of the autopilot and also impose higher requirements on its robustness. In [16], a nonlinear adaptation acceleration controller for tail-controlled missiles was proposed based on the three-loop structure to reject the aerodynamic uncertainties. In [17], a pitch acceleration autopilot based on the continuous time predictive control and generalized extended state observer was designed for a tail-controlled missile. But the cross-coupling characteristics are not involved in these literatures.

Furthermore, considering the gun-launched environment, the control authority provided by GGP is limited, because the onboard electronics suites and control mechanisms must be relatively small due to space limitations. It also requires that the canard deflection is not easy to reach saturations and without sharp oscillations (especially in the initial tracking stage).

Another noteworthy aspect is that GGP must be relatively inexpensive so that a full suite of high-precision sensors to provide estimates of all flight states is not fiscally feasible. Hence, the complex control algorithms that require more information are not suitable for low-cost GGP, and the complexity of control system structure must be minimized to the benefit of the increased reliability. The two/three-loop autopilot for missiles requires at least two gyroscopes and two accelerometers to measure the state information [18,19], which increases the difficulty of its engineering

* Corresponding author.
E-mail addresses: qiupxu@163.com (Q. Xu), ballistics@126.com (S. Chang), zywang@mail.njust.edu.cn (Z. Wang).

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Nomenclature

Symbol	Definition	Unit
A, C	lateral and longitudinal moments of inertial respectively	kg m^2
a_{yc}, a_{zc}	acceleration commands	m/s^2
a_y, a_z	projectile accelerations	m/s^2
a_{ym}, a_{zm}	measured accelerations	m/s^2
a_i, b_i, k_i, κ_i	model parameters	
C_D, C_L, C_u	drag, lift, and Magnus force coefficients	
C_{D0}	zero-lift drag coefficient	
C_L', C_u''	derivatives of lift and Magnus force coefficients	
d	projectile diameter	m
e_{i1}, e_{i2}	state errors of i-th channel	m/s^2
f_i	total disturbances of i-th channel	m/s^4
k_s	gain of canard system	
K_{AB}	induced drag coefficient	
L	reference length	m
m	mass of projectile	kg
m_s, m_u	coefficients of static and Magnus moments	
m_s', m_u''	derivatives of static and Magnus moment coefficients	
m_σ'	coefficient of control moment	
m_w'	coefficient of damping moment	
m_{xw}'	coefficient of roll-damping moment	
m_x'	coefficient of roll-induced moment	
Q	dynamic pressure	N/m^2
r_0	speed factor of tracking differentiator	
S	reference area	m^2
T_s	time constant of canard system	s
T_d	transition time of tracking differentiator	s
$U_{(\bullet)}$	virtual control variable	
v	velocity	m/s
v_{i1}, v_{i2}	states of tracking differentiator	
z_{i1}, z_{i2}, z_{i3}	states of extended state observer	
ρ	air density	kg/m^3
α	total angle of attack	rad
δ_1, δ_2	angle of attack and sideslip angles in the nonspinning coordinate system	rad
δ_t	canted angle of tails	rad
σ_1, σ_2	pitch and yaw canard deflections in the nonspinning coordinate system	rad
σ_{1c}, σ_{2c}	pitch and yaw canard deflection commands in the nonspinning coordinate system	rad
θ, φ	flight-path angle and heading angle	rad
γ, ϑ, ψ	roll, pitch, and yaw angles	rad
$\omega_i(t)$	lumped disturbances in each channel	
ω_y, ω_z	disturbances in acceleration dynamics	
ε, λ	parameters of extended state observer	
ω_c	closed-loop bandwidth	
μ_s	damping ratio of canard system	
τ	time delay of control system	s

application on GGP (especially the alignment problem of the onboard gyroscope) and may induce unnecessary measurement errors as well as further reduce the reliability of the control system of GGP.

This task is especially important for the development of gliding guided projectiles. However, the research considering these aforementioned considerations and performance requirements is, as far as the authors know, very limited in the current research literature. This paper is motivated by the need in offering an elegant and practical scheme, which can be easily popularized and applied in engineering for GGP.

The main contribution of this paper is that a novel acceleration autopilot for gliding guided projectiles with less measurement information is designed. To reduce the cost and the complexity, only the measured accelerations are directly employed as feedback in the autopilot structure. A suitable transition process is arranged based on the tracking differentiator, so that the gradual and gentle rather than abrupt changes in the state errors can be guaranteed, which can effectively avoid the control saturation and oscillation. Meanwhile, a time-varying extended state observer is designed to estimate the acceleration states and total disturbance (consisted of cross-coupling dynamics and uncertainties) in real time, even without knowing the exact form of uncertainties. In addition, the canard deflection commands change slowly from zero at the initial stage, and also yield a smooth and gentle rather than sharp change after each switching of acceleration signals, which is beneficial to the enhancement of the flight stability. The designed autopilot meets the above proposed performance requirements, and has the advantages of simple structure, less effort on computation and measurement on the flight states, and good disturbance-rejection and decoupling performance with quick and no-overshoot tracking. The control parameters are easy and systematic to tune. Once they are well-tuned, the autopilot is still able to maintain good control quality even in the wide perturbation range of aerodynamic parameters, and shows strong adaptability and robustness.

This paper is organized as follows. The cross-coupled acceleration control system with uncertainties is formulated in Section 2. The detailed design of the active-disturbance-rejection acceleration autopilot is demonstrated in Section 3. Several case studies are conducted to verify the feasibility, effectiveness and expected performance of the proposed autopilot in Section 4. Finally, some conclusions are given in Section 5.

2. Cross-coupled acceleration dynamics

In order to facilitate numerical simulations and avoid the financial difficulty of shooting experiment, the acceleration control system dynamics are established.

2.1. Motion equations

In the process of autopilot design, the gravity effect is generally excluded. During the unpowered gliding flight, according to Li [14], the motion governing equations for a spinning gliding guided projectile can be expressed as (for variable definitions, see Nomenclature)

$$\begin{cases} m\dot{v} = -QSC_D \\ mv\dot{\theta}\cos\varphi = QSC_L\dfrac{1}{\sin\alpha}\cos\delta_2\sin\delta_1 - QSC_u\dfrac{1}{\sin\alpha}\sin\delta_2 \\ -mv\dot{\varphi} = -QSC_L\dfrac{1}{\sin\alpha}\sin\delta_2 - QSC_u\dfrac{1}{\sin\alpha}\cos\delta_2\sin\delta_1 \\ C(\ddot{\gamma} - \ddot{\vartheta}\sin\psi - \dot{\vartheta}\dot{\psi}\cos\psi) \\ \quad = QSLm_x'\delta_t - QSLm_{xw}'(d/v)(\dot{\gamma} - \dot{\vartheta}\sin\psi) \\ A\ddot{\psi} + C\dot{\gamma}\dot{\vartheta}\cos\psi - (C-A)\dot{\vartheta}^2\sin\psi\cos\psi \\ \quad = QSLm_\sigma'(\delta_2 + \sigma_2) - QSLm_w'(d/v)\dot{\psi} \\ \qquad + QSLm_s\dfrac{1}{\sin\alpha}\sin\delta_2\cos\delta_1 + QSLm_u\dfrac{1}{\sin\alpha}\sin\delta_1 \\ A(\ddot{\vartheta}\cos\psi - \dot{\vartheta}\dot{\psi}\sin\psi) - C\dot{\gamma}\dot{\psi} + (C-A)\dot{\vartheta}\dot{\psi}\sin\psi \\ \quad = QSLm_\sigma'(\delta_1 + \sigma_1) - QSLm_w'(d/v)\dot{\vartheta}\cos\psi \\ \qquad + QSLm_s\dfrac{1}{\sin\alpha}\sin\delta_1 - QSLm_u\dfrac{1}{\sin\alpha}\sin\delta_2\cos\delta_1 \end{cases} \tag{1}$$

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