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Stability of spinning missile with homing proportional guidance law

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ABSTRACT

The terminal proportional guidance loop has been employed by spinning missiles to improve the attacking accuracy. However, it has been observed that the miss distance increases dramatically during the design of the spinning missile with only a guidance loop. Meanwhile, the conventional stability criteria of the guidance loop applicable to the non-spinning missile are no longer valid in the event of the spinning. To address this problem, in this paper, the stability of the spinning missiles with only a 3D proportional guidance loop is analytically derived from system equations in a form of complex summation and the suitable design criteria for the whole proportional guidance loop are also established. Numerical simulations show that during the terminal guidance phase the stable region for the proportional navigation coefficient is reduced with the increase of flight time, which is also shrunk dramatically due to spinning, and the decrease of the critical stable time of spinning missiles results in the increase of miss distance, which exhibit great agreements to those derived from the analytical stability criteria.

1. Introduction

The terminal guidance loop with the proportional guidance law has been widely employed by spinning missiles to improve the attacking accuracy, which can limit the miss distance within about 10 m [1]. Recently, many terminal guidance devices have been applied to spinning projectiles to enhance their performance and the autopilot loops are not employed considering the cost reduction and system simplification. However, during the trajectory simulations of our study, it has been observed that, with the same proportional navigation coefficient ($N = 5$), the miss distance increases significantly with the increase of the spinning angular velocity of missile, while it is 8.76 m for the non-spinning missiles, as shown in Fig. 1. It has not been reported and discussed in the existing literatures so far.

Based on the proportional guidance equations, the stability of the non-spinning missiles in pitch channel with the proportional guidance loop has been investigated and the stable region of the navigation coefficient has also been given [2]. Considering cost saving and system simplification, Zarchan has studied the proportional guidance loop of the non-spinning missiles without autopilots and has obtained that the open-loop control could be used in a proportional guidance system without parasitic loops such as an infrared system [3]. Nevertheless, different from the non-spinning missiles, the cross-coupling effect between the pitch and yaw channels exists for the spinning missiles, which may even result in a divergent coning motion [4–6]. Previous researches about the coning motion mainly focus on establishing the coning motion equations of spinning missiles with a rate loop [7], an attitude autopilot [8] or an acceleration autopilot [9,10], in which the corresponding analytical stability criteria have been deduced based on the linear theory. Furthermore, other factors, such as the hinge moment and backlash of actuators, that may affect the coning stability have been studied in the previous work of authors [11,12], in which the mechanism how the parasitic loop of strap-down seeker affects the stability of the flight control system for spinning missiles has also been investigated [13].

However, these works mainly focus on exploring the impact of coning motion on the design of autopilot for spinning missiles, which evidently cannot address the above issue that the miss distance of spinning projectiles increases dramatically. Considering the special motion pattern of the spinning missiles, it is the belief of us that the increasing miss distance observed above is caused by the diverging coning motion resulted from the instability of the proportional guidance loop. Nevertheless, researches on the stability of proportional guidance loop for spinning missiles without autopilots has rarely been seen in the existing literature, and its

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Nomenclature

a_{cy}, a_{cz}	acceleration command	m/s^2
a_y, a_z	acceleration of missile	m/s^2
C_D	drag force coefficient	
$C_{L\alpha}$	lift force coefficient slope	
C_δ	control moment coef.	
$C_{m\alpha}$	static moment coef.	
C_{mq}	damping moment coef.	
$C_{mp\alpha}$	magnus moment coef.	
C_{lp}	roll-damping moment coef.	
C_l	roll-induced moment coef.	
I_t	lateral inertial moment	kg m^2
I_x	longitudinal inertial moment	kg m^2
k_r	dynamic gain of servosystem	
k_s	gain of servosystem	
k_A	commands transmitting coef.	
m	mass of missile	kg
N	proportional navigation coef.	
P	thrust force	N
p, q, r	angular rate of airframe	rad/s
Q	dynamic pressure	N/m^2
S	reference area	m^2
r_d	distance between missile and target	m
t_{go}	whole flight time to go	s
t	flight time	s
u, v, w	flight velocity in three-axis direction	m/s
V	flight velocity	m/s
α	non-spinning angle of attack	rad
β	non-spinning sideslip angle	rad
ξ	complex angle of attack	rad
μ_s	damping ratio of servosystem	
γ_c	coupling angle of servosystem	rad
γ_h	delay angle of seeker system	rad
γ_t	total delay angle	rad
δ_{cy}, δ_{cz}	non-spinning control command	rad
δ_y, δ_z	non-spinning rudder angle	rad
τ_1	time delay of control system	s
τ_2	time delay of guidance part	s
θ, ψ, ϕ	pitch, yaw, roll angle	rad
θ_s, ψ_s	sight angle	rad
$\dot{\theta}_s, \dot{\psi}_s$	sight angular velocity	rad/s
ζ	complex sight angle	rad
$\cdot^n$	vector in the non-spinning body coordinate system	
$\cdot^s$	vector in the sight coordinate system	

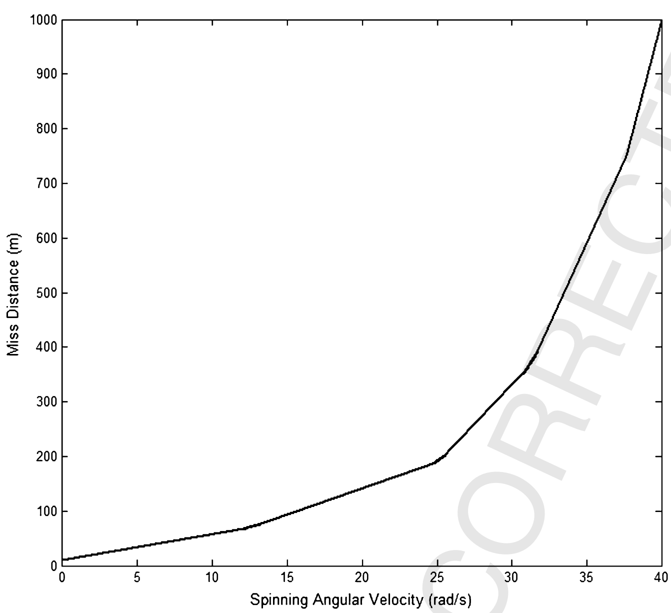

Fig. 1. Miss distance and spinning angular velocity.

sufficient and necessary conditions for the coning motion stability have not been deeply analyzed so far.

Therefore, it is objective of this paper to investigate and establish the stability criteria of the spinning missile equipped with only the proportional guidance loop. Clearly, when the sight angular velocity diverges due to unstable coning motion, the frame angle of the seeker may get saturated, resulting in the evident decline of the hit accuracy. In this work, the 3D engagement equations and the proportional guidance law are formulated, and the dynamic equations of the spinning missile are also given. Subsequently, the whole guidance system equations are constructed in a form of complex summation based on certain assumptions. The sufficient and necessary conditions for the coning motion stability are then derived analytically by neglecting the nonlinear items and further verified by numerical simulations. It is noticed that the stable region of the design parameter for the guidance loop is reduced dramatically with the increase of the spinning speed, providing a good explanation why the miss distance of spinning missiles increases dramatically with the same proportional navigation coefficient.

2. System description

In this work, the canard configuration and symmetrical airframe are employed for the spinning missile. The guidance loop for the spinning missile mainly includes the sight angular velocity feedback loop that is realized by the missile–target relative motion equations, as shown in Fig. 2. The feedback information is measured by the pitch-yaw seeker fixed on a roll-stabilized platform that does not rotate with the airframe. Thus the sight angular velocity of missile can be obtained in the sight coordinate system. Moreover, the coordinate transformation is required to generate overload commands in the non-spinning body coordinate system from the proportional guidance commands. Even though the canards will work simultaneously in the body coordinate system, the control moment can be composited and acted in the non-spinning body coordinate system. In this system, the vector $\dot{\theta}_s$ and $\dot{\psi}_s$ represent the sight angle velocities between the missile and target in the sight coordinate system, a^s_{cy} and a^s_{cz} are the input overload commands in the sight coordinate system, a^n_{cy} and a^n_{cz} represent the input overload commands in the non-spinning body coordinate system, δ_{cy} and δ_{cz} are the input rudder commands in the non-spinning body coordinate system, δ_y and δ_z are the actual control surface angle vectors, a_y and a_z represent the actual lateral overloads in the non-spinning body coordinate system, a_{my} and a_{mz} denote the actual lateral overloads in the sight coordinate system. The constitution and operation process of the guidance system is shown in Fig. 2.

3. Mathematic model

In this section, the three important components of a proportional guidance loop shown in Fig. 2 are mathematically modeled. For the spinning missiles with the proportional guidance law, the

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