Effect of seeker disturbance rejection rate on performance of optimal guidance laws with terminal impact angle constraint

Zhang Wenyuan[1], Lan Zhi[2], Xia Qunli[1], Qi Zaikang[1]

(1. School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China;
2. Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China)

Abstract: In order to study the effect of seeker disturbance rejection rate on performance of optimal guidance law, based on guidance law with terminal impact angle (GLTIA) and extended guidance law with terminal impact angle (EGLIA), the regularization of strapdown seeker disturbance rejection rate on the stability of guidance system was studied. Using adjoint method the miss distance of GLTIA and EGLIA were analyzed. The results show that the stable domain of guidance system is larger when strapdown seeker parasitic loop is negative feedback than positive feedback, the stability will reduce when the value of disturbance rejection rate gets bigger. Though EGLIA has more excellent guidance performance than GLTIA, but the influence of a parasitic loop of seeker disturbance rejection rate will be more serious, the sufferable value of seeker disturbance rejection rate for EGLIA is about 2.5%, and the GLTIA is about 3.5%. In the practical application, if the guidance law would work with advanced performance, the value of seeker disturbance rejection rate should be much stricter to reduce the effect of parasitic loop.

Key words: strapdown seeker; optimal guidance laws with terminal impact angle constraint; parasitic loop of disturbance rejection rate

CLC number: TJ765 **Document code:** A **DOI:** 10.3788/IRLA201746.0331001

导引头隔离度对最优落角制导律制导性能影响研究

张文渊[1]，兰 志[2]，夏群利[1]，祁载康[1]

(1. 北京理工大学 宇航学院，北京 100081；2. 南京航空航天大学，江苏 南京 210016)

摘 要： 针对工程应用中最优落角制导律性能受导引头隔离度影响的问题，基于最优落角制导律(GLTIA)和拓展最优落角制导律(EGLIA)，建立了包含捷联导引头隔离度寄生回路的最优落角制导律系统，研究了捷联导引头隔离度对制导系统稳定性的影响，利用伴随函数法，通过仿真对比分析了捷联导引头隔离度对 GLTIA 和 EGLIA 制导精度的影响。仿真结果表明：相比正反馈情况，当捷联导引头隔离度寄生回路为负反馈时，最优落角制导律具有较高的稳定域，系统稳定性会随着隔离度幅值的增大而减小。相比于 GLTIA，EGLIA 的制导性能更优，但导引头隔离度对其制导性能的影响也更为严

收稿日期： 2016-07-05； **修订日期：** 2016-08-10

基金项目： 国家科技重大专项

作者简介： 张文渊(1987-)，博士生，主要从事高超声速飞行器制导与控制方面的研究。Email:zhwy_bit@163.com

导师简介： 夏群利(1971-)，副教授，博士生导师，主要从事飞行器总体设计与制导控制方面的研究。Email:1010@bit.edu.cn

重，在实际工程应用中，要保证最优落角制导律有较高的制导性能，EGLIA 和 GLTIA 需将导引头隔离度水平分别控制在 2.5%和 3.5%以下，以降低寄生回路对制导系统稳定性的影响。

关键词： 捷联导引头； 最优落角制导律； 隔离度寄生回路

0 Introduction

The disturbance rejection rate is an important indicator of a strapdown seeker, which indicates the level of the rejection of missile body disturbance from the information output by a seeker. The disturbance rejection rate may cause a parasitic loop of guidance, which seriously affects the stability of guidance system, changes guidance dynamics, and decreases the guidance accuracy[1-4]. In practice, the guidance performance of a guidance law is closely related to the seeker disturbance rejection rate.

Current researches on guidance laws with terminal impact angle constraint are mostly based on various guidance law derivation approaches[5-11], where guidance law characteristics are studied from the perspective of mathematic derivation. Meanwhile, the scholars study mainly the effects of a parasitic loop of disturbance rejection rate in a guidance system with proportional navigation guidance (PNG) law on the guidance stability and accuracy[12-14] and rarely discuss about the guidance matching between strapdown seeker disturbance rejection rate and the guidance law with terminal impact angle constraint, but the latter has great guiding significance on the engineering application of a guidance law with impact angle constraint.

Focusing on the above problems, based on two typical guidance laws with terminal impact angle constraint, the paper establishes the model of guidance system which contains parasitic loop of strapdown seeker disturbance rejection rate. The research studies the regularization of the effect of guidance parameters, strapdown seeker disturbance rejection rate of the stability of guidance system, and the relationship between the variation of the guidance precision of the two guidance laws and the strapdown seeker disturbance rejection rate is analyzed through numeric simulation and comparison.

1 Problem formulation

1.1 Optimal guidance laws with terminal impact angle constraint

Reference [6] gives a guidance law with terminal impact angle (GLTIA) by Zarchan, it can solve the problem of guidance with terminal position and angular constraints but cannot effectively constrain the terminal acceleration. To control the terminal acceleration, an extended guidance law with terminal impact angle (EGLIA) can be derived based on GLTIA. Because the detail derivation process of guidance law is not the key research in this paper, we omit that. Figure 1 shows the system model of guidance law with terminal impact angle constraint.

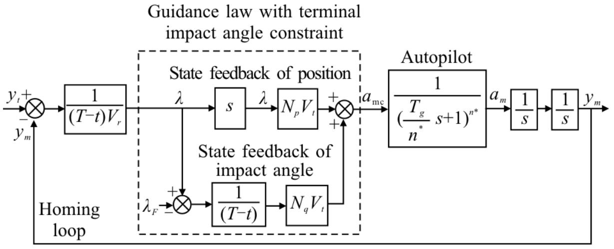


Fig.1 System model of guidance law with terminal impact angle constraint

In Fig.1, y_t is position of target, y_m is position of missile, a_{mc} is command acceleration of missile, a_m is response acceleration of missile, V_r is missile-target relative velocity, λ is the angle of LOS, λ_F is expected terminal impact angle, $T-t$ is time-to-go, i.e. t_{go}.

The weight coefficient of GLTIA is a fixed value, and

$$N_p=4 \quad N_\lambda=2 \tag{1}$$

The weight coefficient of EGLIA is determined by the guidance factor n, and

$$N_p=2(n+2)\quad N_\lambda=(n+1)(n+2) \tag{2}$$

When $n=0$, EGLIA is degraded into GLTIA. EGLIA can make the terminal acceleration command close to zero by adjusting the guidance factor n, while ensuring the accuracy of both the terminal position and angle.

1.2 Strapdown seeker disturbance rejection rate

Figure 2 gives the angle relation of strapdown seeker in the vertical plane. And ϕ_y is field angle of strapdown seeker, ϑ is pitching angle of missile. We can get λ as shown in Eq.(3).

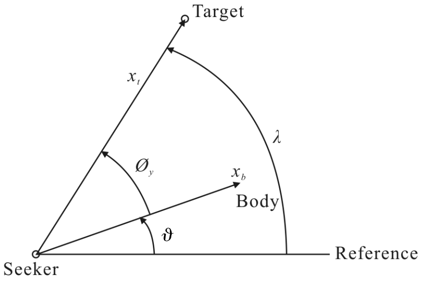


Fig.2 Angle relation of strapdown seeker

$$\dot{\lambda}=\dot{\phi}_y+\dot{\vartheta}=(\dot{\lambda}-\dot{\vartheta})+\dot{\vartheta} \tag{3}$$

In Eq.(3), $-\dot{\vartheta}$ is contained within the differential of output information ϕ_y from seeker, so attitude motion of missile is 100% coupling into the information of seeker. $\dot{\vartheta}$ is measured by angular rate gyro of missile. When $-\dot{\vartheta}$ and $\dot{\vartheta}$ measured respectively by seeker and gyro are completely consistent, the coupling can be eliminated.

But in engineering application, the dynamics, graduated scale and signal processing delay of seeker and gyro are different, these factors will cause attitude motion coupling into the output information of seeker[12]. So the definition of strapdown seeker disturbance rejection rate shows as Eq.(4).

$$R_{\rm dr}=\frac{\Delta\dot{\lambda}}{\dot{\vartheta}} \tag{4}$$

When $\Delta\dot{\lambda}$ is additional information of seeker caused by the missile disturbance.

Based on the guidance laws with terminal impact angle constraint, a parasitic loop of strapdown seeker disturbance rejection rate is introduced to establish a model of guidance system, as shown in Fig.3.

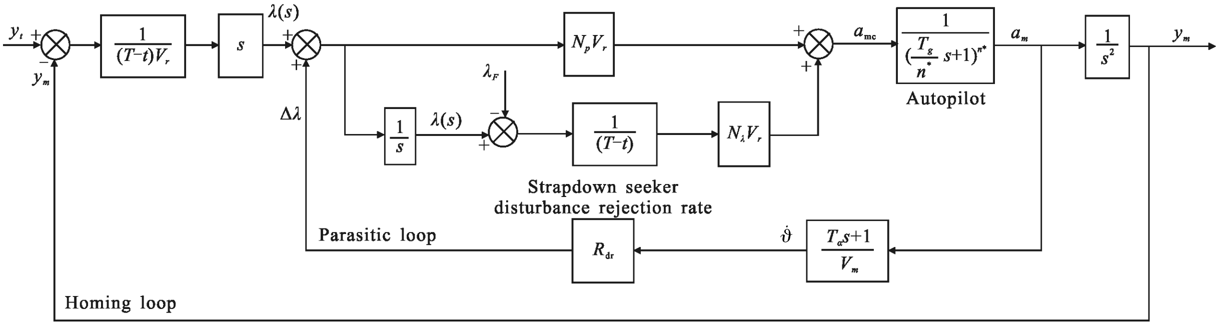


Fig.3 Guidance system diagram with parasitic loop of strapdown seeker disturbance rejection rate

For the convenience of analysis, it is assumed that $R_{\rm dr}$ is an amplifying element, $R_{\rm dr}$ is the value of strapdown seeker disturbance rejection rate, when $R_{\rm dr}>0$, the parasitic loop is positive feedback; when $R_{\rm dr}<0$, the parasitic loop is negative feedback.

2 Stability of optimal guidance system

With the introduction of seeker disturbance rejection rate, the stability of optimal guidance system is influenced by parasitic loop. Now, the guidance system is a kind of multi-parameter and time-varying system. For analyzing the stability of system, we use the dimensionless method to simplify the system as shown in Fig.3. Meanwhile, λ_F can be considered as a disturbance input, of which the value may not affect the stability of the whole system, so λ_F can be zero.

Benchmarked against the guidance time constant T_g, the nondimensionalized parameter is $\bar{T}_\alpha=\frac{T_\alpha}{T_g}$, $\bar{t}_{\rm go}=\frac{t_{\rm go}}{T_g}$, $s=\frac{\rm d}{{\rm d}t}=\frac{1}{T_g}\frac{\rm d}{{\rm d}\bar{t}}=\frac{\bar{s}}{T_g}$, we can get the nondimensionalized optimal guidance system, as shown in Fig.4.

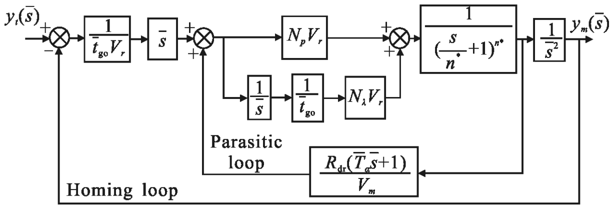


Fig.4 Nondimensionalized optimal guidance system

The closed-loop transfer function of optimal guidance system with parasitic loop can be derived, as shown in Eq.(5).

$$\frac{y_m(\bar{s})}{y_t(\bar{s})}=\frac{\bar{s}N_p+\frac{1}{\bar{t}_{\rm go}}N_\lambda}{\bar{s}^2\bar{t}_{\rm go}\left(\frac{\bar{s}}{n^*}+1\right)^{n^*}-\bar{s}\,\bar{t}_{\rm go}\frac{V_r}{V_m}R_{\rm dr}\left(\bar{s}N_p+\frac{1}{\bar{t}_{\rm go}}N_\lambda\right)(\bar{T}_\alpha\bar{s}+1)+\left(\bar{s}N_p+\frac{1}{\bar{t}_{\rm go}}N_\lambda\right)} \tag{5}$$

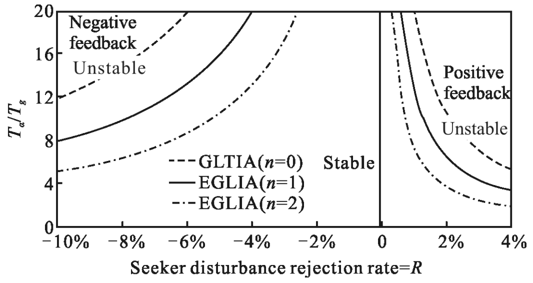
The stability of a guidance system is determined by the closed-loop pole of the system only. It can be seen from the Eq. (5) that the stability of optimal guidance system is affected by $\bar{t}_{\rm go}$, $R_{\rm dr}$, $\bar{T}_\alpha$, N_p and N_λ.

Here the system is approximated as a time-invariant system and the theory of time-invariant control is used to analyze the stability of a guidance system with different $t_{\rm go}$.

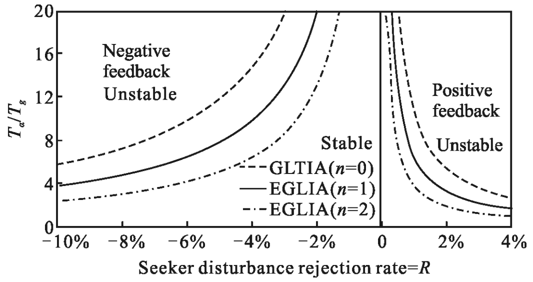
The typical guidance parameters are shown in Tab.1, by using the Routh stability criterion, we can get the stability of a guidance system under different guidance parameters.

Tab.1 Typical guidance parameters

Description	Notation	Values
Missile initial conditions	Y_{m0} V_{m0} θ_0	1 000 m 300 m/s 0°
Target initial conditions	X_{t0} Y_{t0} V_{t0}	0 m 5 000 m 0 m/s
Engagement time	T	20 s
Expected terminal impact angle	λ_F	−90°
Guidance time constant	T_g	0.3 s
Aerodynamic lag	T_α	0.9 s
Autopilot order	n*	1



(a) Time-to-go $t_{\rm go}/T_g$=50



(b) Time-to-go $t_{\rm go}/T_g$=5

Fig.5 Stable domain with seeker disturbance rejection rate when different $\bar{t}_{\rm go}$

As shown in Fig.5, for the guidance system with terminal impact angle constraint which contains parasitic loop of seeker disturbance rejection rate, the magnitude of stable domain of GLTIA is bigger than EGLIA; the stable domain of guidance system is larger when seeker parasitic loop is negative feedback than positive feedback; the stability of guidance system will reduce when the value of disturbance rejection rate $R_{\rm dr}$ or aerodynamic lag T_α gets bigger, guidance time constant T_g or time-to-go $t_{\rm go}$ gets smaller. Meanwhile, the guidance factor n will influence the stability of system, so when we use EGLIA in practice, the guidance factor n should be designed reasonably to ensure the stability of a guidance system.

3 Precision of optimal guidance laws

As the miss distance is a final indicator reflecting the precision of a guidance law, the effects of parasitic loop of strapdown seeker disturbance rejection rate on the guidance law with terminal multiple constraints can be derived from the analysis on the guidance miss distance.

Firstly based on the air-to-ground guided missile, the typical guidance parameters are shown in Tab.1, we can get the trajectory simulation curves with different guidance laws according to Fig.1.

As shown in Fig.6–8, GLTIA can satisfy the terminal position and angle constraints, EGLIA can ensure also the terminal position and angle, meanwhile making the terminal acceleration command close to zero by adjusting the guidance factor n. So EGLIA has more excellent guidance performance.

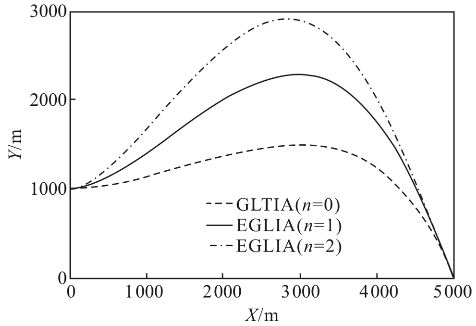


Fig.6 Trajectory curves with different guidance laws

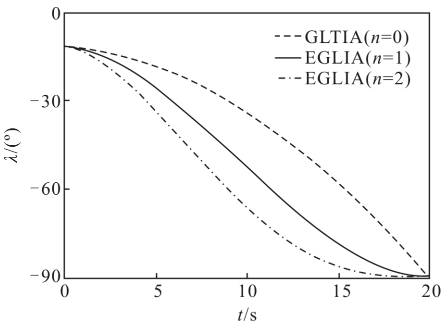


Fig.7 Angle of LOS curves with different guidance laws

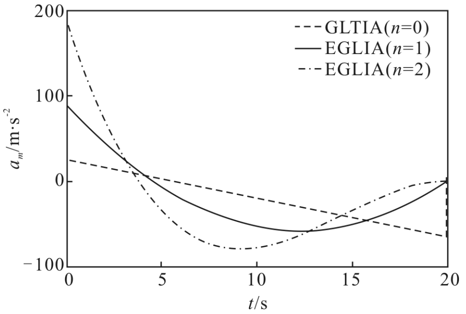


Fig.8 Acceleration curves of missile with different guidance laws

Secondly based on Fig.3, adopting the adjoint method[6], the miss distance of guidance laws caused by the strapdown seeker disturbance rejection rate can be calculated expediently.

The simulation results indicate that the miss distance of two guidance laws will enlarge when the value of disturbance rejection rate get bigger as shown in Fig.9–11, the miss distance will remain small when the value of disturbance rejection rate is less than a constant, the miss distance will increase sharply when value of disturbance rejection rate is more than the constant.

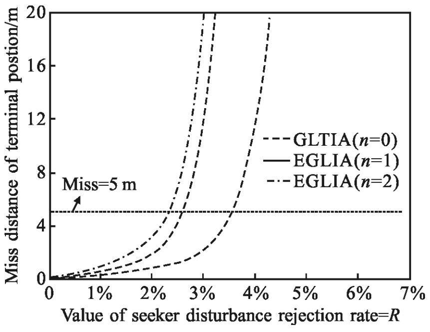


Fig.9 Terminal miss distance of position with the value of strapdown seeker disturbance rejection rate

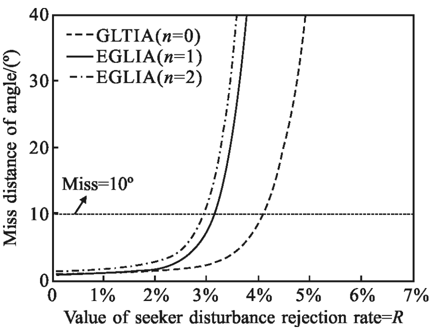


Fig.10 Terminal impact angle error with the value of strapdown seeker disturbance rejection rate

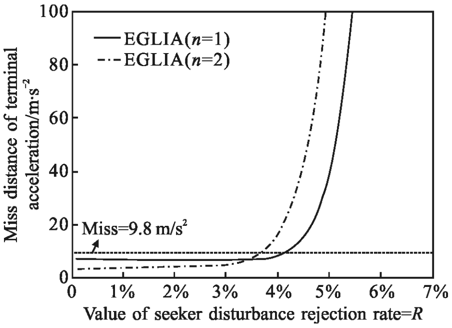


Fig.11 Terminal acceleration command error with the value of strapdown seeker disturbance rejection rate

Under the simulation parameters in this paper, GLTIA can work well when the value of seeker disturbance rejection rate is less than 3.5%, EGLIA is less than 2.5%. The influence of seeker disturbance rejection rate will be more serious with the guidance factor increased.

4 Conclusions

Based on two different optimal guidance laws with terminal impact angle constraint, the paper establishes guidance system model with parasitic loop of strapdown seeker disturbance rejection rate, then studies the effect of strapdown seeker disturbance rejection rate on stability and precision of two guidance laws, the stability of optimal guidance laws is affected by many factors, i.e. the value of disturbance rejection rate, aerodynamic lag T_α, guidance time constant T_g, time-to-go t_{go} and the guidance factor n. Meanwhile, the research provides the sufferable value of strapdown seeker disturbance rejection rate for two different guidance laws, though EGLIA has more excellent guidance performance than GLTIA, but the influence of a parasitic loop of seeker disturbance rejection rate will be more serious. If the optimal guidance law with terminal impact angle constraint would work with advanced performance in engineering, the value of the disturbance rejection rate should be much stricter to reduce the effect of parasitic loop.

References:

[1] Song Tao, Lin Defu, Qi Zaikang. Analysis on the models of seeker disturbance rejection Rate [J]. ***Transactions of Beijing Institute of Technology***, 2013, 33(6): 575-580. (in Chinese)

[2] Wang Jiaxin, Lin Defu, Qi Zaikang. Study on disturbance rejection rate parasitical loop of strapdown phased array radar seeker [J]. ***Transactions of Beijing Institute of Technology***, 2013, 33(11): 1124-1129. (in Chinese)

[3] Du Yunli, Xia Qunli, Qi Zaikang. Research on effect of seeker disturbance rejection rate with phase lag on stability of parasitical loop [J]. ***Acta Armamentar* II**, 2011, 32(1): 28-32. (in Chinese)

[4] Li Fugui, Xia Qunli, Qi Zaikang. Effect of parasitic loop on strap-down seeker and compensated with identification method [J]. ***Systems Engineering and Electronics***, 2013, 35 (8): 1717-1722. (in Chinese)

[5] Kim M, Grider K. Terminal guidance for impact attitude angle constrained flight trajectories [J]. ***IEEE Transactions on Aerospace and Electronic Systems***, 1973, 9(6): 852-859.

[6] Zarchan P. Tactical and Strategic Missile Guidance [M]. 6th ed. Virginia: AIAA Inc, 2012.

[7] Ryoo C K, Cho H, Tahk M J. Optimal guidance laws with terminal impact angle constraint [J]. ***Journal of Guidance, Control, and Dynamics***, 2005, 28(4): 724-732.

[8] Ryoo C K, Cho H, Tahk M J. Time-to-go weighted optimal guidance with impact angle constraints [J]. ***IEEE Trans on Control Systems Technology***, 2006, 14(3): 483-492.

[9] Ohlmeyer E J, Phillips C A. Generalized vector explicit guidance[J]. ***Journal of Guidance, Control, and Dynamics***, 2006, 29(2): 261-268.

[10] Chang-Kyung Ryoo, Hangju Cho. Time-to-Go weighted optimal guidance with impact angle constraints [J]. ***IEEE Transactions on Control Systems Technology***, 2006, 14(3): 483-492.

[11] Hangju Cho, Chang-Kyung Ryoo. Optimal impact angle control guidance law based on linearization about collision triangle [J]. ***Journal of Guidance, Control and Dynamics***, 2014, 37(4): 958-964.

[12] Wen Qiuqiu, Li Ran. Disturbance rejection rate and parasitical loop stability for strapdown imaging seeker [J]. ***Infrared and Laser Engineering***, 2014, 43(1): 260-265. (in Chinese)

[13] Wang Jiaxin, Lin Defu, Qi Zaikang. Effect of strapdown seeker disturbance rejection rate on stability of PNG system [J]. ***Infrared and Laser Engineering***, 2013, 42(10): 2608-2613. (in Chinese)

[14] Xu Ping, Wang Wei, Lin Defu. Effect of seeker isolation on guidance and control of terminal guided projectile [J]. ***Journal of Ballistics***, 2012, 24(1): 17-22.