International Journal of Control, Automation and Systems 17(6) (2019) 1369-1377
http://dx.doi.org/10.1007/s12555-017-0731-9
ISSN:1598-6446 eISSN:2005-4092
http://www.springer.com/12555

Three-dimensional Adaptive Sliding Mode Guidance Law for Missile with Autopilot Lag and Actuator Fault

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Abstract: This paper investigates guidance scheme for missile with actuator failure and dynamics of autopilot. Firstly, considering first-order dynamics of autopilot, the guidance model with actuator failure is established. Secondly, an adaptive sliding mode fault-tolerant guidance law is designed on the basis of passive fault-tolerant technique and a novel nonsingular fast terminal sliding mode (NFTSM) manifold. Then, the adaptive algorithm with the feature of low-pass filter is proposed to ensure that adaptive parameters are bounded when the sliding mode is non-ideal. Finally, Lyapunov stability theory is adopted to prove that the states of closed-loop system are practical finite-time stability. Simulation results demonstrate the effectiveness and robustness of the proposed guidance strategy under the certain actuator failure.

Keywords: Actuator fault, adaptive control, autopilot lag, guidance law, sliding mode control.

1. INTRODUCTION

The higher guidance accuracy is always pursued in complex air battle circumstance. Hence, a three-dimensional system model should be developed with explicit consideration of the relative motion between missile and targets in order to facilitate the description of the truth guidance model for a practice guidance systems [1]. In addition, in guidance systems, the dynamics of missile autopilot is a major factor that effects on guidance accuracy, especially for the maneuvering targets. It is difficult that the guidance accuracy can be guaranteed if the dynamics of autopilot are ignored. Due to the aging of equipment and the circumstance factors, the actuators and sensors have usually high failure rates in guidance system [2]. Actuator failures always bring adverse effects to the performance of missile terminal guidance system, especially for interception. Therefore, the dynamics of autopilot and actuator failures should be considered in the design of guidance law, which make a significance role in practice.

Guidance law is usually classified as classical guidance law and modern guidance law. The former was based on the geometrical relationship for missile and targets. Such as parallel approaching method, pursuit guidance and proportional navigation [3–5]. However, there exist the complex circumstance of air battle, maneuvering and intelligent targets. Due to these factors, the above maintained control methods failed to reach high guidance accuracy. Therefore, the modern guidance law is widely adopted [6,7]. The optimal guidance law [8–10], differential game guidance law [11], the guidance strategy based on robust control theory [12].

In practical applications, due to the outstanding merit of robustness for parameter uncertainties and external disturbances, sliding mode control techniques were widely applied to the design of guidance law [13–16]. In [17], a novel sliding mode guidance law was designed for maneuvering targets, which can guarantee that the system states converge in finite time. In [18], the finite time sliding mode guidance law was proposed for the maneuver of targets using the disturbance observer technique.

The autopilot lag of missile usually can lead to adverse influence on the miss distance, especially in the presence of target maneuvers evasive. In [19], a terminal sliding mode guidance law was designed for maneuvering or non-maneuvering targets considering impact angle constraints and the dynamics of missile autopilot. In [20], a new composite guidance law was proposed to intercept manoeuvring targets without line-of-sight angular rate information in the presence of autopilot lag. Based on fast nonsingular terminal sliding mode control theory and disturbance observer, a robust guidance law with terminal angle constraint in the presence of autopilot lag was proposed [21]. In [22], a composite sliding mode guidance law was

Manuscript received November 22, 2017; revised April 12, 2018 and October 10, 2018; accepted January 13, 2019. Recommended by Associate Editor Chang Kyung Ryoo under the direction of Editor Duk-Sun Shim. This work was supported by Natural Science Foundation of Heilongjiang Province of China (Grant No. F2018024) and Fundamental Research Fund for Heilongjiang Provincial Universities of China (Grant No. HDJCCX-201622).

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designed in the case of constrained impact angle and a first-order-lag autopilot.

Another problem encountered in practice for missile system is actuator fault. Both the problems of autopilot lag and actuator failure can cause guidance system performance deterioration, and lead to miss the target or even catastrophic accidents. Therefore, it is necessary to take autopilot lag and actuator failure into consideration in the design of guidance law. In [23], the actuator failure was viewed as the lumped system uncertainty and the extended state observers were designed. Three-dimensional guidance law in [23] ensures only that the closed-loop system was uniformly ultimately bounded. In [24], a fault tolerant guidance law was proposed based on backstepping and an adaptive law designed to estimate the unknown effectiveness factor. In [25], a control law using combination of adaptive backstepping and sliding mode approaches was designed to achieve interception in the presence of bounded uncertainties and actuator fault. In [26], three-dimensional fault-tolerant control guidance law was proposed for interception of maneuvering targets in the presence of actuator failures.

In this study, the problem of missile interception is a three-dimensional interception geometry. The adaptive fault-tolerant guidance law is proposed to further solve the terminal guidance problem of dynamic lag of autopilot on the base of passive fault-tolerant technique. Compared with other methods, the contributions of this paper are as follows:

1) Considering the dynamics of autopilot and actuator faults, the information of actuator faults is estimated online by the proposed adaptive algorithm in the absence of the information of the actuator failures.

2) Compared with [22], the finite-time guidance law is designed proposed such that this point is of more theoretical and practical significance in this paper.

3) Compared with [14, 15], a new adaptive algorithm is proposed to ensure that the adaptive parameters are bounded even when the sliding mode is non-ideal.

2. FORMULATION OF GUIDANCE MODEL

It is assumed that the missile and the target are point masses, the three-dimensional interception geometry is shown in Fig. 1. And T denotes the target, M denotes the missile, M_{xyz} is an inertial reference frame, $M_{x_1y_1z_1}$ is a line-of-sight (LOS) frame, R is the relative distance between the missile and the target, q_ε and q_β are the elevation and azimuth LOS angle, respectively.

The complete dynamic equations of the three-dimensional relative motion dynamics of the missile and the target on the base of the principles of the kinematics [15] are

$$\ddot{R} - R\dot{q}_\varepsilon^2 - R\dot{q}_\beta^2\cos^2 q_\varepsilon = a_{TR} - a_{MR}, \tag{1}$$

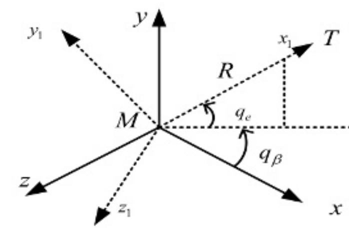

Fig. 1. Three-dimensional interception geometry.

$$R\ddot{q}_\varepsilon + 2\dot{R}\dot{q}_\varepsilon + R\dot{q}_\beta^2 \sin q_\varepsilon \cos q_\varepsilon = a_{T\varepsilon} - aM\varepsilon, \tag{2}$$

$$\begin{aligned} &- R\ddot{q}_\beta \cos q_\varepsilon - 2\dot{R}\dot{q}\cos q_\varepsilon + 2R\dot{q}_\varepsilon\dot{q}_\beta \sin q_\varepsilon \\ &= a_{T\beta} - a_{M\beta}, \end{aligned} \tag{3}$$

where $[a_{MR}, a_{M\varepsilon}, a_{M\beta}]^T$ and $[a_{TR}, a_{T\varepsilon}, a_{T\beta}]^T$ are the acceleration vectors of the missile and target in the LOS frame, respectively.

Practically, for aerodynamically controlled missile, the missile acceleration a_{MR} is not available usually. And only the acceleration normal to the LOS direction, $a_{M\varepsilon}$ and $a_{M\beta}$, can be adjusted during the terminal guidance phase. The purpose of designing the guidance law is to make sure that the elevation and azimuth LOS angular rates $\dot{q}_\varepsilon$ and $\dot{q}_\beta$, converge to zero or a small neighborhood of zero. The relative speed $\dot{R}$ is not controlled, but the engagement is guaranteed as long as the relative velocity and relative range satisfy the following condition [15]:

$$\dot{R} < 0, \quad 0 < R < R(0). \tag{4}$$

Hence, only (2) and (3) are used in guidance law design. From (2) and (3), it can be obtained that there exist serious cross couplings between them.

In guidance processes, the autopilot dynamics of the missile are assumed to be approximately described by the following first-order term:

$$\dot{a}_{M\varepsilon} = -a_{M\varepsilon}/\tau + u_1/\tau, \quad \dot{a}_{M\beta} = -a_{M\beta}/\tau + u_2/\tau, \tag{5}$$

where τ is the time constant of the autopilont, u_1 and u_2 are the acceleration command which are to be obtained by the guidance law design.

From (2) and (3), the elevation and azimuth LOS angular accelerations have the following forms:

$$\begin{aligned} \ddot{q}_\varepsilon &= -2\dot{R}\dot{q}_\varepsilon/R_\varepsilon - \dot{q}^2 \sin q_\varepsilon \cos q_{\varepsilon\beta} + (a_{T\varepsilon} - a_{M\varepsilon})/R, \\ \ddot{q}_\beta &= -2\dot{R}\dot{q}_\beta/R + 2\dot{q}_\beta\dot{q}_\varepsilon \tan q_\varepsilon - (a_{T\varepsilon} - a_{M\varepsilon})/R\cos q_\varepsilon. \end{aligned} \tag{6}$$

Then, we get the following expression for $a_{T\varepsilon}$, $a_{T\beta}$:

$$\begin{aligned} a_{T\varepsilon}/R &= \ddot{q}_\varepsilon + 2\dot{R}\dot{q}_\varepsilon/R + \dot{q}_\beta^2 \sin q_\varepsilon \cos q_\varepsilon + a_{M\varepsilon}/R, \\ a_{T\beta}/(R\cos q_\varepsilon) &= -\ddot{q}_\beta - 2\dot{R}\dot{q}_\beta/R + 2\dot{q}_\varepsilon\dot{q}_\beta \tan q_\varepsilon \\ &\quad + a_{M\beta}/(R\cos q_\varepsilon). \end{aligned} \tag{7}$$

Differentiating (6) with respect to time, the dynamic equations of the missile and the target become

$$\begin{cases} \dot{\boldsymbol{x}}_1 = \boldsymbol{x}_2, \\ \dot{\boldsymbol{x}}_2 = \boldsymbol{A} + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{d}, \end{cases} \tag{8}$$

where the variables $\boldsymbol{x}_1 = [\dot{q}_\varepsilon,\ \dot{q}\beta]^T$, $\boldsymbol{x}_2 = [\ddot{q}\varepsilon,\ \ddot{q}_\beta]^T$, $\boldsymbol{u}$ and $\boldsymbol{d}$ denote the control input and disturbance, respectively, $\boldsymbol{u} = [u_1\ u_2]^T$, $\boldsymbol{A} = [A_1\ A_2]^T$,

$$\begin{aligned} A_1 &= (-3\dot{R}\ddot{q}_\varepsilon + a_{M\varepsilon}/\tau - \dot{q}_beta^2 \sin 2q_\varepsilon \dot{R}/2)/R \\ &\quad - \dot{q}_\varepsilon \dot{q}_\beta^2 \cos 2q_\varepsilon - \dot{q}_\beta \ddot{q}\beta \sin 2q_\varepsilon - 2\ddot{R}\dot{q}_\varepsilon/R, \\ A_2 &= -3\dot{R}\ddot{q}_\beta/R + 3\dot{q}_\varepsilon \ddot{q}_\beta \tan q_\varepsilon + 2\dot{q}_\varepsilon^2 \dot{q}\beta + 2\ddot{q}\varepsilon\dot{q}\beta \tan q_\varepsilon \\ &\quad + (4\dot{R}\dot{q}_\varepsilon \dot{q}_\beta \tan q_\varepsilon - 2\ddot{R}\dot{q}_\beta)/R - a_{M\beta}/R\tau \cos q_\varepsilon, \\ \boldsymbol{B} &= diag(-1/(R\tau), 1/(R\tau \cos q_\varepsilon)), \\ \boldsymbol{d} &= [\ \dot{a}_{T\varepsilon}/R \quad -\dot{a}_{T\beta}/(R\cos q_\varepsilon)\ ]^T. \end{aligned}$$

Considering the actuator faults, control law is given by

$$\boldsymbol{u} = (I - E)\boldsymbol{u}^{\boldsymbol{f}}, \tag{9}$$

where $\boldsymbol{u}^{\boldsymbol{f}}$ is nominal control input, $\boldsymbol{u}$ is actural control input, I is idential matrix, $\boldsymbol{E} = diag(E_1, E_2)$ denotes the factor of actuator faults. $E_i = 0$ $(i = 1,\ 2)$ denotes that actuator is under a sound condition, $E_i = 1$ $(i = 1,\ 2)$ denotes that actuator get out of control. $0 < E_i < 1$ $(i = 1,\ 2)$ denotes that actuator partly get out of control. In this study, $0 \le E_i < 1$ $(i = 1,\ 2)$ is only considered.

Applying (10), system (9) can be rewritten as

$$\begin{cases} \dot{\boldsymbol{x}} = \boldsymbol{x}_2, \\ \dot{\boldsymbol{x}}_2 = \boldsymbol{A} + \boldsymbol{B}(I - E)\boldsymbol{u}^{\boldsymbol{f}} + \boldsymbol{d}. \end{cases} \tag{10}$$

3. PREPARATION KNOLEDGE AND ASSUMPTIONS

In order to facilitate the design of guidance law, some assumptions and Lemma are given as follows:

Assumption 1: The lumped disturbance is assumed to be bounded and satisfy $\|\boldsymbol{d}\|_\infty \le d_M$, where d_M is an unknown positive constant, and $\|\boldsymbol{d}\|_\infty$ is infinity-norm of $\boldsymbol{d}$.

Remark 1: Owing to physical limits, the time derivative of target acceleration is always bounded. Moreover, the singular problem, i.e., $q_\varepsilon = \pm\frac{\pi}{2}$, can be avoided by properly choosing the inertial reference coordinate system during terminal guidance phase. And, technically, owing to a certain size of the target, the interception by impact happens when $R \ne \boldsymbol{0}$ [26]. So, from the definition of lumped disturbance $\boldsymbol{d}$, one can obtain that Assumption 1 is reasonable.

Notation: For a vector $\boldsymbol{y} = [y_1,\ ...,\ y_n]^T$, the notation y^r with $r > 0$ represents the vector $[y_1^r,\ ...,\ y_n^r]^T$ and the notation $diag(y)$ represents the matrix $diag(y_1,\ ...,\ y_n)$. I_n represents the $n \times n$ identity matrix. The notation $\text{sig}(\boldsymbol{y})$ represents the vector $[\text{sig}^r(y_1),\ ...,\ \text{sig}^r(y_n)]^T$, where $\text{sig}^r(y_i) = |y_i|^r \text{sign}(y_i)$, and $\text{sign}(\cdot)$ denotes the signum function.

Lemma 1 [26]**:** Consider the system

$$\dot{x} = f(x(t)),\ \ x(0) = 0,\ \ f(0) = 0,\ \ x \in R.$$

Suppose that there exists a Lyapunov function $V(x)$, scalars $\zeta \in (0,1)$, $\alpha > 0$, and $0 < \sigma < \infty$, such that

$$\dot{V}(x) \le -\alpha V^\zeta(x) + \sigma. \tag{11}$$

Then, we define the trajectory of this system as PFTS.

Lemma 2 [26]**:** Suppose $b_1, b_2, ..., b_n$ are positive numbers and $0 < q < 2$. Then, the following inequality holds:

$$(b_1^2 + b_2^2 + \cdots + b_n^2)^q \le (b_1^q + b_2^q + \cdots + b_n^q)^2. \tag{12}$$

4. DESIGN OF GUIDANCE LAW

In order to make the system states and approach to zero fast along the sliding mode surface in finite time, a NFTSM manifold vector [27] based on the guidance system states can be described as follows:

$$\boldsymbol{s} = \boldsymbol{x}_2 + \boldsymbol{f}(\boldsymbol{x}_1) + \beta_1 \boldsymbol{x}_1 + \beta_2 e^{-\lambda t} \left(\boldsymbol{x}_1^T \boldsymbol{x}_1\right)^{-\alpha} \boldsymbol{x}_1, \tag{13}$$

where $\boldsymbol{s} = [a_1,\ s_2]^T$, β_1, β_2, λ are positive constants, respectively, $0 < \alpha < 1$, $\boldsymbol{f}(\boldsymbol{x}_1)$ is defined as

$$\begin{aligned} \boldsymbol{f}(\boldsymbol{x}_1) &= [f(x_{11}), f(x_{12}]^T, \\ f(x_{1i}) &= \begin{cases} r_{1i}x_{1i} + r_1 \text{sign}(x_{1i}) x_{1i}^2, & |x_{1i}| \le \eta, \\ \text{sig}^{\gamma_i}(x_{1i}), & \text{otherwise}, \end{cases} \end{aligned} \tag{14}$$

where $0 < \gamma_i < 1$, $r_{1i} = (2 - \gamma_i)\eta^{\gamma_i - 1}$, $r_{2i} = (\gamma_i - 1)\eta^{\gamma_i - 2}$, $i = 1,\ 2$, η are positive constant.

Differentiating (13) with respect to time and combing (10), it follows that

$$\begin{aligned} \dot{\boldsymbol{s}} &= \dot{\boldsymbol{x}}_2 + \dot{\boldsymbol{f}}(\boldsymbol{x}_1) + \beta_1 \dot{\boldsymbol{x}}_1 + \beta_2 \boldsymbol{C} \\ &= \boldsymbol{A} + \boldsymbol{B}(I - \boldsymbol{E})\boldsymbol{u}^{\boldsymbol{f}} + \boldsymbol{d} + \dot{\boldsymbol{f}}(\boldsymbol{x}_1) + \beta_1 \dot{\boldsymbol{x}}_1 + \beta_2 \boldsymbol{C}, \end{aligned} \tag{15}$$

where

$$\begin{aligned} C = \Big[&(-\lambda) e^{-\lambda t} \left(\boldsymbol{x}_1^T \boldsymbol{x}_1\right)^{-\alpha} \boldsymbol{x}_1 + e^{-\lambda t} \left(\boldsymbol{x}_1^T \boldsymbol{x}_1\right)^{-\alpha} \boldsymbol{x}_2 \\ &+ e^{-\lambda t} (-2\alpha) \left(\boldsymbol{x}_1^T \boldsymbol{x}_1\right)^{-\alpha - 1} \left(\boldsymbol{x}_1^T \boldsymbol{x}_2\right) \boldsymbol{x}_1 \Big]. \end{aligned} \tag{16}$$

Due to external disturbances, it is difficult for the guidance system to get the exact knowledge of the factor of actuator fault $\boldsymbol{E}$. The online estimate technique via adaptive parameters is adopted to solve this problem.

THe constant μ is defined as

$$\mu = \lambda_{\max}(\boldsymbol{E}) = \|\boldsymbol{E}\|_\infty. \tag{17}$$

Based on the NFTSM and the adaptive control technology, a sliding mode fault-tolerant guidance law and an adaptive laws are given as follows:

$$\boldsymbol{u}^{\boldsymbol{f}} = \boldsymbol{u} - \boldsymbol{u}_{com}, \tag{18}$$

$$\boldsymbol{u} = \boldsymbol{B}^{-1}\boldsymbol{u}_0/(1-\mu), \tag{19}$$

$$\boldsymbol{u}_0 = -\boldsymbol{A} - \dot{\boldsymbol{f}}(\boldsymbol{x}_1) - \beta_1\boldsymbol{x}_2 - \beta_2\boldsymbol{C} - \hat{d}_M \tanh(\boldsymbol{s}/\eta) - k_1\boldsymbol{s} - k_2\text{sig}^{\gamma_3}(\boldsymbol{s}), \tag{20}$$

$$\boldsymbol{u}_{com} = \rho\|\boldsymbol{u}_0\|\boldsymbol{B}^{-1}\boldsymbol{s}, \tag{21}$$

$$\dot{\rho} = p_1(\|\boldsymbol{u}_0\|\|\boldsymbol{s}\| - h_1\rho), \tag{22}$$

$$\dot{\hat{d}}_M = p_2\left(|\boldsymbol{s}|^T \tanh(\boldsymbol{s}/\eta) - h_2\hat{d}_M\right), \tag{23}$$

where k_1, k_2, p_1, h_1, p_2, h_2, $0 < \gamma_3 < 1$, ρ are adaptive parameters, and $\hat{d}_M$ is the estimators for d_M. Here, the knowledge of the upper bound of the lumped disturbance is not needed.

Theorem 1: Considering system (10) with Assumption 1, and the NFTSM is chosen as (13). While the state of closed-loop system is regulated under the guidance law (18) and the adaptive laws (22)-(23), the following conclusion can be made:

1) The sliding mode manifold s_i converges in finite time to a region around $s_i = 0$ as

$$|s_i| \le \sqrt{2}(D/\varepsilon_1)^{1/(2\beta)}, \tag{24}$$

where s_i is the ith component of vector $\boldsymbol{s}$,

$$\begin{aligned}
&\delta_i > 1/2,\ \ o < \gamma_4 < 1,\ \ 0 < \gamma_5 < 1,\ \ i = 1,2,\\
&\beta = (\gamma+1)/2,\ \ \gamma = \min\{\gamma_3,\gamma_4,\gamma_5\},\\
&D = h_2\delta_1 d_M^2/2 + 0.2785 d_M\eta + h_1(1-\mu)\delta_2/2\rho^2 + 2,\\
&\varepsilon = \min\left\{2^{\frac{\gamma_3+1}{2}}k_2, \left(\frac{h_2 p_1(2\delta_2-1)}{\delta_2}\right)^{\frac{\gamma_4+1}{2}}, \left(\frac{p_2 h_1(2\delta_1-1)}{\delta_1}\right)^{\frac{\gamma_4+1}{2}}\right\}.
\end{aligned}$$

2) The states of the system will converge to the following regions respectively in finite time

$$|x_{1i}| \le \max\left\{\eta, \min\left\{|\psi_1|/\beta_1, (|\psi_i|)^{1/\gamma_i}\right\}\right\}, \tag{25}$$

$$|x_{2i}| \le \Delta_i + \beta\eta + \eta^{\gamma_i} + \beta_2\eta^{3-\alpha}, \tag{26}$$

where x_{1i} and x_{2i} are the ith component of vector $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$, $i = 1, 2$.

Proof: Choose the following Lyapunov function

$$V_1 = \boldsymbol{s}^T\boldsymbol{s}/2 + (1-\mu)\rho^2/2p_1 + \tilde{d}_M^2/2p_2, \tag{27}$$

where $\tilde{d}_M = d_m - \hat{d}_M$, $0 < \mu < 1$. The time derivative of V_1 along system (11) can be computed by

$$\dot{V}_1 = \boldsymbol{s}^T\dot{\boldsymbol{s}} - \tilde{d}_M\dot{\hat{d}}_M/2p_2 + (1-\mu)\rho\dot{\rho}/p_1. \tag{28}$$

Substituting (15) and (18) into (28),The time derivative of V_1 becomes

$$\begin{aligned}
\dot{V}_1 = &-\boldsymbol{s}^T(k_1\boldsymbol{s} + k_2\text{sig}^{\gamma_3}(\boldsymbol{s}) + \boldsymbol{s}^T(\boldsymbol{d} - \hat{d}_M\tanh(\boldsymbol{s}/\eta))\\
&-\boldsymbol{s}^T\boldsymbol{BEu^f} - \mu\boldsymbol{s}^T\boldsymbol{u}_0/(1-\mu) - \tilde{d}_M\dot{\hat{d}}_M/p_2\\
&-\rho\|\boldsymbol{u}_0\|\|\boldsymbol{s}\| + \rho\dot{\rho}(1-\mu)/p_1.
\end{aligned} \tag{29}$$

Substituting (22) and (23) into (29) and applying the following inequations:

$$\begin{aligned}
&\hat{d}_M|\boldsymbol{s}|^T\tanh(\boldsymbol{s}/\eta) \le \hat{d}_M\boldsymbol{s}^T\tanh(\boldsymbol{s}/\eta),\\
&\boldsymbol{s}^T\boldsymbol{d} \le d_M\|\boldsymbol{s}\|,
\end{aligned}$$

it follows that

$$\begin{aligned}
\dot{V}_1 = &-\boldsymbol{s}^T(k_1\boldsymbol{s} + k_2\text{sig}^{\gamma_3}(\boldsymbol{s})) - \rho\|\boldsymbol{u}_0\|\|\boldsymbol{s}\| - \boldsymbol{s}^T\boldsymbol{BEu^f}\\
&+ d_M\left(\|\boldsymbol{s}\| - |\boldsymbol{s}|^T\tanh(\boldsymbol{s}/\eta)\right) + h_2\tilde{d}_M\hat{d}_M\\
&+ \mu\boldsymbol{s}^T\boldsymbol{u}_0/(1-\mu) - (1-\mu)\rho(\|\boldsymbol{u}_0\|\|\boldsymbol{s}\| - h_1\rho).
\end{aligned} \tag{30}$$

Note that

$$d_M(|\boldsymbol{s}| - |\boldsymbol{s}|^T\tanh(\boldsymbol{s}/\eta)) \le 0.2785 d_M\eta. \tag{31}$$

Then, using (31) yeilds

$$\begin{aligned}
\dot{V}_1 \le &-\boldsymbol{s}^T\left(k_1\boldsymbol{s} + k_2\text{sig}^{\gamma_3}(\boldsymbol{s})\right) + h_2\tilde{d}_M\hat{d}_M\\
&-\rho\|\boldsymbol{u}_0\|\|\boldsymbol{s}\| - \boldsymbol{s}^T\boldsymbol{BEu^f} + \mu/(1-\mu)\boldsymbol{s}^T\boldsymbol{u}_0\\
&-(1-\mu)\rho(\|\boldsymbol{u}_0\|\|\boldsymbol{s}\| - h_1\rho) + 0.2785 d_M\eta.
\end{aligned} \tag{32}$$

According to (18), the following result will be obtained

$$-\boldsymbol{s}^T\boldsymbol{BEu^f} = -\boldsymbol{s}^T\boldsymbol{BEB}^{-1}(\boldsymbol{u}_0/(1-\mu) - \rho\|\boldsymbol{u}_0\|\boldsymbol{s}). \tag{33}$$

If

$$\boldsymbol{s}^T\boldsymbol{BB}^{-1}(1/(1-\mu)\boldsymbol{u}_0 - \rho\|\boldsymbol{u}_0\|\boldsymbol{s}) \ge 0, \tag{34}$$

applying (34), equation (33) can be written as

$$\begin{aligned}
-\boldsymbol{s}^T\boldsymbol{BEu^f} &\le -\boldsymbol{s}^T\boldsymbol{BB}^{-1}(\boldsymbol{u}_0/(1-\mu) - \rho\|\boldsymbol{u}_0\|\boldsymbol{s})\|\boldsymbol{E}\|_{\min}\\
&\le -\boldsymbol{s}^T\boldsymbol{u}_0/(1-\mu) + \rho\|\boldsymbol{u}_0\|\|\boldsymbol{s}\|\|\boldsymbol{E}\|_\infty\\
&= -\mu\boldsymbol{s}^T\boldsymbol{u}_0/(1-\mu) + \mu\rho\|\boldsymbol{u}_0\|\|\boldsymbol{s}\|.
\end{aligned} \tag{35}$$

If

$$\boldsymbol{s}^T\boldsymbol{BB}^{-1}(\boldsymbol{u}_0/(1-\mu) - \rho\|\boldsymbol{u}_0\|\boldsymbol{s}) < 0, \tag{36}$$

applying (36), equation (33) can also be written as

$$\begin{aligned}
-\boldsymbol{s}^T\boldsymbol{BEu^f} &\le -\boldsymbol{s}^T\boldsymbol{BB}^{-1}(\boldsymbol{u}_0/(1-\mu) - \rho\|\boldsymbol{u}_0\|\boldsymbol{s})\|\boldsymbol{E}\|_\infty\\
&= -\mu\boldsymbol{s}^T\boldsymbol{u}_0/(1-\mu) + \mu\rho\|\boldsymbol{u}_0\|\|\boldsymbol{s}\|.
\end{aligned} \tag{37}$$

Considering (35) and (37), equation (33) can be finally written as

$$-\boldsymbol{s}^T\boldsymbol{BEu^f} \le -\mu\boldsymbol{s}^T\boldsymbol{u}_0/(1-\mu) + \mu\rho\|\boldsymbol{u}_0\|\|\boldsymbol{s}\|. \tag{38}$$

Substituting (38) into (32), yields

$$\begin{aligned}
\dot{V}_1 \le &-\boldsymbol{s}^T\left(k_1\boldsymbol{s} + k_2\text{sig}^{\gamma_3}(\boldsymbol{s})\right) + h_2\tilde{d}_M\hat{d}_M\\
&+ (1-\mu)h_1\rho^2 + 0.2785 d_M\eta.
\end{aligned} \tag{39}$$

For positive constant δ_1 satisfying $\delta_1 > 0.5$, inequality can be derived as:

$$\begin{aligned} h_2\tilde{d}_M\hat{d}_M =& h_2(d_M\tilde{d}_M - \tilde{d}_M^2) \\ \leq& h_2(-\tilde{d}_M^2 + \tilde{d}_M^2/2\delta_1) \\ =& -h_2(2\delta_1 - 1)\tilde{d}_M^2/2\delta_1 + h_2 d_M^2\delta_1/2. \end{aligned} \tag{40}$$

The following inequality holds:

$$\left(h_2(2\delta_1 - 1)\tilde{d}_M^2/2\delta_1\right)^{\frac{\gamma_4+1}{2}} - h_2(2\delta_1 - 1)\tilde{d}_M^2/2\delta_1 \leq 1. \tag{41}$$

In the same ways, for positive constant δ_2 satisfying $\delta_2 > 1/2$, the following inequality also holds:

$$\left(\frac{(1-\mu)h_1(2\delta_2-1)}{2\delta_2}\rho^2\right)^{\frac{\gamma_5+1}{2}} - \frac{(1-\mu)h_1(2\delta_2-1)}{2\delta_2}\rho^2 \leq 1. \tag{42}$$

Using the above inequalities (40)-(42) and Lemma 2, equation (39) can be further simplified as

$$\dot{V}_1 \leq -\varepsilon_1 V_1^\beta + D. \tag{43}$$

It is noted that D is bounded. Hence, the state of guidance system is PFTS. Further more, the following inequality can be obtained from (43):

$$\dot{V}_1 \leq -\left(\varepsilon_1 - D/V_1^\beta\right)V_1^\beta. \tag{44}$$

From (44), it can be seen that V_1 converges to compact region $V_1 \leq (D/\varepsilon_1)^{1/\beta}$. According to (27), it can be obtained that $0.5\boldsymbol{s}^T\boldsymbol{s}$ converges to compact region $0.5\boldsymbol{s}^T\boldsymbol{s} \leq (D/\varepsilon_1)^{1/\beta}$. The convergence domain of s is $|s_i| \leq \Delta_i$, $\Delta_i = \sqrt{2}(D/\varepsilon_1)^{1/(2\beta)}$.

According to (13)

$$\begin{aligned} & x_{2i} + f(x_{1i}) + \beta_1 x_{1i} + \beta_2 e^{-\lambda t}(x_{1i}^T x_{1i})^{-\alpha} x_{1i} = s_i, \\ & |s_i| \leq \Delta_i. \end{aligned} \tag{45}$$

The convergence of x_{1i} and x_{2i} are analyzed in the following part:

Case I: When $|x_{1i}| > \eta$,

$$x_{2i} + \beta_1 x_{1i} + \beta_2 e^{-\lambda t}(x_{1i})^{2-\alpha} x_{1i} + f(x_{1i}) = \psi_i, \tag{46}$$

where $|\psi_i| \leq \Delta_i$. In order to prove the convergence of x_{1i}, choose the Lyapunov function as

$$V_2 = x_{1i}^2/2. \tag{47}$$

Compute the first order derivative of V_2

$$\begin{aligned} \dot{V}_2 \leq& -x_{1i}\left(\beta_1 x_{1i} + \beta_2 e^{-\lambda t}(x_{1i})^{2-\alpha} x_{1i} + f(x_{1i})\right) \\ &+ |x_{1i}||\psi_i| \\ \leq& -\beta_1(x_{1i})^2 - ((x_{1i})^2)^{\frac{\gamma_i+1}{2}} + |x_{1i}||\psi_i|. \end{aligned} \tag{48}$$

To further deal with $|x_{1i}||\psi_i|$, $\dot{V}_2$ can be rewritten as two forms

$$\dot{V}_2 \leq -(\beta_1 - |\psi_i|/x_{1i})(x_{1i})^2 - \left((x_{1i})^2\right)^{\frac{\gamma_i+1}{2}}, \tag{49}$$

$$\dot{V}_2 \leq -\beta_1(x_{1i})^2 - \left(1 - |\psi_i|/(x_{1i})^\gamma\right)\left((x_{1i})^2\right)^{\frac{\gamma_i+1}{2}}. \tag{50}$$

When $\beta_1 - |\psi_i|/x_{1i} > 0$, $x_{1i}\sigma_1^i$ can converge to region the $|x_{1i}| \leq \psi_i/\beta_1$ in finite time; when $1 - |\psi_i|/x_{1i}^{\gamma_i} > 0$, x_{1i} can converge to region the $|x_{1i}| \leq (|\psi_i|)^{1/\gamma_i}$ in finite time. Thus, x_{1i} can converge to region the $|x_{1i}| \leq \Delta x_{1i}$ in finite time

$$|x_{1i}| \leq \Delta x_{1i} = \max\left\{\eta, \min\left\{|\psi_1|/\beta_1, (|\psi_i|)^{1/\gamma_i}\right\}\right\}. \tag{51}$$

Case II: When $|x_{1i}| \leq \eta$, which means x_{1i} already converges to region the $|x_{1i}| \leq \eta$, applying (45),

$$x_{2i} + \beta_1 x_{1i} + \beta_2 e^{-\lambda t}(x_{1i})^{2-\alpha} x_{1i} + f(x_{1i}) = \psi_i. \tag{52}$$

Furthermore, equation (52), x_{2i} can converge to the region $|x_{2i}| \leq \Delta x_{2i}$ in finite time

$$\begin{aligned} |x_{2i}| \leq& \left|\beta_1 x_{1i} + f(x_{1i}) + \beta_2 e^{-\lambda t}(x_{1i})^{2-\alpha} x_{1i} - \psi_i\right| \\ \leq& \Delta_i + \beta_1\eta + \eta^{\gamma_i} + \beta_2\eta^{3-\alpha}. \end{aligned} \tag{53}$$

The proof of Theorem 1 is completed. □

5. SIMULATION RESULTS

The validity of the proposed guidance law (18)-(23) is tested using numerical simulations. The dynamic equations [22] of the missiles with varying speed are given by $\dot{x}_M = V_M\cos\theta_M\cos\varphi$, $\dot{y}_M = V_M\sin\theta_M$, $\dot{z}_M = -V_M\cos\theta_M\sin\varphi_M$, $\dot{V}_M = (T-D)/m - g\sin\theta_M$, $\dot{\theta}_M = (a_y - g\cos\theta_M)/V_M$, $\dot{\varphi}_M = -a_z/(V_M\cos\theta_M)$, where x_M, y_M and z_M are the position of the missile; m, V_M, θ_M and φ_M represent the mass, the velocity, the flight path angle and the heading angle of the missile, respectively; T and D denote the thrust and the drag of the missile, respectively; a_y and a_z are the horizontal and vertical components of the missile normal acceleration, and g denotes the acceleration due to gravity. For the guidance problem, the zero-lift drag coefficient and the induced drag coefficient are given as [22].

The initial position of the missile parameters are $x_M(0) = 0$ km, $y_M(0) = 0$ km, and $z_M(0) = 0$ km; Initial velocity: $V_M = 1100$ m/s. Its initial flight path angle and heading angle: $\theta_M(0) = 30$ deg and $\varphi_M(0) = 0$ deg. The maximum value of the available missile acceleration is assumed to be $25g$ ($g = 9.8$ m/s^2), respectively. The time constant of the autopilot $\tau = 0.3$. To show the robustness of the proposed guidance law, the time-varying factor of actuator faults are assumed as $E_1 = 0.5 + 0.1\sin t$ and $E_2 = 0.5 + 0.1\cos t$.

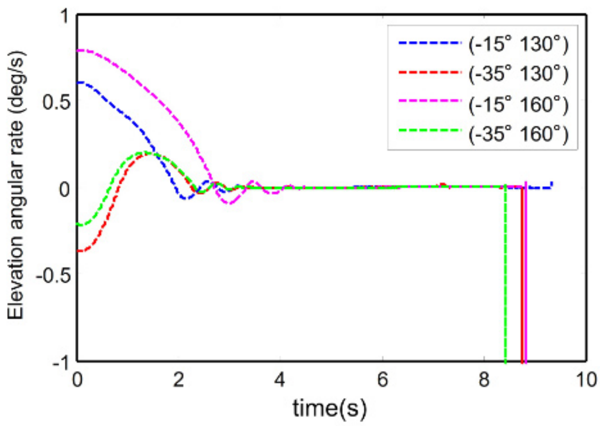

Fig. 2. Elevation angular rate.

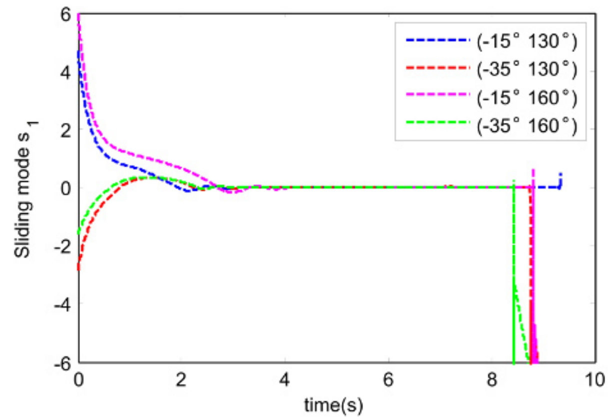

Fig. 4. Sliding mode surface s_1.

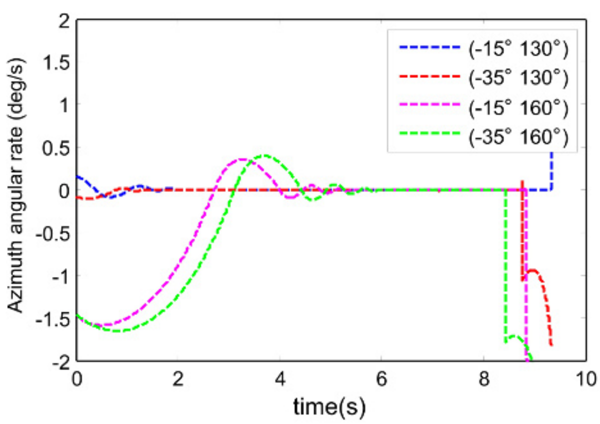

Fig. 3. Azimuth angular rate.

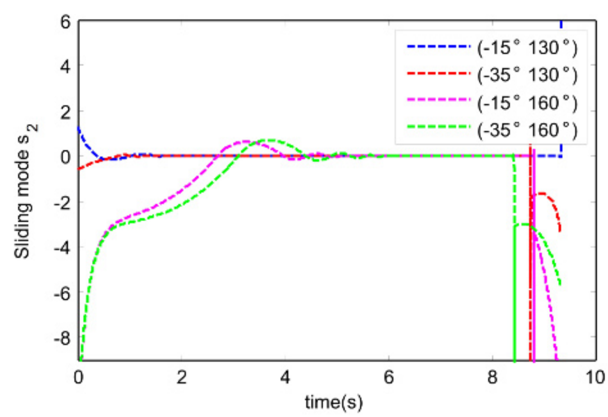

Fig. 5. Sliding mode surface s_2.

Case 1: It is assumed that the target maneuver is chosen as $a_{T\varepsilon} = 7g\sin(t)$ and $a_{T\beta} = 7g\cos(t)$. Initial position coordinates of target are $x_T(0) = 16$ km, $y_t(0) = 10.4$ km, and $z_T(0) = 6$ km. Its initial velocity: $V_T = 1000$ m/s. The starting fault time of missile $t = 0$. The parameters of guidance law are selected as $\beta_1 = 10$, $\beta_2 = 20$, $k_1 = 100$, $k_2 = 100$, $\lambda = 3$, $\alpha = 0.6$, $\gamma_1 = 0.6$, $\gamma_2 = 0.6$, $\gamma_3 = 0.8$, and the initial flight path angle and heading angle of the simulated taget are $(-15, 130)$ deg, $(-35, 130)$ deg, $(-15, 160)$ deg, $(-35, 160)$ deg, separately. The appropriate parameters of adaptive laws are selected as $p_1 = p_2 = 20$, $h_1 = h_2 = 10$. The parameters related to convergence region are set to be $\gamma_4 = 0.8$, $\gamma_5 = 0.8$, $\eta = 0.1$, $\delta_1 = 0.75$, $\delta_2 = 0.75$.

It can be observed from Figs. 2-5 that the $\dot{q}_\varepsilon$, $\dot{q}_\beta$, s_1 and s_2 converged to a small regions, respectively. Due to a large initial heading error between missile and target, missile quickly steer toward target under the guidance commands.

Case 2: To investigate the performance of the proposed guidance law when target maneuver proceeds with abrupt changes, we suppose that target acceleration is the following square-wave form

$$a_{T\varepsilon} = a_{T\beta} = \begin{cases} 7g, & 0 \le t < 7, \\ -7g, & 7 \le t < 8, \\ 7g, & t \ge 8. \end{cases} \tag{54}$$

Initial flight path angle and heading angle of target: $\theta_T(0) = -15$ deg and $\varphi_t(0) = 145$ deg. The fault time of missile is $t \ge 6$. The parameters needed for proposed guidance law and initial states are all the same as Case 1.

In order to show that it is necessary to consider the autopilot lag in the design of guidance law. In view of this point, the comparison results are shown in Figs. 6-9, where the guidance law w/o autopilot lag is the guidance law (18)-(23) with the time constant of autopilot $\tau = 0.001$, which is equivalent to the guidance law without autopilot lag.

From Fig. 6 and Fig. 7, the state $\dot{q}_\varepsilon$ and $\dot{q}_\beta$ change abruptly due to the occurrence of actuator failures at $t \ge 6$. After short adjustments, the angular rates rapidly converge to a small neighbourhood of zero in finite time, respectively.

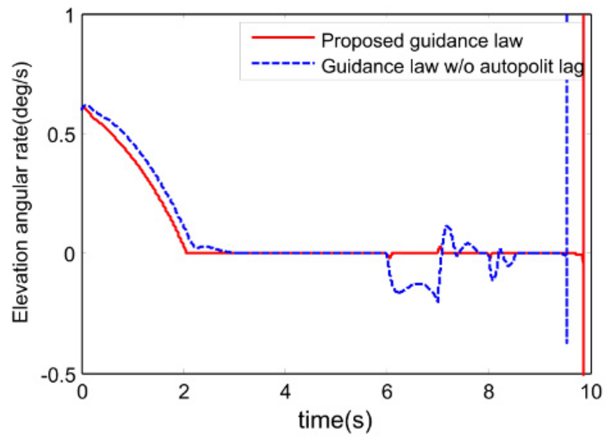

Fig. 6. Elevation angular rate.

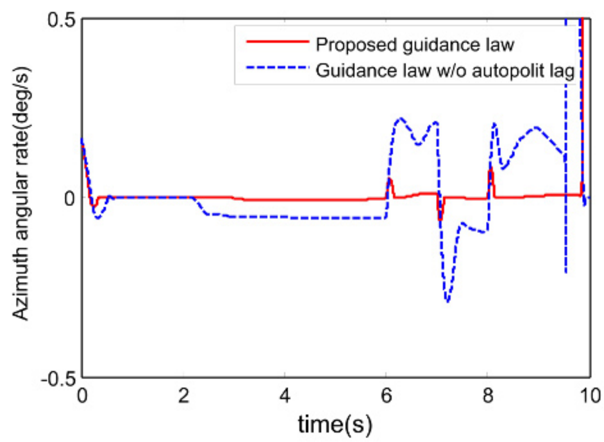

Fig. 7. Azimuth angular rate.

The responses of sliding mode surface in elevation loop and sliding mode manifold in azimuth loop s_2 are show in Figs. 8-9. During initial phase, s_1 and s_2 have a larger value. However both s_1 and s_2 converge to a small neighbourhood of zero exactly after a transient period of adjustment. And it can be seen that s_1 and s_2 rapidly also converge once more to a small neighbourhood of zero after the square-wave maneuver evasive of target.

From the aforementioned simulations, it clear that the autopilot lag of missile results in the system states cannot converge to zero rapidly. This adverse influence on the precision of guidance is significant, especially in the presence of target maneuvers.

For comparison, the traditional sliding mode control (TSMC) guidance law without adaptive compensation control is considered. Based on the traditional sliding mode control theory, the TSMC guidance law is given by

$$\boldsymbol{u}^{\boldsymbol{f}} = 1/(1-\mu)\boldsymbol{B}^{-1}(\boldsymbol{u}_0 + \varepsilon_0 \mathrm{sign}(s)), \tag{55}$$

where $\delta = \boldsymbol{d} - E\boldsymbol{u}^{\boldsymbol{f}}$ and $\boldsymbol{u}_0$ is given as (20) and the corresponding parameters are selected as the proposed guidance law (18)-(23). It can easily be proved that the closed-loop system (10) can be driven onto the sliding surface (13) $\boldsymbol{s} = 0$. Disturbance is assumed to be satisfied $\|\Delta\| \leq \varepsilon_0$, ε_0 is the upper bound of Δ [18].

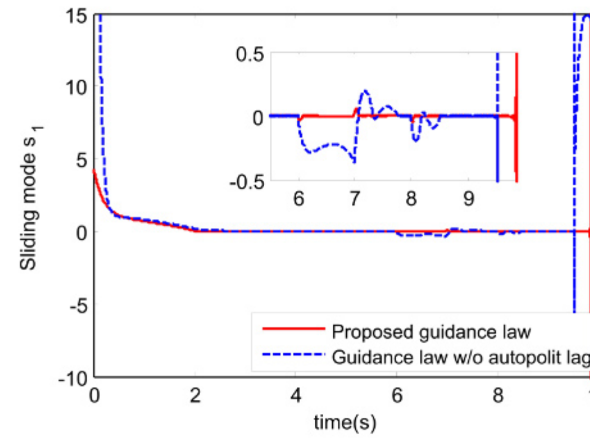

Fig. 8. Sliding mode surface s_1 and s_2.

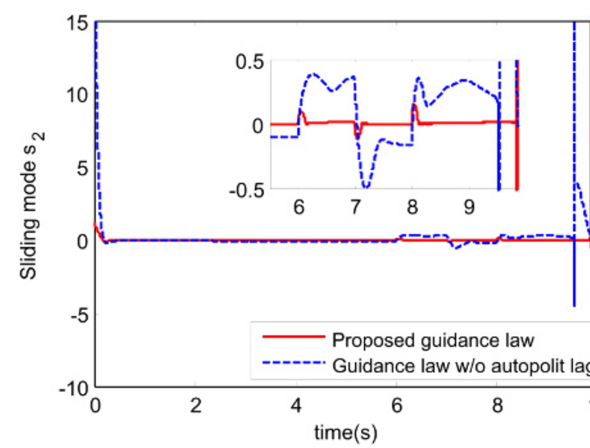

Fig. 9. Sliding mode surface.

It is clear that the upper bound Δ need to be selected large enough when the bound is not exactly known in order to suppress the both the disturbance and the uncertainties existing in guidance system. Thus, due to the sign function in (55), the violent chattering in control input is inevitable. This point can be seen form Fig. 10.

The input signal of the proposed adaptive guidance law $\boldsymbol{u}^{\boldsymbol{f}}$ is shown in Fig. 11. It is noted that $\boldsymbol{u}^{\boldsymbol{f}}$ changes abruptly due to actuator fautls at $t \geq 6$. After short adjustments, the states of the system remain stable, respectively. It can be seen from Fig. 11 that the undesired chattering can be reduced effectively with the adaptive compensation control u_{com} in the presence of actuator faults at $t \geq 6$. The performance of adaptive parameter ρ is shown in Fig. 12.

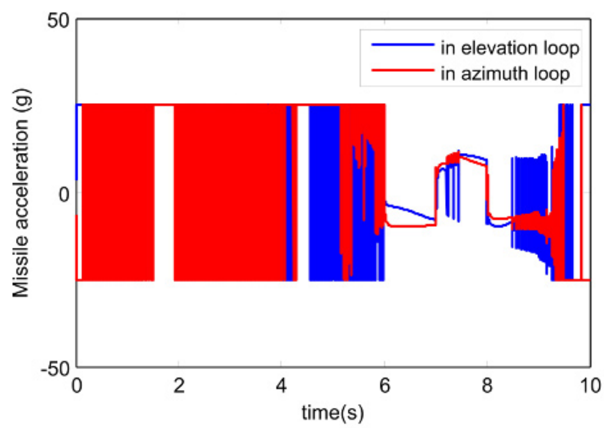

Fig. 10. Control input of the TSMC guidance law.

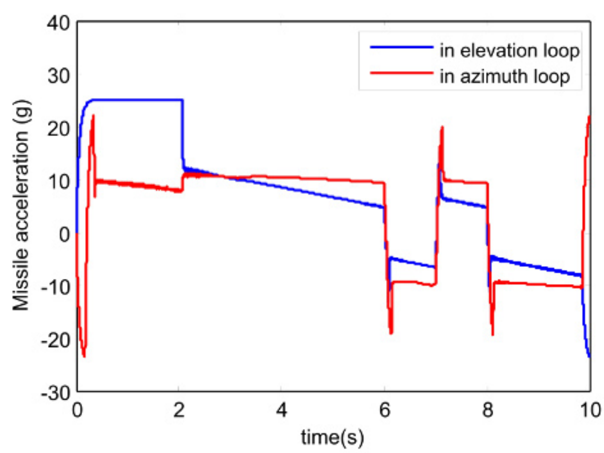

Fig. 11. Control input of proposed guidance law.

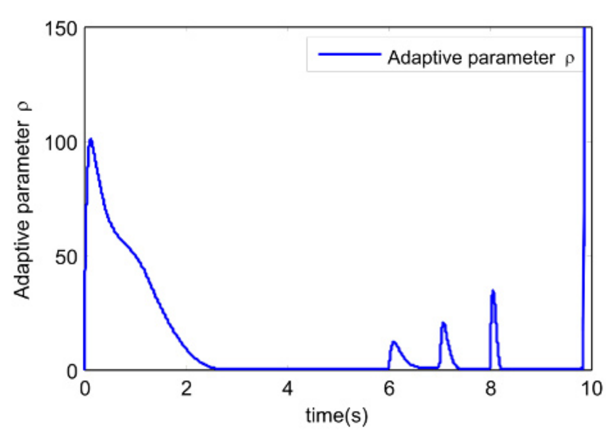

Fig. 12. The proposed adaptive parameter ρ.

6. CONCLUSIONS

In this study, the problems both partial loss of actuator effectiveness and autopilot lag are considered. The actuator faults and the dynamics of missile autopilot are covered in this model. Based on passive fault-tolerant control method, the adaptive sliding mode guidance law has been developed for the case when the faults appear in actuator of missile. This approach has three distinct advantages: 1) The information of actuator faults is estimated online by a designed adaptive algorithm. 2) The fault-tolerant control is also implemented even without the need of prior knowledge of the failures in advance. 3) All the adaptive parameters are also bounded even in non-ideal states of sliding mode system. The stability of the closed-loop guidance law is proved based on Lyapunov stability theory. Simulation studies have shown that the targets can be intercepted successfully for the three cases of target maneuvers and have varified the proposed adaptive guidance law for the time-varying actuator faults.

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