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Integrated Guidance and Control of Homing Missiles Against Ground Fixed Targets

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Abstract

This paper presents a scheme of integrated guidance and autopilot design for homing missiles against ground fixed targets. An integrated guidance and control model in the pitch plane is formulated and further changed into a normal form by nonlinear coordinate transformation. By adopting the sliding mode control approach, an adaptive nonlinear control law of the system is designed so that the missile can hit the target accurately with a desired impact attitude angle. The stability analysis of the closed-loop system is also conducted. The numerical simulation has confirmed the usefulness of the proposed design scheme.

Keywords: integrated guidance and control; pitch plane; ground fixed target; nonlinear; adaptive

1 Introduction

The traditional way to design a missile guidance and control system is to form subsystems separately followed by integrating them. Although this approach proves successful so far in building up a number of missile guidance and control systems with outstanding performance, it is arguable that the overall system performance is constrained because synergistic relationships between the interacting subsystems are not fully exploited.

In order to improve the whole system performance, a new approach known as the integrated guidance and control (IGC) system design method is developed by incorporating various control theories. Menon and Ohlmeyer[1] used the feedback linearization method associated with the linear quadratic regulator technique to formulate a nonlinear integrated guidance and control laws for homing missiles; Palumbo et al[2] used the state-dependent Riccati equation technique to deal with a more comprehensive model characterized by nonlinear motion in three dimensions; Shkolnikov et al[3] and Shima et al[4-5] developed an integrated guidance and control design by using sliding mode control; Choi and Chwa[6-7] proposed an adaptive nonlinear guidance law considering the target uncertainties and control loop dynamics by way of sliding mode control approach; Sharma and Richards[8] introduced an integrated guidance and control design for homing missiles based on the backstepping strategy. Still, there were suggested other interesting and effective methods such as subspace stabilization method[9] and θ-D method[10]. Therefore, it stands to reason that the integrated guidance and control system design will be one of the most noticed subjects in missile technology.

This work focuses on developing integrated guidance and control for homing missiles against ground fixed targets, which usually requires the minimum miss-distance and the desired impact atti-

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tude angle to enable the warheads of the missile to acquire better killing effects[11]. To achieve this, Zha et al[12] gave out the guidance law design by taking into account the dynamics of the missile control system. Different from this idea, this paper firstly establishes the model of the integrated guidance and control loop in the pitch plane, and then directly gives the fin deflection command by adopting the sliding mode control approach. Hence, the proposed method deserves more to be called an integrated guidance and control system design method.

2 Model Derivation

This section presents the model derivation of the integrated guidance and control system in the pitch plane.

Linearized missile dynamics in the pitch plane is described by

$$\left.\begin{array}{l} \dot{\alpha} = \omega_z - \dfrac{(57.3QSc_y^{\alpha} + P)}{mV}\alpha + \varDelta_{\alpha} \\ \dot{\omega}_z = \dfrac{QSL^2 m_z^{\bar{\omega}_z}}{J_z V}\omega_z + \dfrac{57.3QSLm_z^{\alpha}}{J_z}\alpha + \\ \quad \dfrac{57.3QSLm_z^{\delta_z}}{J_z}\delta_z + \varDelta_{\omega} \end{array}\right\} \tag{1}$$

where α is the attack angle, ω_z the angular pitch rate, δ_z the deflection angle for pitch control, Q the dynamic pressure, S the aerodynamic reference area, J_z the moment of inertia about z-axis, m the missile mass, P the thrust of the missile, L the reference length, V the velocity of the missile, c_y^{α} the lift force derivative with respect to the attack angle, m_z^{α}, $m_z^{\bar{\omega}_z}$ and $m_z^{\delta_z}$ represent the pitch moment derivatives with respect to the attack angle, the nondimensional angular pitch rate and the deflection angle for pitch control, respectively, $\varDelta_{\alpha}$ and $\varDelta_{\omega}$ are unknown bounded uncertainties.

As shown in Fig.1, dynamics of the missile to the ground fixed target range and the line-of-sight (LOS) angle are governed by

$$\dot{R} = -V\cos(q+\theta) \tag{2a}$$

$$R\dot{q} = V\sin(q+\theta) \tag{2b}$$

where R, q and θ are the relative distance, the LOS angle and the flight path angle of the missile, respectively.

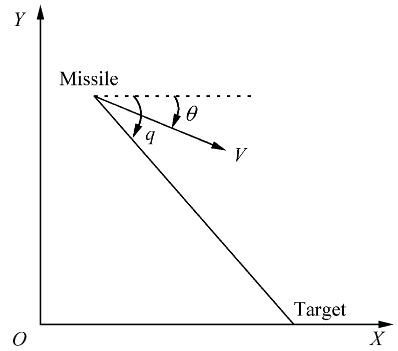

Fig.1 Two-dimensional engagement geometry.

By differentiating the Eq.(2b) and substituting Eqs.(2a)-(2b) into the derivative, it is easy to obtain that

$$\ddot{q} = \left[\frac{\dot{V}}{V} - \frac{2\dot{R}}{R}\right]\dot{q} - \frac{\dot{R}}{R}\dot{\theta} \tag{3}$$

As shown in Fig.2, the flight path angle is related with the pitch angle and the attack angle as

$$\theta = \vartheta - \alpha \tag{4}$$

or equivalently

$$\dot{\theta} = \dot{\vartheta} - \dot{\alpha} \tag{5}$$

where ϑ is the pitch angle, which satisfies

$$\dot{\vartheta} = \omega_z$$

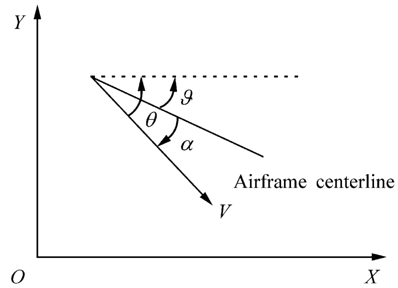

Fig.2 Schematic of angular relationship.

Considering that the terminal attack angle is very small in the proposed design scheme, it is easy to obtain from Eq.(4) that

$$\theta_{\mathrm{d}} \approx \vartheta_{\mathrm{d}}$$

where θ_{d} and ϑ_{d} are the desired impact flight and the desired impact attitude angles, respectively.

Assume that q_{d} is the desired impact LOS angle at the engagement time, the following equation and inequality hold true

$$\begin{cases} R\dot{q} = V\sin(q_{\mathrm{d}} + \theta_{\mathrm{d}}) = 0 \\ |q_{\mathrm{d}} + \theta_{\mathrm{d}}| < \dfrac{\pi}{2} \end{cases}$$

Thus

$$q_{\mathrm{d}} = -\theta_{\mathrm{d}}$$

and hence

$$q_{\mathrm{d}} \approx -\vartheta_{\mathrm{d}}$$

Let

$$\sigma = q - q_{\mathrm{d}}$$

then differentiation yields

$$\dot{\sigma} = \dot{q} \tag{6}$$

According to the above analysis, the integrated guidance and control model of the homing missile in the pitch plane can be written into

$$\left.\begin{aligned}
&\begin{bmatrix} \dot{\sigma} \\ \ddot{\sigma} \\ \dot{\alpha} \\ \dot{\omega}_z \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & \bar{a}_{22} & \bar{a}_{23} & 0 \\ 0 & 0 & \bar{a}_{33} & 1 \\ 0 & 0 & \bar{a}_{43} & \bar{a}_{44} \end{bmatrix} \begin{bmatrix} \sigma \\ \dot{\sigma} \\ \alpha \\ \omega_z \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \bar{b}_4 \end{bmatrix} u + \begin{bmatrix} 0 \\ \bar{\varDelta}_2 \\ \bar{\varDelta}_3 \\ \bar{\varDelta}_4 \end{bmatrix} \\
&\boldsymbol{y} = \begin{bmatrix} \sigma \\ \dot{\sigma} \end{bmatrix}
\end{aligned}\right\} \tag{7}$$

where $\bar{a}_{22} = \frac{\dot{V}}{V} - \frac{2\dot{R}}{R}$, $\bar{a}_{23} = -\frac{\dot{R}}{mVR}(57.3QSc_y^{\alpha} + P)$, $\bar{a}_{33} = -\frac{1}{mV}(57.3QSc_y^{\alpha} + P)$, $\bar{a}_{43} = \frac{57.3QSL}{J_z} m_z^{\alpha}$, $\bar{a}_{44} = \frac{QSL^2}{J_z V} m_z^{\bar{\omega}_z}$, $\bar{b}_4 = \frac{57.3QSL}{J_z} m_z^{\delta_z}$, $u = \delta_z$, $\bar{\varDelta}_2 = \frac{\dot{R}}{R}\varDelta_{\alpha}$, $\bar{\varDelta}_3 = \varDelta_{\alpha}$, $\bar{\varDelta}_4 = \varDelta_{\omega}$.

The object of this paper is to design an appropriate control law for the integrated guidance and control system Eq.(7), which not only guarantees a stable resulted closed-loop system but also acquires a zero miss-distance together with a desired impact attitude angle. In the missile engagement, the null rate of rotation of the LOS $\dot{q}$ presents the ideal condition for zero miss-distance, and the terminal impact attitude angular constraint can be satisfied by the null LOS angle error $\sigma = q - q_{\mathrm{d}}$.

3 Adaptive Nonlinear Control Law Design

This section presents the process of designing the control law for the integrated guidance and control system described by Eq.(7).

Because the system Eq.(7) is a time-varying system, based on the idea in Ref.[6], it is changed into a normal form with the help of nonlinear coordinate transformation and the sliding mode control approach is used to design its feedback control law.

Let $x_1 = \sigma$ and $x_2 = \dot{\sigma}$, then it is easy to obtain

$$\dot{x}_1 = x_2$$

and

$$\dot{x}_2 = \bar{a}_{22}\dot{\sigma} + \bar{a}_{23}\alpha + \bar{\varDelta}_2 = x_3 + \varDelta_2$$

where $x_3 = \bar{a}_{22}\dot{\sigma} + \bar{a}_{23}\alpha$ and $\varDelta_2 = \bar{\varDelta}_2$.

Hence

$$\alpha = \bar{a}_{23}^{-1}x_3 - \bar{a}_{23}^{-1}\bar{a}_{22}x_2 \tag{8}$$

Differentiating the term x_3 yields

$$\begin{aligned}
\dot{x}_3 &= \dot{\bar{a}}_{22}x_2 + \dot{\bar{a}}_{23}\alpha + \bar{a}_{22}\ddot{\sigma} + \bar{a}_{23}\dot{\alpha} = \dot{\bar{a}}_{22}x_2 + \\
&\dot{\bar{a}}_{23}\alpha + \bar{a}_{22}x_3 + \bar{a}_{23}(a_{33}\alpha + \omega_z) = (\dot{\bar{a}}_{22} - \\
&\bar{a}_{23}^{-1}\bar{a}_{22}\dot{\bar{a}}_{23} - \bar{a}_{22}\bar{a}_{33})x_2 + (\bar{a}_{22} + \bar{a}_{23}^{-1}\dot{\bar{a}}_{23} + \\
&a_{33})x_3 + \bar{a}_{23}\omega_z + \bar{a}_{22}\bar{\varDelta}_2 + \bar{a}_{23}\bar{\varDelta}_3 = x_4 + \varDelta_3
\end{aligned}$$

where

$$\begin{aligned}
x_4 = {}& (\dot{\bar{a}}_{22} - \bar{a}_{23}^{-1}\bar{a}_{22}\dot{\bar{a}}_{23} - \bar{a}_{22}\bar{a}_{33})x_2 + \\
&(\bar{a}_{22} + \bar{a}_{23}^{-1}\dot{\bar{a}}_{23} + a_{33})x_3 + \bar{a}_{23}\omega_z
\end{aligned}$$

and

$$\varDelta_3 = \bar{a}_{22}\bar{\varDelta}_2 + \bar{a}_{23}\bar{\varDelta}_3$$

hence

$$\begin{aligned}
\omega_z = {}& \bar{a}_{23}^{-1}x_4 - (\bar{a}_{23}^{-1}\bar{a}_{22} + \bar{a}_{23}^{-2}\dot{\bar{a}}_{23} + \bar{a}_{23}^{-1}\bar{a}_{33})x_3 - \\
&(\bar{a}_{23}^{-1}\dot{\bar{a}}_{22} - \bar{a}_{23}^{-2}\bar{a}_{22}\dot{\bar{a}}_{23} - \bar{a}_{23}^{-1}\bar{a}_{22}\bar{a}_{33})x_2
\end{aligned} \tag{9}$$

Similarly,

$$\dot{x}_4 = a_2x_2 + a_3x_3 + a_4x_4 + b_4u + \varDelta_4$$

where

$$\begin{aligned}
a_2 = {}& \ddot{\bar{a}}_{22} - \bar{a}_{23}^{-1}\bar{a}_{22}\ddot{\bar{a}}_{23} - \bar{a}_{23}^{-1}\dot{\bar{a}}_{22}\dot{\bar{a}}_{23} + 2\bar{a}_{23}^{-2}\bar{a}_{22}\dot{\bar{a}}_{23}^{2} - \\
&\dot{\bar{a}}_{22}\bar{a}_{33} - \bar{a}_{22}\dot{\bar{a}}_{33} - \bar{a}_{23}^{-1}\dot{\bar{a}}_{22}\dot{\bar{a}}_{23} + \bar{a}_{23}^{-1}\dot{\bar{a}}_{23}\bar{a}_{22}\bar{a}_{33} - \\
&\bar{a}_{44}\dot{\bar{a}}_{22} + \bar{a}_{23}^{-1}\bar{a}_{22}\dot{\bar{a}}_{23}\bar{a}_{44} + \bar{a}_{22}\bar{a}_{33}\bar{a}_{44} - \bar{a}_{22}\bar{a}_{43}
\end{aligned}$$

$$\begin{aligned}
a_3 = {}& 2\dot{\bar{a}}_{22} - 2\bar{a}_{23}^{-2}\dot{\bar{a}}_{23}^{2} + \bar{a}_{23}^{-1}\ddot{\bar{a}}_{23} + \dot{\bar{a}}_{33} - \bar{a}_{23}^{-1}\dot{\bar{a}}_{23}\bar{a}_{22} + \bar{a}_{43} - \\
&2\bar{a}_{23}^{-1}\dot{\bar{a}}_{23}\bar{a}_{33} - \bar{a}_{22}\bar{a}_{33} - \bar{a}_{44}\bar{a}_{22} - \bar{a}_{23}^{-1}\bar{a}_{44}\dot{\bar{a}}_{23} - \bar{a}_{44}\bar{a}_{33}
\end{aligned}$$

$$a_4 = 2\bar{a}_{23}^{-1}\dot{\bar{a}}_{23} + \bar{a}_{22} + \bar{a}_{33} + \bar{a}_{44}$$

$$b_4 = \bar{a}_{23}\bar{b}_4$$

$$\begin{aligned}
\varDelta_4 = {}& (\dot{\bar{a}}_{22} - \bar{a}_{23}^{-1}\bar{a}_{22}\dot{\bar{a}}_{23} - \bar{a}_{22}\bar{a}_{33})\bar{\varDelta}_2 + (\bar{a}_{22} + \bar{a}_{23}^{-1}\dot{\bar{a}}_{23} + \\
&a_{33})\bar{\varDelta}_3 + \bar{a}_{23}\bar{\varDelta}_4
\end{aligned}$$

Let $\boldsymbol{x} = [x_1 \quad x_2 \quad x_3 \quad x_4]^{\mathrm{T}}$

then

$$\left.\begin{aligned}
&\dot{\boldsymbol{x}} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & a_2 & a_3 & a_4 \end{bmatrix} \boldsymbol{x} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ b_4 \end{bmatrix} u + \begin{bmatrix} 0 \\ \varDelta_2 \\ \varDelta_3 \\ \varDelta_4 \end{bmatrix} \\
&\boldsymbol{y} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \boldsymbol{x}
\end{aligned}\right\} \tag{10}$$

Clearly, in order to attain the predetermined objective, it is only needed to design an appropriate control law for the system Eq.(10) so that the resulted closed-loop system is stable with the outputs converging to zero asymptotically.

The adaptive nonlinear control law is designed under the following assumption.

Assumption $|\Delta_i| \le T_i$ (i=2,3,4), $|\dot{\Delta}_2| \le N_2$, $|\dot{\Delta}_3| \le N_3$ and $|\ddot{\Delta}_2| \le W_2$, where T_i, N_2, N_3 and W_2 are all unknown constants.

Let $M_2 = T_2, M_3 = N_2 + T_3, M_4 = W_2 + N_3 + T_4$, then based on the sliding mode control theory, the proposed adaptive nonlinear control law can be expressed as

$$u = -b_4^{-1}[(c_1 + a_2)x_2 + (c_2 + a_3)x_3 + (c_3 + a_4)x_4 + ks + (c_2\hat{M}_2 + c_3\hat{M}_3 + \hat{M}_4)\operatorname{sgn}(s)] \tag{11}$$

with the adaptation law described by

$$\dot{\hat{M}}_2 = c_2\lambda_2|s|,\quad \dot{\hat{M}}_3 = c_3\lambda_3|s|,\quad \dot{\hat{M}}_4 = \lambda_4|s|$$

where $k > 0$, $\lambda_2 > 0$, $\lambda_3 > 0$, $\lambda_4 > 0$ are design parameters, $\hat{M}_i$ is an estimate of M_i (i=2,3,4), and

$$s = c_1x_1 + c_2\dot{x}_1 + c_3\ddot{x}_1 + \dddot{x}_1$$

with the design parameters c_j, where $j = 1,2,3$, satisfying the Hurwitz polynomial

$$g(\rho) = c_1 + c_2\rho + c_3\rho^2 + \rho^3$$

Remark In fact, it is easy to check that the inequality $b_4 \ne 0$ always holds true, so Eq.(11) is always nonsingular.

Then the following theorem can be deducted.

Theorem The system described by Eq.(10) and Eq.(11) is stable in the sense that its states are all bounded and its outputs converge to zero asymptotically under Assumption.

Before conducting the proof, some useful lemmas and propositions are introduced as follows.

Lemma (Babalat's lemma) If $f(t)$ is a uniformly continuous function and $\lim\limits_{t\to\infty}\int_0^t f(\tau)\mathrm{d}\tau$ exists, then $f(t)$ converges to zero asymptotically.

Proposition 1 For the system

$$\dot{\boldsymbol{z}} = \boldsymbol{\Phi}\boldsymbol{z} + \boldsymbol{d}$$

where $\boldsymbol{\Phi}$ is a Hurwitz matrix, if there exists such a positive scalar κ_1 that $\|\boldsymbol{d}\| \le \kappa_1$, then there exists such a positive scalar κ_2 that $\|\boldsymbol{z}\| \le \kappa_2$.

Proposition 2 For the system

$$\dot{\boldsymbol{\eta}} = \boldsymbol{\Psi}\boldsymbol{\eta} + \boldsymbol{v}$$

if $\boldsymbol{\Psi}$ is a Hurwitz matrix and $\boldsymbol{v}$ converges to zero asymptotically, then $\boldsymbol{\eta}$ also converges to zero asymptotically.

Propositions 1 and 2 can be easily confirmed from the conclusions in Ref.[13], so the proofs are omitted. From Proposition 2, the following proposition can be obtained.

Proposition 3 If the coefficients in the ordinary differential equation

$$e_1\xi + e_2\dot{\xi} + \cdots + e_n\xi^{(n-1)} + \xi^{(n)} = \upsilon$$

satisfy the Hurwitz polynomial

$$g(\rho) = e_1 + e_2\rho + \cdots + e_n\rho^{n-1} + \rho^n$$

and υ converges to zero asymptotically, then $\xi^{(m)}$ (m=0,$\cdots$,n−1) converge to zero asymptotically, too.

Next, the Proof of Theorem is given.

Proof of Theorem Let

$$\tilde{M}_i = M_i - \hat{M}_i$$

then

$$\dot{\tilde{M}}_i = -\dot{\hat{M}}_i$$

where i=2,3,4.

Define the Lyapunov function as

$$E = \frac{1}{2}\left(s^2 + \frac{1}{\lambda_2}\tilde{M}_2^2 + \frac{1}{\lambda_3}\tilde{M}_3^2 + \frac{1}{\lambda_4}\tilde{M}_4^2\right)$$

and take a time derivative to have

$$\begin{aligned}
\dot{E} &= s\dot{s} + \frac{1}{\lambda_2}\tilde{M}_2\dot{\tilde{M}}_2 + \frac{1}{\lambda_3}\tilde{M}_3\dot{\tilde{M}}_3 + \frac{1}{\lambda_4}\tilde{M}_4\dot{\tilde{M}}_4 = \\
& s[c_1x_2 + c_2(x_3 + \Delta_2) + c_3(x_4 + \dot{\Delta}_2 + \Delta_3) + a_2x_2 + \\
& a_3x_3 + a_4x_4 + b_4u + \ddot{\Delta}_2 + \dot{\Delta}_3 + \Delta_4] + \frac{1}{\lambda_2}\tilde{M}_2\dot{\tilde{M}}_2 + \\
& \frac{1}{\lambda_3}\tilde{M}_3\dot{\tilde{M}}_3 + \frac{1}{\lambda_4}\tilde{M}_4\dot{\tilde{M}}_4 = s[c_2\Delta_2 + c_3(\dot{\Delta}_2 + \Delta_3) + \\
& (\ddot{\Delta}_2 + \dot{\Delta}_3 + \Delta_4) - (c_2\hat{M}_2 + c_3\hat{M}_3 + \hat{M}_4)\operatorname{sgn}(s)] - \\
& |s|(c_2\tilde{M}_2 + c_3\tilde{M}_3 + \tilde{M}_4) - ks^2 \le -ks^2 + |s|[c_2 \cdot \\
& (M_2 - \hat{M}_2) + c_3(M_3 - \hat{M}_3) + (M_4 - \hat{M}_4)] - \\
& |s|(c_2\tilde{M}_2 + c_3\tilde{M}_3 + \tilde{M}_4) = -ks^2
\end{aligned}$$

From the above computation, it can be concluded that $E \in L_\infty$ and

$$\int_0^\infty s^2\mathrm{d}t \le \frac{1}{k}[E(0) - E(\infty)] < \infty$$

that is $s^2 \in L_2$.

From $E \in L_\infty$, it can be obtained that $\tilde{M}_2 \in L_\infty$, $\tilde{M}_3 \in L_\infty$, $\tilde{M}_4 \in L_\infty$ and $s \in L_\infty$, and accordingly,

$\hat{M}_2 \in L_\infty$, $\hat{M}_3 \in L_\infty$ and $\hat{M}_4 \in L_\infty$. In addition, a simple calculation gives

$$|\dot{s}| \le k|s| + c_2(M_2 + \hat{M}_2) + c_3(M_3 + \hat{M}_3) + (M_4 + \hat{M}_4)$$

so $\dot{s} \in L_\infty$. Thus, $\mathrm{d}s^2/\mathrm{d}t \in L_\infty$. This means that s^2 is uniformly continuous. Combining this with the L_2-property of s^2, Lemma can be used to conclude that s^2 converges to zero asymptotically. Hence, s converges to zero asymptotically. Using Proposition 3, it can be concluded that x_1 and x_2 converge to zero asymptotically, that is, the outputs of the system described by Eqs.(10)-(11) converge to zero asymptotically.

In addition, the closed-loop system described by Eqs.(10)-(11) can be rewritten into

$$\dot{\boldsymbol{x}} = \boldsymbol{A}_\mathrm{c}\boldsymbol{x} + \boldsymbol{F} \tag{12}$$

where

$$\boldsymbol{A}_\mathrm{c} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -kc_1 & -(c_1+kc_2) & -(c_2+kc_3) & -(c_3+k) \end{bmatrix}$$

$$\boldsymbol{F} = [0 \quad f_2 \quad f_3 \quad f_4]^\mathrm{T}$$

$$f_2 = \Delta_2, \quad f_3 = \Delta_3$$

$$f_4 = -(c_2\hat{M}_2 + c_3\hat{M}_3 + \hat{M}_4)\mathrm{sgn}(s) - k[c_3\Delta_2 + (\dot{\Delta}_2 + \Delta_3)] + \Delta_4$$

From Assumption and the above description, $\|\boldsymbol{F}\| \in L_\infty$ holds true, which means that there exists such a positive number $\bar{F}$ that $\|\boldsymbol{F}\| \le \bar{F}$. In addition, under the conditions that $k > 0$ and that the polynomial

$$g(\rho) = c_1 + c_2\rho + c_3\rho^2 + \rho^3$$

is Hurwitzian, it can be concluded that $\boldsymbol{A}_\mathrm{c}$ is a Hurwitz matrix. Therefore, Proposition 1 can be used to conclude that the states of the system Eq.(12) are all bounded, that is, the states of the system described by Eqs.(10)-(11) are all bounded. Here the proof is completed.

4 Numerical Simulations

In this section, the feasibility and applicability of the proposed integrated guidance and control logic is verified by the numerical simulations for some passive homing missile's nonlinear dynamic model in the pitch plane.

The simulation step is set to be 0.001 s, the desired impact pitch angle −90°, the position coordinate of the target (2 000, 0) m,; the initial velocity of the missile *Ma*=0.6, the initial body rotational rate of the missile 0 rad/s, the initial flight path angle of the missile 0°, the initial attitude angle of the missile 0°, and the initial position coordinate of the missile (0, 2 500) m. Design parameters of control law Eq.(11) are set to be $\lambda_2 = \lambda_3 = \lambda_4 = 2.7\times10^{-5}$, $c_1 = 9, c_2 = 11, c_3 = 8$ and $k = 0.105$.

In addition, the deflection angle and the deflection angle rate for pitch control used in all simulations are assumed to satisfy $|\delta_z| \le$ 30°, $|\dot{\delta}_z| \le 3$ (°)/s.

For the nominal system, Fig.3 shows the trajectory of the missile; Fig.4 the curve of the relative distance between the missile and the target with the terminal relative distance only 0.039 m; Fig.5 the curve of the pitch angle with the desired impact pitch angle −89.948°; Fig.6 the small attack angle at the engagement time as mentioned in Section 2, and Fig.7 the curve of the deflection angle for pitch control.

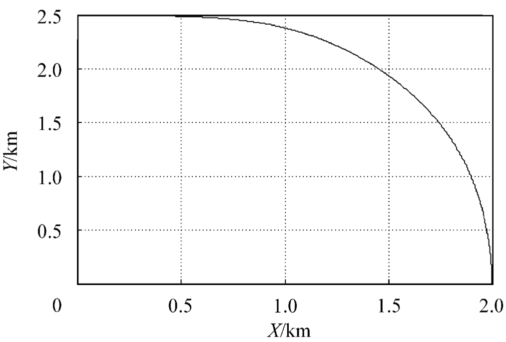

Fig.3　The trajectory of the missile.

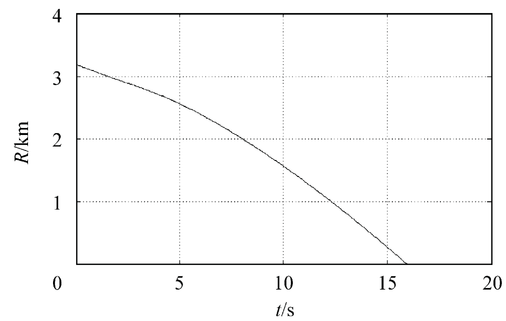

Fig.4　The curve of the relative distance.

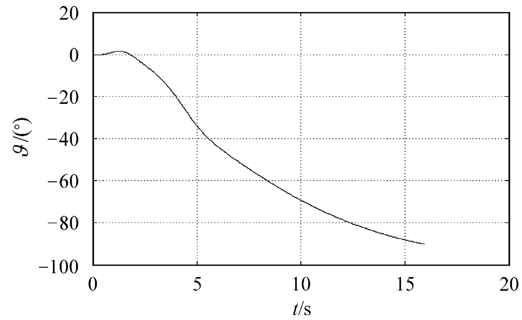

Fig.5 The curve of the pitch angle.

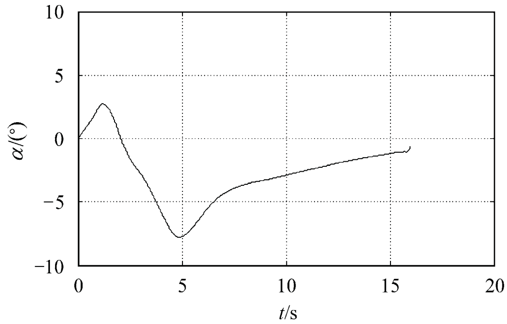

Fig.6 The curve of the attack angle.

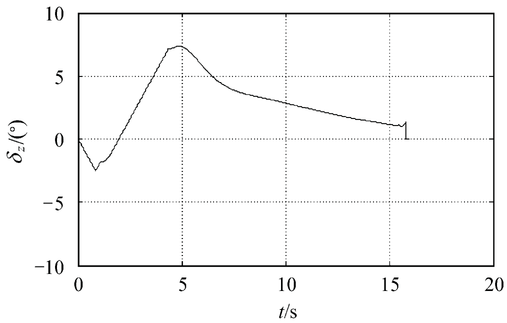

Fig.7 The curve of the deflection angle.

In order to show the robust characteristics of the proposed method, two cases are selected as follows:

(1) All of the aerodynamic parameters are assumed to increase by 20% relative to the nominal values. The terminal relative distance is 0.024 m and the terminal impact pitch angle −88.272°.

(2) All of the aerodynamic parameters are all assumed to decrease by 20% relative to the nominal values. The terminal relative distance is 0.248 m and the terminal impact pitch angle −91.893°.

All of the simulation results testify to the feasibility and practicability of the proposed method.

5 Conclusions

This paper presents a scheme of integrated guidance and autopilot design for homing missiles against ground fixed targets to improve the performance of the missile guidance and control system. An integrated model of guidance and control loop in the pitch plane is first formulated, and then the adaptive nonlinear control law is designed by adopting the sliding mode control approach. Numerical simulation results have confirmed a simultaneous attainment of small miss-distance and a desired impact attitude angle, which demonstrates the usefulness of the proposed design scheme.

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