Research Article

Discrete Sliding Mode Control for Hypersonic Cruise Missile

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Received 24 December 2015; Revised 18 February 2016; Accepted 7 March 2016

Academic Editor: Driss Boutat

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A discrete variable structure control (DVSC) with sliding vector is presented to track the velocity and acceleration command for a hypersonic cruise missile. In the design an integrator is augmented to ensure the tracking with zero steady-state errors. Furthermore the sliding surface of acceleration is designed using the error of acceleration and acceleration rate to avoid the singularity of control matrix. A proper power rate reaching law is utilized in this proposal; therefore the state trajectory from any initial point can be driven into the sliding surface. Besides, in order to validate the robustness of controller, the unmolded dynamic and parameter disturbance of the missile are considered. Through simulation the proposed controller demonstrates good performance in tracking velocity and acceleration command.

1. Introduction

Recently hypersonic vehicle has attracted attention because of its potential military and civil application [1–7]. With the breakthrough of the scramjet and heat safeguard, the hypersonic vehicle can be developed into cruise missile to realize global strike. The control system of hypersonic cruise missile exhibits high performance of tracking both velocity command and guidance command. Moreover the model of hypersonic missile has unmolded dynamic and parameter disturbance. Thus it is a challenge for hypersonic missile autopilot design [8].

The exploration of the various design methods for hypersonic aircraft has been an active field. Matthew [9] reported an adaptive linear quadratic (ALQ) altitude and velocity tracking control algorithm for the longitudinal model of a generic air-breathing hypersonic flight vehicle. A nonlinear controller for an air-breathing hypersonic vehicle was designed by Fiorentini et al. [10]. The sliding variable structure control also shows its advantage in robustness to the disturbance [11–14]. Using this method, Xu et al. [4] presented an adaptive sliding mode control for hypersonic aircraft with nonlinear and model uncertainty. A high-order sliding mode control was investigated by Yang and Tian [11] and then a sliding variable structure controller is designed for a reentry hypersonic missile. Yu and Yuri [12] used high-order sliding

surface to design a hypersonic missile controller with the trajectory restriction. In case there is uncertainty, neural network based hypersonic flight control research could be found in literatures [14–17].

Although these literatures have satisfactory effect for a continuous plant, the computer on board always works discontinuously, and thus controller on the basis of continuous system cannot offer the same performance by a digital computer with a certain sampling interval. This can cause the system instability [13, 18–20].

This paper presents a design method of hypersonic cruise missile autopilot using discrete variable structure control. The main task of autopilot is to track commands of the acceleration and velocity simultaneously. So the multiple sliding surfaces are designed (for both subsystems of acceleration and velocity). To track with zero steady errors, an integrator is introduced into them. In this paper, chattering is reduced by a proper design of power rate reaching law. The unmolded dynamics and uncertainties are also included to examine the robustness of the discrete variable structure controller.

This paper is organized as follows. The dynamics and discrete model of hypersonic cruise missile are given in Section 2. And the design of discrete variable structure controller is presented in Section 3. Then we conduct simulations and give the results to demonstrate the reasonability of our design. Finally, we make a conclusion in Section 5.

FIGURE 1: Configuration of hypersonic cruise missile.

2. Model of Hypersonic Cruise Missile

2.1. Description of Hypersonic Cruise Missile. The configuration of hypersonic cruise missile with scramjet is shown as in Figure 1.

The cowl of scramjet is arranged in the mandible of hypersonic cruise missile. The fore body is unsymmetrical, where the guidance system and warhead are located. And the lower fore body is the inlet of engine. Two elevator-aileron and two rudders are used to control pitch, roll, and yaw movement. The thrust is adjusted by throttle. The longitudinal model of the cruise missile considered in this paper is

$$\begin{aligned}
 \dot{V} &= \frac{T \cos \alpha - D}{m} - g \sin \gamma, \\
 \dot{\gamma} &= \frac{L + T \sin \alpha}{mV} - \frac{g \cos \gamma}{V}, \\
 \alpha &= \theta - \gamma, \\
 \dot{q} &= \frac{M_{yy}}{I_{yy}}, \\
 T &= \frac{1}{2} \rho V^2 S C_T, \\
 D &= \frac{1}{2} \rho V^2 S C_D, \\
 L &= \frac{1}{2} \rho V^2 S C_L, \\
 M_{yy} &= \frac{1}{2} \rho V^2 S \bar{c} [C_M(\alpha) + C_M(\delta_e) + C_M(q)],
 \end{aligned} \tag{1}$$

where the expressions of aerodynamic coefficients are denoted by C_L , C_D , and C_M , respectively, and C_T denotes thrust coefficient.

2.2. Discrete Model of Cruise Missile. Let $x = [\theta, \gamma, \alpha, V, q]^T$ be the state vector, and $u = [\delta_t, \delta_e]^T$ is the control vector. The longitudinal model of the cruise missile can be linearized:

$$\dot{X}(t) = AX(t) + BU(t), \tag{2}$$

$$X = [\theta, \gamma, \alpha, V, q]^T, \tag{3}$$

$$U = [\delta_t, \delta_e]^T = [U_1, U_2]^T, \tag{4}$$

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & V \cos \gamma & 0 & \sin \gamma & 0 \\ 0 & \frac{g \sin \gamma}{V} & \frac{T + L^\alpha}{mV} & \frac{T^V \alpha + L^V}{mV} & 0 \\ 0 & -\frac{g \sin \gamma}{V} & -\frac{T + L^\alpha}{mV} & -\frac{T^V \alpha + L^V}{mV} & 1 \\ 0 & \frac{M_{yy}^\gamma}{I_{yy}} & \frac{M_{yy}^\alpha}{I_{yy}} & \frac{M_{yy}^V}{I_{yy}} & \frac{M_{yy}^q}{I_{yy}} \end{bmatrix}, \tag{5}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{T^{\delta_t}}{m} & 0 \\ 0 & 0 & \frac{L^{\delta_e}}{mV} & -\frac{L^{\delta_e}}{mV} & 0 & \frac{M_{yy}^{\delta_e}}{I_{yy}} \end{bmatrix}^T, \tag{6}$$

where θ , γ , α , V , and q represent velocity, pitch angle, flight trajectory angle, angle of attack, and pitch rate, respectively. δ_e is the angle of elevator and δ_t is the control of throttle setting.

Assuming T_s is the sampling interval of onboard computer and the plant is integrated in a sampling interval, the discrete state equations are

$$X(k+1) = dA \cdot X(k) + dB \cdot U(k), \tag{7}$$

$$X(k) = [\theta(k) \ \gamma(k) \ \alpha(k) \ V(k) \ q(k)]^T, \tag{8}$$

$$dA = e^{AT_s}, \tag{9}$$

$$dB = \left(\int_0^{T_s} e^{At} dt \right) B, \tag{10}$$

$$U(k) = [\delta_t(k) \ \delta_e(k)]^T.$$

3. Design of Variable Structure Controller

The flight control system of hypersonic cruise missile is designed to track the commands of velocity and acceleration. Define the error of tracking as

$$\begin{aligned}
 a_y(k) - a_{yc}(k) &\longrightarrow 0, \\
 V(k) - V_c(k) &\longrightarrow 0.
 \end{aligned} \tag{11}$$

Let

$$E = a_y + \dot{a}_y. \tag{12}$$

a_y is longitudinal acceleration, $\dot{a}_y$ is the rate of longitudinal acceleration, and the tracking error can be written as

$$\begin{aligned}
 E(k) - E_c(k) &\longrightarrow 0, \\
 V(k) - V_c(k) &\longrightarrow 0.
 \end{aligned} \tag{13}$$

The structure of the discrete control system of the hypersonic cruise missile is shown as in Figure 2.

FIGURE 2: Structure of the discrete control system.

3.1. Design of Discrete Sliding Surface. Selecting multiple sliding surfaces,

$$S(k+1) = \begin{bmatrix} S_1(k+1) \\ S_2(k+1) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}. \quad (14)$$

If the acceleration and velocity subsystem are chosen directly as the sliding surface,

$$S_1(k+1) = [a_y(k+1) - a_y(k) + c_1 [a_y(k) - a_{yc}(k)]] \quad (15)$$

$$S_2(k+1) = [V(k+1) - V(k)] + c_2 [V(k) - V_c(k)], \quad (16)$$

where c_1 and c_2 are the unknown parameters.

The acceleration can be written as

$$a_y = V\dot{\gamma}. \quad (17)$$

Differentiating the acceleration expression, (17) yields

$$\dot{a}_y = V\ddot{\gamma} = V(\ddot{\theta} - \dot{\alpha}) = V(\dot{q} - \dot{\alpha}). \quad (18)$$

Substituting $\dot{q}$ and $\dot{\alpha}$ in terms of the sate equation (2) into (18) yields

$$\dot{a}_y = -VA_{33}\dot{\alpha}. \quad (19)$$

Discretizing (19) yields

$$\begin{aligned} a_y(k+1) &= -VA_{33}\alpha(k+1), \\ a_y(k) &= -VA_{33}\alpha(k). \end{aligned} \quad (20)$$

Substituting (20) and $V(k+1)$ in terms of the sate equation (7) into (15) and (16), respectively, yields

$$S(k+1) = S_X X(k) + S_Y U(k) + S_Z. \quad (21)$$

To be simple, $dA(2, 1)$ is written as dA_{21} ; the other similar denotation is the same. Therefore the matrixes in (21) are

$$\begin{aligned} S_X &= \begin{bmatrix} -VA_{33}dA_{31} & -VA_{33}dA_{32} & -VA_{33}(dA_{33} + c_1 - 1) & -VA_{33}dA_{34} & -VA_{33}dA_{35} \\ dA_{41} & dA_{42} & dA_{43} & dA_{44} + c_2 - 1 & dA_{45} \end{bmatrix}, \\ S_Y &= \begin{bmatrix} -VA_{33}dB_{31} & -VA_{33}dB_{32} \\ dB_{41} & dB_{42} \end{bmatrix}, \\ S_Z &= \begin{bmatrix} -c_1 a_{yc}(k) \\ -c_2 V_c(k) \end{bmatrix}. \end{aligned} \quad (22)$$

For $dB_{31} = dB_{32} = 0$, the matrix S_Y^{-1} will not exist. Then, $U(k)$ cannot be achieved. Therefore the sliding surface cannot be chosen as (15). As long as the differential of state variable includes $\Delta\dot{q}$, the matrix S_Y is invertible. From the derivative of (19), the second-order derivative of acceleration is

$$\ddot{a}_y = -VA_{33}(A_{33}\dot{\alpha} + \dot{q}). \quad (23)$$

In the right-hand side of (23), $\Delta\dot{q}$ is included and the matrix S_Y is invertible; the control law $U(k)$ can be obtained. Thereby, the form of control variable is as follows:

$$E = a_y + \dot{a}_y. \quad (24)$$

Differentiating (24), we have

$$\dot{E} = \dot{a}_y + \ddot{a}_y = -VA_{33}[(A_{33} + 1)\dot{\alpha} + \dot{q}]. \quad (25)$$

In terms of discretization (25) is

$$E(k) = -VA_{33}[(A_{33} + 1)\alpha(k) + q(k)], \quad (26)$$

$$\begin{aligned} E(k+1) - E(k) &= -VA_{33}[(A_{33} + 1) \\ &\quad \cdot (\alpha(k+1) - \alpha(k)) + (q(k+1) - q(k))]. \end{aligned} \quad (27)$$

Substituting the discrete state equations $\alpha(k+1)$ and $q(k+1)$ into (27) yields

$$E(k+1) - E(k) = S_{E1}X(k) + S_{E2}U(k). \quad (28)$$

The elements of matrix S_{E2} are not all zeros.

Choosing the sliding surface of the acceleration subsystem,

$$S_1(k+1) = b[E(k+1) - E(k)] + c[E(k) - E_c(k)], \quad (29)$$

where b and c are designed parameters.

To enable the system for tracking the command with zero steady-state errors, a discrete integrator is added in the sliding surface:

$$\begin{aligned} S_1(k+1) &= aS_1(k) \\ &+ T_s \{b[E(k+1) - E(k)] + c[E(k) - E_c(k)]\}, \end{aligned} \quad (30)$$

where a is an unknown coefficient to enhance the performance of integrator. Let $a = a_1$, $T_s b = 1$, and $T_s c = c_1$; rearranging the equation yields

$$\begin{aligned} S_1(k+1) &= a_1 S_1(k) + [E(k+1) - E(k)] \\ &+ c_1 [E(k) - E_c(k)], \end{aligned} \quad (31)$$

$$\begin{aligned} S_1(k+1) - S_1(k) &= [E(k+1) - E(k)] \\ &+ c_1 [E(k) - E_c(k)] \\ &- (1 - a_1) S_1(k). \end{aligned} \quad (32)$$

With solution of (31) and (32) for $E(k+1) - E(k)$ and $E(k)$ can be obtained. Substituting $E(k+1) - E(k)$ and $E(k)$ into (32), we have

$$S_1(k+1) - S_1(k) = S_{X1}X(k) + S_{Y1}U(k) + S_{Z1}, \quad (33)$$

where, $S_{X1} \in R^{1 \times 6}$, $S_{Y1} \in R^{1 \times 2}$, with S_{X1} , S_{Y1} , and S_{Z1} given by

$$\begin{aligned} S_{X1} &= -A_{33}V \begin{bmatrix} (A_{33}+1)dA_{31} + dA_{51} \\ (A_{33}+1)dA_{32} + dA_{52} \\ (A_{33}+1)dA_{33} + dA_{53} + (c_1-1)(A_{44}+1) \\ (A_{33}+1)dA_{34} + dA_{54} \\ (A_{33}+1)dA_{35} + dA_{55} + c_1 - 1 \end{bmatrix}^T, \end{aligned} \quad (34)$$

$$S_{Y1} = -A_{33}V \begin{bmatrix} (A_{33}+1)dB_{31} + dB_{51} \\ (A_{33}+1)dB_{32} + dB_{52} \end{bmatrix}^T,$$

$$S_{Z1} = -c_1 E_c(k) - (1 - a_1) S_1(k).$$

For the velocity subsystem, the sliding surface can be chosen as

$$\begin{aligned} S_2(k+1) &= a_2 S_2(k) + [V(k+1) - V(k)] \\ &+ c_2 [V(k) - V_c(k)], \end{aligned} \quad (35)$$

$$\begin{aligned} S_2(k+1) - S_2(k) &= [V(k+1) - V(k)] \\ &+ c_2 [V(k) - V_c(k)] \\ &- (1 - a_2) S_2(k). \end{aligned} \quad (36)$$

Substituting the discrete state equation $V(k+1)$ into (36) yields

$$S_2(k+1) - S_2(k) = S_{X2}X(k) + S_{Y2}U(k) + S_{Z2}, \quad (37)$$

where

$$\begin{aligned} S_{X2} &= [dA_{41} \ dA_{42} \ dA_{43} \ dA_{44} + c_2 - 1 \ dA_{45}], \\ S_{Y2} &= [dB_{41} \ dB_{42}], \\ S_{Z2} &= -c_2 V_c(k) - (1 - a_2) S_2(k). \end{aligned} \quad (38)$$

Solving (33) and (37), we have

$$\begin{bmatrix} S_1(k+1) - S_1(k) \\ S_2(k+1) - S_2(k) \end{bmatrix} = S_X X(k) + S_Y U(k) + S_Z, \quad (39)$$

$$\text{where } S_X = \begin{bmatrix} S_{X1} \\ S_{X2} \end{bmatrix}, S_Y = \begin{bmatrix} S_{Y1} \\ S_{Y2} \end{bmatrix}, S_Z = \begin{bmatrix} S_{Z1} \\ S_{Z2} \end{bmatrix}.$$

3.2. Design of Discrete Variable Structure Controller. Choose the power rate reaching law as

$$\dot{S} = -\varepsilon \operatorname{sgn} S - \delta S. \quad (40)$$

The discrete form of (40) is

$$S(k+1) - S(k) = -T_s \delta S(k) - \varepsilon T_s \operatorname{sgn} S(k), \quad (41)$$

where T_s , $\varepsilon > 0$, and $\delta > 0$ denote sampling interval, reaching rate, and exponent of reaching rate, respectively. The monotone reaching condition of the discrete power rate reaching law is

$$T_s \delta < 1. \quad (42)$$

Therefore the reaching conditions of acceleration subsystem and velocity subsystem are

$$\begin{aligned} S_1(k+1) - S_1(k) &= -T_s \delta_1 S_1(k) - \varepsilon_1 T_s \operatorname{sgn} S_1(k), \\ S_2(k+1) - S_2(k) &= -T_s \delta_2 S_2(k) - \varepsilon_2 T_s \operatorname{sgn} S_2(k). \end{aligned} \quad (43)$$

Rearranging (43) yields

$$\begin{bmatrix} S_1(k+1) - S_1(k) \\ S_2(k+1) - S_2(k) \end{bmatrix} = -S_{nd1} S(k) - S_{nd2} \operatorname{sgn} S(k), \quad (44)$$

where

$$\begin{aligned} S_{nd1} &= \begin{bmatrix} T_s \delta_1 & 0 \\ 0 & T_s \delta_2 \end{bmatrix}, \\ S_{nd2} &= \begin{bmatrix} \varepsilon_1 T_s & 0 \\ 0 & \varepsilon_2 T_s \end{bmatrix}. \end{aligned} \quad (45)$$

FIGURE 3: Response of acceleration.

With the solutions of (39) and (44), the control law in terms of vector is

$$U(k) = (-S_Y)^{-1} \cdot [S_X X(k) + S_Z + S_{nd1} S(k) + S_{nd2} \operatorname{sgn} S(k)], \quad (46)$$

where $\delta_t(k) = U_1(k)$, $\delta_e(k) = U_2(k)$.

4. Simulations

Assuming the hypersonic cruise missile flight height is $H_0 = 25$ Km, $V_0 = 6$ Ma, the equilibrium condition can be given as

$$\begin{aligned} L_0 + T_0 \sin \alpha_0 &= mg, \\ T_0 \cos \alpha_0 &= D_0, \\ M_{z0} &= 0. \end{aligned} \quad (47)$$

From solution of (47), the trim angle of attack $\alpha_0 = 3.3420^\circ$, the trim angle of actuator $\delta_{e0} = -0.6257^\circ$, and the trim of throttle setting $\delta_{t0} = 0.2418$. At this equilibrium point, the coefficient matrixes of the longitudinal linearization model are

$$\begin{aligned} A &= \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 3.3 \times 10^{-11} & 0.0364 & 9.3 \times 10^{-7} & 0 \\ 0 & -3.3 \times 10^{-11} & -0.0364 & -9.3 \times 10^{-7} & 1 \\ 0 & -9.7489 & -21.3171 & 0 & 0 \\ 0 & 0 & 0.3126 & 1.5 \times 10^{-18} & -0.0584 \end{bmatrix}, \\ B &= \begin{bmatrix} 0 & 8.7 \times 10^{-5} & -8.7 \times 10^{-5} & 6.8603 & 0 \\ 0 & 0 & 0 & 0 & 2.7378 \end{bmatrix}^T. \end{aligned} \quad (48)$$

Suppose that the sample interval $T_s = 0.005$ s; the state matrix in terms of discretization can be given:

$$\begin{aligned} dA &= \begin{bmatrix} 1 & 7.3 \times 10^{-17} & 3.9 \times 10^{-6} & -6 \times 10^{-15} & 0.005 \\ 0 & 1 & 1.8 \times 10^{-4} & 4.6 \times 10^{-9} & 4.6 \times 10^{-7} \\ 0 & 1.1 \times 10^{-10} & 0.9998 & -4.6 \times 10^{-9} & 0.005 \\ 0 & -0.0487 & -0.1066 & 1 & -2.7 \times 10^{-4} \\ 0 & 5.8613 & 0.0016 & -3.6 \times 10^{-12} & 0.9997 \end{bmatrix}, \\ dB &= \begin{bmatrix} -5.7 \times 10^{-13} & 4.4 \times 10^{-7} & -4.4 \times 10^{-7} & 0.0343 & -3.4 \times 10^{-10} \\ 3.4 \times 10^{-5} & 2.1 \times 10^{-9} & 3.4 \times 10^{-5} & -1.2 \times 10^{-6} & 0.0137 \end{bmatrix}^T. \end{aligned} \quad (49)$$

Let $a_1 = 0.99$, $a_2 = 0.98$, $c_1 = 0.68$, $c_2 = 0.3$, $\delta_1 = 0.815$, $\delta_2 = 0.4$, $\varepsilon_1 = 0.005$, and $\varepsilon_2 = 0.005$; the control laws $\delta_t(k)$ and $\delta_e(k)$ can be obtained as in (40). The control system tracks a 2 g acceleration command and velocity command during cruising flight; the simulations are shown as in Figures 3–9.

The simulation results of discrete VSS controller law are shown as in Figures 3–9. In Figures 3 and 4, the solid lines are the command and the dashed lines are the response of the control system. It is observed that the hypersonic missile can track both acceleration and velocity command. The controller also has no steady error. The sliding surfaces of acceleration

and velocity subsystem are also reaching zero with the power reaching rate as in Figures 5 and 6. The steady response of angle of attack is 6.5 deg. with 2 g maneuver acceleration, and the elevator and throttle setting response are shown as in Figures 7 and 8. With the discrete VSS controller, perfect tracking is achieved.

To validate the controller robustness to the model errors, the uncertainties of the model are considered as $|\Delta m| \leq 0.03$, $|\Delta I| \leq 0.05$, $|\Delta S| \leq 0.03$, $|\Delta C_D| \leq 0.15$, $|\Delta C_L| \leq 0.10$, $|\Delta C_m| \leq 0.10$, $|\Delta \rho| \leq 0.06$, and $|\Delta C_T| \leq 0.03$. The Monte Carlo simulation results of 100 times are shown as in Figures 10–16.

FIGURE 4: Response of velocity.

FIGURE 6: Response of velocity sliding surface.

FIGURE 5: Response of acceleration sliding surface.

FIGURE 7: Response of throttle setting.

It is shown that the controller has satisfactory performance to track the acceleration and velocity command with the model parameters uncertainties. For the errors of model mostly affect the acceleration of the missile, the sliding surface of acceleration has obvious response as shown in Figure 12. However, the velocity subsystem is less affected by the parameters disturbance as shown in Figure 13. The elevator is $-8 \sim 5$ deg. with the uncertainties which is more great than result of the norm plant as shown in Figure 14.

5. Conclusion

In this paper a hypersonic cruise missile flight control system is designed using discrete variable structure controller to

track the acceleration and velocity commands. An integrator is augmented to ensure that the tracking has no steady error. The multiple sliding surfaces are designed. And the control laws of acceleration and velocity subsystem are obtained. The uncertain missile plant with unmolded dynamic and parameter variations are considered. Simulation results demonstrate that the control system has good performance in tracking acceleration and velocity command and still has strong robustness to the uncertainties of model.

Competing Interests

The authors declare that they have no competing interests.

FIGURE 8: Response of elevator.

FIGURE 11: Results of velocity.

FIGURE 9: Response of angle of attack.

FIGURE 12: Results of sliding surface of acceleration.

FIGURE 10: Results of acceleration.

FIGURE 13: Results of sliding surface of velocity.

FIGURE 14: Results of elevator.

FIGURE 15: Results of throttle setting.

FIGURE 16: Results of angle of attack.

Acknowledgments

This paper is supported by Fundamental Research Funds for the Central Universities under Grant 3102015BJ008 and Aeronautical Science Foundation of China under Grant no. 2015ZA53003 and this work is also supported by the Special Science Research Foundation of Doctor Subject for Higher Education under Grant no. 20136102120012.

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